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LHC Note 109

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CM-P00061480

DEVELOPMENT OF A SUPERCONDUCTING SEXTUPOLE-DIPOLE CORRECTOR MAGNET

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Paper presented at the 11th International Conference on Magnet Technology
28 August - 1 September 1989, Tsukuba, Japan

Prévessin, November 1989

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ABSTRACT

Each half cell of the proposed Large Hadron Collider (LHC) lattice [1] will be equipped with a 1.25 meter long superconducting corrector magnet which will combine a 4000 T/m^2 sextupole and a 1.5 T dipole. The correction magnets of the two rings will be mounted in pairs in the cryostat of the main quadrupoles. The sextupole coil is wound from a solid, NbTi based, superconducting wire. The dipole coil is wound from a preassembled ribbon containing 12 parallel wires. The two concentric coils are precompressed by shrink fitted aluminium rings. The yoke is simply a thick walled iron tube. The paper describes the magnet design, discusses the results of the field and stress calculations with emphasis on the superposition of the two types of field. It comments on the choice of the conductors and describes the developed fabrication techniques.

INTRODUCTION

The sextupole is designed to correct for chromaticity as well as for sextupolar errors from other machine elements like the main dipoles and will operate between -4000 T/m^2 and $+4000 \text{ T/m}^2$. The dipole will provide

a means for orbit corrections and operates between -1.5 T and $+1.5 \text{ T}$.

Figure 1 shows a transverse cross-section of the paired magnets. Each pair will correct the horizontal orbit in one ring and the vertical orbit in the other ring and vice versa. The LHC will need at least 800 of these magnets and

Vertical orbit correction - Horizontal orbit correction

FIGURE 1. Schematic cross section of two paired magnets.

therefore fabrication techniques have been chosen that are applicable to large series production. This project is being carried out in the frame of a cooperation agreement between CERN and Tesla Engineering with the active participation of Rutherford Appleton Laboratory.

GENERAL DESIGN

From the centre outwards the main components are :

the sextupole coils, the dipole coils, the aluminium alloy shrink fitted rings and the iron yoke. The sextupole coil is placed close to the centre in order to minimize the necessary excitation. Another reason is that the dipolar field does not create such intense fields in the inner sextupole as would be the case if their positions were reversed. The field quality aimed at is such that the effect of its higher

multipoles stays below about one tenth of that of the machine half cell at injection. The design parameters are given in Table 1.

The sextupoles are connected in series by means of superconducting lines in the machine cryostat. The dipoles are powered individually and their nominal current of 47 A is as small as possible to minimise the heat losses at the connections but large enough to keep quench voltages at an acceptable level. The wires are monolithic conductors consisting of NbTi filaments in a copper matrix and insulated with an enamel.

The overall diameter of the yoke has been limited to 170 mm to allow for 10 mm of air gap between the paired magnets. This will suppress the magnetic cross-talk between the two magnets which must operate independantly. The length was chosen to fit in the cryostat of the main quadrupoles.

Figure 2 shows a picture of a magnet model where the coils were made of copper wire.

TABLE 1

Design parameters

Values of the prototype given in brackets.

	<u>Sextupole Coil</u>		<u>Dipole Coil</u>	
Field (gradient)	4000	T/m ²	1.5	T
Peak field in coil	4.2	T	3.5	T
Current	458	A	47	A
Number of turns/coil	104		1200	
Ampere turns/coil	47.6	kA	56.4	kA
Stored energy/magnet	6.2	kJ	5	kJ
Inductance	0.059	H	4.6	H
Inner radius	25	mm	36	mm
Outer radius	34.6	mm	40.2	mm
Length straight sectn	1	m	1	m
Operating temp.	1.8	K	1.8	K
	<u>Sextupole Conductor</u>		<u>Dipole Conductor</u>	
Overall section	0.7x1.2	mm ²	Diam 0.35	mm
Metal section	0.5x1.0(0.58x1.08)	mm ²	Diam 0.3	mm
Filament size	~ 25	(64) μ m	~ 10	(21.5) μ m
Number of filaments	~ 340	(54)	~180	(36)
Twist pitch	~ 15	(25) mm	5	(15) mm
Copper/NbTi ratio	2/1	(1.6/1)	4/1	(4.4/1)
Insulation enamel	Polyimide	(PVA)	Polyimide	(PVA)
Breakdown voltage	2	kV	2	kV
Current density	915	A/mm ²	666	A/mm ²
Current dens. NbTi	2747	(2379) A/mm ²	3332	(3596) A/mm ²
% of short sample	59	(51) %	65	(71) %

FIGURE 2. Cross section of a magnet model (coils of copper wire)

SEXTUPOLE COILS

Field calculations with POISSON [2] showed that the desired field quality could be obtained with coils consisting of one single block. The tangential height of the block has been optimised to suppress the 18-pole field component.

The iron yoke enhances the sextupole field only slightly; it accounts for $\sim 5\%$ of the total field. The loadline is perfectly linear up to the full excitation. Its slope is reduced by ~ 1 o/oo when the dipole is excited simultaneously. The latter causes additional sextupole errors and the overall effect is shown in Table 2.

The insulated conductor is wound around an insulated central island made of hard copper in 13 radial layers of 8 turns each. Each coil is vacuum impregnated. The required accuracy is ± 0.02 mm on the position of the radial

sides. To obtain this, the central islands are precisely machined and the coils are preassembled on a mandrel, dowelled in position and the gaps between the coils are then filled with preimpregnated spacers.

The interconnections between the coils and the connections to the leads are made at one end by soldering the wire ends side by side in grooved copper pieces over a length of 40 mm. The specific resistance of such soldered joints has been measured to be a constant of $2.1 \cdot 10^{-8}$ Ohm-cm at 4.2 K. The joint resistance is thus inversely proportional to the length of the joint. The total heat loss (3 joints) will be 3.3 mW at 4.2 K.

Quench calculations predict a local temperature rise of 136 K and a voltage peak of 290 Volts. The current decays with a time constant of 140 msec.

TABLE 2

Calculated multipole fields errors at nominal excitation of both magnets
At radius of 1 cm. (units of 10^{-6} Tesla meter)

Pole	Sextupole Coil	Dipole Coil	Sextupole + Dipole	Sextupole - Dipole	Specified Tolerance
2 -pole*	-69		-18'025	+2'483	150
6 -pole*		-188	-844	-3	700
10-pole	2	36	16	-36	100
14-pole	5	-4	-3	6	6
18-pole	-6	3	-1	-7	2

*) These errors can be corrected by adjusting the currents.

DIPOLE COILS

The desired field quality of the dipole field can only be obtained by subdividing the coil into at least two blocks. The iron yoke enhances the dipole field and contributes $\sim 35\%$ to the total field. The load line is not perfectly linear; the field at full excitation is reduced by about 10/100 due to the iron saturation. A simultaneous excitation of the sextupole coil increases this effect to about 70/100. Table 2 shows the field quality and the influence of the saturation effects in the yoke. The dipole error, a field reduction caused by the iron saturation when the sextupole is excited, appears to be far beyond the tolerance. However at injection energy, basis for the tolerance, the dipole is not expected to be powered to nominal field and at one tenth of its field, the dipole error is of the order of the tolerance value.

Winding a regular pattern with the extremely thin wire of 0.35 mm outer diameter appeared to be very difficult. Therefore the wire is preassembled to form a ribbon of 12 parallel wires which is then wound around a central island of insulated hard copper and connected at the end to form a series wound coil. Figure 3 shows a picture of the ribbon cross-section in the impregnated coil.

The whole coil is wound with one continuous ribbon, 100 layers overall, and the second block has been subdivided into 3 nearly rectangular sub-blocks separated by wedge shaped copper spacers in order to approximate a circular sector

FIGURE 3 Detail of the coil cross section

FIGURE 4 Winding operation.

geometry. Figure 4 shows the winding operation.

The interconnections in the coil and the connections between the coils and the leads are made at one end where the wires are soldered side by side in small copper tubes over a length of about 20 mm. The specific resistance over such joints has been measured to be $13 \cdot 10^{-8}$ Ohm-cm at 4.2 K. The total heat loss (25 joints) will be 3.6 mW at 4.2 K.

Quench calculations, assuming that all the energy is absorbed in the coil itself, showed that stabilisation with a copper content of 2:1 gives unacceptably high quench voltages and this ratio had to be increased to 4:1. The expected local temperature rise in case of a quench is 130 K and the voltage peak 950 Volts with a time constant of 180 msec for the current decay.

ASSEMBLY OF THE COILS

The assembly must be such as to guarantee the necessary mechanical precision, especially the ± 0.02 mm on the radial positions of the coil faces. In addition, it must make the coils hold together as a single mechanical body to obtain a sufficient stiffness against radial bending of the coils due to the magnetic forces. This is obtained by a final vacuum impregnation. The assembly

procedure goes as follows:

The sextupole coils, preassembled on the inner mandrel are wrapped at 7 positions with bands of preimpregnated glass tape to obtain a precise machineable outer diameter for the positioning of the dipole coil later on. Clamps are put on and the whole is cured in an oven.

The diameter of the 7 bands is measured and if necessary machined and one layer of preimpregnated tape is wound around. The space between the bands is filled by wrapping with glass tape.

The dipole coils are then put on the precise bands and the angles adjusted with jigs, one at each end. The spaces between the two coil halves are filled with preimpregnated spacers. As for the sextupole coils, bands of preimpregnated tape are wrapped around at 7 positions to obtain a precise machineable outer diameter, the coils are clamped and the whole is cured in an oven. The diameter of the bands is measured and machined if necessary and the spaces between the bands are filled by wrapping with glass tape.

The final impregnation is done in a mould composed of an especially designed retractable mandrel to fill up the bore and an outer mould located on the bands. Finally, the diameter is measured and machined if necessary and the aluminium rings are shrunk on.

FIGURE 5. Principal bending forces in coil assembly

CONTAINMENT OF THE E.M. FORCES

Due to the two independantly operated magnet coils, there are three basic types of magnetic forces: one caused by excitation of the sextupole coils only, one caused by excitation of the dipole coils only, and one which comes in addition from the interaction when the two coils are powered simultaneously. Figure 5 shows schematically these principal forces. The first two always have the same sign independantly of the polarity of the magnetic field but the third changes sign when the polarity of one of the two coils is inverted. It consists of strong bending forces in the sextupole coil whereas the additional forces in the dipole coil hardly contribute to the bending and therefore have not been shown in Figure 5. Thus there are four load cases to be considered: sextupole only, dipole only, sextupole + dipole, sextupole - dipole or vice versa. The bending moments are shown in Figure 6; the largest moments are due to the effect of the dipole field on the sextupole coil.

The stresses in the coils consist of the bending stresses together with

FIGURE 6. Principal bending moments in coil assembly

TABLE 3
Coil stresses (N/mm²)

	Min.	Max.
From Rings: Shrink fit	-40	-15
Therm.contract.	-10	+10
From Field: Sext.+ Dipole	-13	+13
Sext.- Dipole	-4	+11
Total*: Sext+Dip+Rings	-58	-7
Sext-Dip+Rings	-52	-8

*) The extreme stresses occur in different locations for each case and the stresses do not add up algebraically.

the local inner coil stresses. The stress distribution is complicated by the presence of materials of very different Youngs moduli ranging from the relatively soft insulation to the stiff copper. Finite element calculations have been made with the programme CASTOR [3] for the assumption that the coils and the shrink fitted rings hold together as one single body. The ranges of stresses in the coils are given in Table 3.

To avoid quenches caused by the tensile stresses, the 9 mm thick aluminium rings precompress the coils when shrink fitted on assembly and further compress the coils by contraction on cooldown from room temperature to 1.8 K. Table 3 shows the effect of the precompression. The shrink fit of 0.05 mm is just sufficient to keep the powered coils compressed.

The prestress calculations have been checked by strain gauge measurements made on the model shown in Figure 2.

YOKE

The yoke is a simple thick walled tube made of low carbon iron. The inner diameter has been fixed at 100 mm to keep the induction in the iron below 2 T. A calculation with POISSON, made to check the importance of the iron thickness, showed that an increase of the inner diameter (with a fixed outer diameter) although reducing the enhancement of the dipole field and increasing the saturation in the iron, does not notably increase the multipole components. However, the stray field

just outside the yoke changes from 0.016 T for the present inner diameter to 0.41 T for an extreme inner diameter of 160 mm

The coil assembly is centred in the yoke by a number of pins, stiff enough to counteract the force of 45 N per μm of radial offset that will pull the coil away from the centre in case of a slight off centre position. These pins are made of two different materials, aluminium and tungsten, to compensate for the difference in contraction between the coil and the yoke (Figure 2).

CONCLUSION

The development of the sextupole-dipole magnet is progressing satisfactorily. The complications caused by the presence of two types of coil in one magnet and by the extremely thin wire used for the dipole coil, have been solved in view of a future mass production. Critical points like the interconnections and the prestress have been checked by measurements on models. The prototype is expected to be powered by the end of this year.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the contributions of R. Mauris (CERN) and M. Parr (Tesla) for the design, of D. Landgrebe (Tesla) for the development work and of B. Crépin (CERN) for the typing of the paper.

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