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FURTHER DEVELOPMENT OF THE SEXTUPOLE AND DECAPOLE SPOOL CORRECTOR MAGNETS FOR THE LHC

M. Allitt[1], A. Ijspeert[1], M. Karppinen[1], J. Mazet[1], J. Perez[1], J. Salminen[1]
S. Bapna[2], M. Karmarkar[2], A. Puntambekar[2], K. Ruwali[2], A. Thipsay[2]

Abstract

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1 CERN, LHC Division, Geneva, Switzerland
2 CAT, Indore, India

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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M. Allitt, A. Ijspeert, M. Karppinen, J. Mazet, J. Perez , J. Salminen
CERN, LHC Division, Geneva, Switzerland

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

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I. Introduction

The main dipoles of LHC will be equipped with Sextupole (MCS) and Decapole (MCD) "spool" correctors. Each decapole corrector will in addition have an Octupole insert (MCO) and these together are designated as MCDO. In total 2464 MCS and 1232 MCDO assemblies are required for the LHC. Half of these will be made in India in a collaboration between CERN and CAT (Centre for Advanced Technology, Indore), the remainder will be built by European industry. A number of prototypes of both MCS and MCD have been built and tested to confirm the design and to refine the construction techniques, and results have been reported in MT-15. This paper focuses on further development that has been undertaken in relation to choice of materials, assembly techniques and test requirements for the series production of the LHC spool correctors.

II. Description

The heart of the MCS and MCD spool correctors for which the main parameters are given in Table I, consists of a cylindrical coil assembly. This is surrounded by a glass fiber insulation layer and centered inside steel laminations. Radial pressure is obtained from an aluminum cylinder shrink-fitted around the laminations. The assembly is completed with end plates for coil connections and a parallel resistor for magnet protection. The magnet is housed in a magnetic shield also acting as a support [1,2].

TABLE-I
Main Parameters of Spool Correctors

Parameters	MCS	MCD	
Nominal strength	1630 T/m^2	1.2×10^6	T/m^4
Magnetic length	111	66	mm
Overall length with shield	160	110	mm
Aperture	58	63.6	mm
I.D. and O.D. shrinking cyl.	95/101.4	89.9/96	mm
Nominal current	550	550	A
Working/Test temp.	1.9/4.2	1.9/4.2	K
Turns per coil/ no. of coils	2x13/6	2x20/5	
Self inductance	0.8	0.4	mH
Critical current at 1.9K/4.2K	1300/950	1250/915	A
Peak field in coil in 3D	1.9	2.4	T
Mass.	~5.5	~4.0	Kg

The sextupole MCS has six coils whereas the decapole MCD has five [3]. Each of these coils consist of a double pancake wound from a monolithic rectangular superconducting wire, PVA (poly-vinyl-acetate) enameled (parameters in Table II). The coils are wound by "counter winding" [4] on a specially contoured central island and held rigidly with end-spacers. Central islands and end spacers are made of G11 grade fiberglass epoxy which matches the thermal contraction of the coil. The coils in each corrector are connected in series by ultrasonic welding, achieving contact resistances of less than then 5 nΩ /connection at liquid helium (LHe) temperature.

Pre-compression is applied to the coils by shrink fitting the aluminum cylinder (aluminium grade AA 5086) over the eccentric steel laminations which are stacked over the coils (Scissors action) [5]. 80-μm hard-anodizing of the cylinder prevents corrosion between the cylinder and the steel laminations. A radial interference of 0.07 mm yields an azimuthal pre-compression in the coils of 20 – 50 MPa at room temperature and 30 – 60 MPa at cold.

The spool correctors are mounted at the ends of the main dipole close to 12 kA busbars. To prevent these from saturating the yoke of the correctors the latter are encapsulated in an iron-shielding cylinder with coercivity <120 A/m. The mounting flange of this shield contains precision dowel holes for alignment to the main dipole. A 30-μm protective coating of nickel is applied for corrosion protection of the shield.

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TABLE-II
WIRE PARAMETERS FOR MCS AND MCD

Parameters	Values	
Material	NbTi in Cu matrix	
Dimensions insulated wire	1.25 x 0.73 ± 0.01	mm
Insulation	PVA	
Insulation thickness	0.06 ± 0.01	mm
Filament Twist pitch	18 ± 2	mm
Cu/Sc ratio	1.6 ± 0.1	
RRR of Cu matrix	> 100	
Critical current (5T, 4.2K) (perpendicular / parallel to broad side)	> 630/700	A

In the LHC the MCS spool correctors will be powered in families of 154 connected in series. If one magnet quenches the energy of the whole family (~25kJ) will be dissipated in that corrector. Therefore each MCS corrector has been protected with a 0.1 Ohm shunt resistor made of ø 5 mm stainless steel wire, wound non-inductively around the magnet in the cylindrical space between magnet and shield.

III. PRODUCTION TECHNIQUES

Because of the tight tolerances, the fabrication of the intricately shaped central islands and end spacers from glass-fiber epoxy material, and the winding of the coils and their assembly, are demanding operations [6].

A. Coil Winding Machines.

After the initial development of a twin-arm manual coil winding fixture, more advanced automatic coil winding machines were developed based on different principles, one at Ferrara Univ., Italy, through Instituto Nazionale di Fisica Nucleare (INFN) and another at CAT through Patel's Analog and Digital Measurement Co Ltd. (PADMC), Pune, India. MCS and MCD coils have been successfully wound on these machines. The Ferrara machine is an elaborate intelligent robot with a rocking coil mandrel. It is capable of winding coils of different widths and lengths. The CAT machine (Fig.1) is rather simple and suited for small MCS and MCD coils. It employs mechanical cams and tilted rotating arms. The coil mandrel is of the non-rocking type. CAT also designed a second type, a simple motorized version of the earlier twin-arm manual winding fixture. For series production anyone of these could be used.

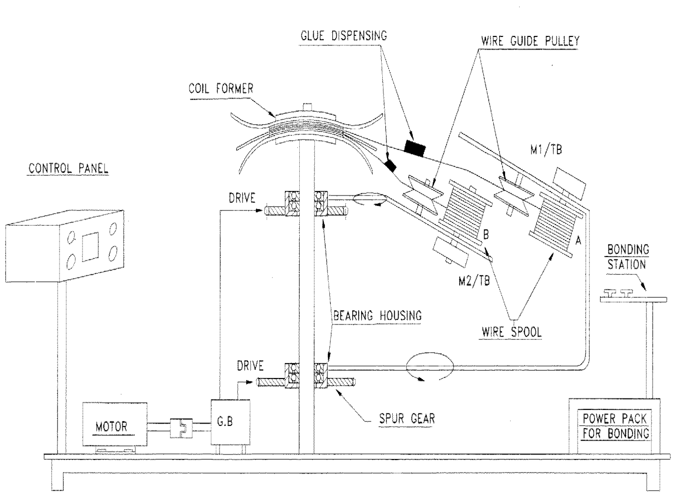

Fig. 1. Tilted-arm automatic coil winding machine.

B. Central Islands and End Spacers.

These complex shapes are produced from glass-fiber epoxy (Fig.2), an unfriendly material for machining. Molding appeared to be the first choice for a large series. Prototypes were made both by Resin Transfer molding and Compression molding, using an adapted curing process and a special CNC (Computer Numerical Control) machined mould. However given the large number of pieces to be produced the risk of inconsistent quality due to variation in the distribution of resin and fibers is non-negligible and therefore fabrication of these pieces by CNC milling from a standard G11 glass-fiber tube is preferred. In this case, care has to be taken to use tube which is stress-relieved by pre-slitting, and also the wear of the cutting tool must be considered when machining bulk quantities.

C. Coil Curing.

The coils are wet wound using epoxy AW 106 resin & HV 953 U hardener in ratio of 10:8 pbw (part by weight) of CIBA Chemicals and cured either by oven heating of the coil in its mould or by resistive heating of the coil passing a current through its wire. Coating the inside of the mould with a thermal insulation material like Teflon® avoids heat transfer from the coil to the tooling and also helps in releasing the coil from the mould after curing.

D. Insulation Around the Coil Assembly.

A slotted glass-fiber tube charged with epoxy glue is slipped and glued over the coil assembly. The slot is carefully measured and filled with G-11 shims to avoid locally a resin rich area. This method has successfully replaced the earlier method of wrapping a B-stage glass cloth around the coil, the curing of which was a rather lengthy process. After curing, the insulating slit tube is machined to a precise outside diameter to obtain the correct interference (Fig.3).

E. Coil Terminal Joining.

First generation prototypes employed soldered connections using standard tin-lead solder with long connections to keep the contact resistance as low as possible. A more elegant Ultrasonic Welding (USW) has been adopted for terminal joining. With this a joint resistance as low as 5 nΩ per connection has been achieved.

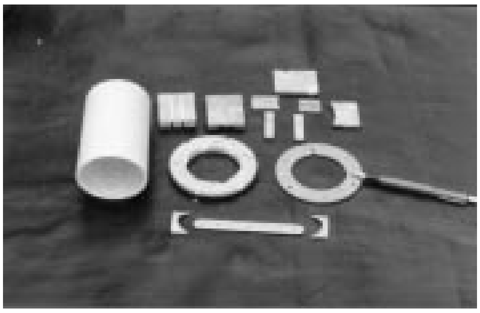

Fig. 2. G-11 glass-fiber components

F. Steel Laminations.

Laminations of 1mm thick low carbon steel (Fe 99.99%) and 0.5mm thick cold-rolled silicon steel (type AISI M 45) have successfully been used in prototypes. For series production 1.5 mm thick low carbon steel has been selected as it is of relatively low cost and reduces the number of laminations required. The laminations are produced by the fine blanking technique which ensures the close dimensional accuracy required to guarantee correct pre stress, and also enables straightforward production of 0.03 mm nipples to facilitate sliding of laminations over each other as the shrinking cylinder contracts. The low carbon steel laminations need a surface treatment for corrosion protection.

G. Shrink-Fitting of Aluminium Cylinder.

Experience has shown that a custom made electric band heater around the cylinder is sufficient to heat the cylinder. A conical tool of Teflon® placed on top of the stack of laminations helps align the shrinking cylinder. A simple steel cylinder, with the same inner diameter as the heated aluminum cylinder, is first slipped over the stack of laminations to check their alignment.

H. Alignment Dowels.

The spool corrector needs to be aligned very precisely (+/- 0.1mm) with respect to the axis of the main dipole magnet. Two alternative methods have been used. In the first method the magnetic axis of the corrector magnet is determined by measurement on the magnetic measurement bench at room temperature [7] and the dowel holes are then drilled according to measurement. In the second method all the components are produced with dowel holes of sufficient precision (0.04mm) and the measurement on the magnetic bench is used to verify the accuracy. The second method has been adopted as the preferred method.

IV. Quality Checks

To ensure reliable and fail safe operation of the spool correctors rigorous quality checks are necessary at every stage. Mechanical measurement of each of the critical components like central islands, end-spacers, coils, shrinking cylinders and dowels in the steel screen as well as electrical checks on each coil and assembly of coils are required. In addition all tooling, fixtures and process parameters like coil curing cycle time and temperature and contact welding parameters are checked and certified before use in production. The acceptance limits are found in the technical specifications of the MCS and MCD [1,2].

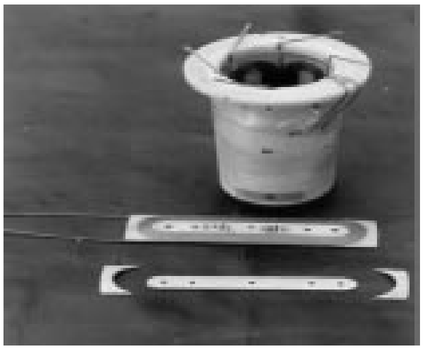

Fig. 3. Assembled coils and coil terminations

A. Training at 4.2k.

In addition all spool correctors will be cold tested by the manufacturer at 4.2 K in liquid helium and trained up to the critical current. Special cryostats, power-converter (3V, 1500A) and PC based quench data acquisition system have been designed for testing of the series production (Fig.4). During this test the resistance of the joints of each corrector is measured at 600A at 4.2K. The allowable limit is 27 nΩ for the total resistance of a corrector magnet.

B. Magnetic Measurements at Room Temperature.

The magnetic field quality as well as the precision of alignment (dowel-pin holes) is measured at room temperature on a dedicated test bench using a rotating search coil, powering the correctors with 1-2 A current. Table-III shows typical acceptance criteria for the MCS.

V. Estimated Production Times and Cost

A production rate of about 50 MCS magnets and 25 MCDO magnets per month is required to match the production of the main dipoles of LHC. The typical fabrication cycle consists of 8 hours for winding, curing and assembly of the coils, 3 hours for the assembly of laminations, shrinking cylinder, iron screen including mechanical and electrical checks, 1 hour for the magnetic measurements at room temperature, 8 hours for training at

Table III
Typical Magnetic Field Acceptance Criteria for the MCS

Parameter	Acceptance Criteria
	For Alignment Precision
Normal/Skew Quad.	<1% of sext. field at R=17 mm (= axis shift of 0.1 mm)
Skew Sextupole	<0.5% of normal sextupole (= twist angle of 1.5 mrad)
	For Quality Control
Sextupole strength	Within 1% of theor. strength
Any other multipole	<1% of sext. field at R=17 mm

4.2K. With three coil winding and assembly stations, one magnetic measurement bench and two cryostats (each holding three to five MCS or MCDO at a time) it is expected to achieve the required production rate safely. An estimate of the cost break-down of manufacture and testing of the MCS based on the prototype work is given in Table IV. The development of the coil winding machines, tooling, fixtures and construction techniques has been done at CERN and CAT while making prototypes and the know-how for initial production and training is provided to the European and Indian manufacturers. In addition the test bench for warm magnetic measurements and the quench detection system is provided to the manufacturers.

VI. Conclusions

Further development of the spool correctors has led to final choices of materials and processes assuring economic and robust magnets. The options have been successfully tested on prototypes and with this experience we are now starting up the series production with confidence. CERN has awarded the contract for the series production and testing of 1232 MCS to European industry. The training test and magnetic field measurement will be done at the factory. CAT has also placed an order with an Indian industry for manufacture of 1300 MCS. The testing at 4.2K of the latter series will be done in-house at CAT for which all necessary cryostats, powering and data acquisitions system etc. have been ordered.

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TABLE IV
Estimated Break-Down of Manufacturing Cost.

Work Package	Percent of Total Cost
Design/documentation	5 %
Machines, tooling	10 %
Component fabrication	25 %
Coil winding, magnet assembly	25 %
Inspection, Testing (R.T.and cold)	35 %

Fig. 4. Cold test set up in Indore.

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