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LHC Note 247

Electromagnetic and Mechanical Design of a 56 mm Aperture Model Dipole for the LHC

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Abstract

The Large Hadron Collider (LHC) project is proposed as the future extension of the CERN accelerator complex. The LHC requires twin aperture superconducting dipoles of highest possible field to guide the proton beams in the existing LEP tunnel of 26.7 km circumference. This paper describes the electromagnetic and mechanical design of a 56 mm aperture model dipole for the LHC.

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13th International Conference on Magnet Technology (MT13), Victoria, Canada
20-24 September 1993

Geneva, Switzerland
Octobre 12 1993

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Abstract - The Large Hadron Collider (LHC) project is proposed as the future extension of the CERN accelerator complex. The LHC requires twin aperture superconducting dipoles of highest possible field to guide the proton beams in the existing LEP tunnel of 26.7 km circumference. This paper describes the electromagnetic and mechanical design of a 56 mm aperture model dipole for the LHC.

I. INTRODUCTION

CERN is preparing the construction of a new particle collider, the Large Hadron Collider (LHC), which will be installed in the existing 27 km tunnel of LEP [1]. The space constraints have led to the development of high-field superconducting magnets assembled in a common yoke and cryostat following the "two-in-one" concept [2]. The LHC magnets will use the technology of NbTi superconductors and operate at super fluid helium temperature ($T < 2.1$ K).

Twin aperture model dipoles have been constructed and tested. Long prototype dipoles are now under construction. They have a coil diameter of 50 mm and use NbTi superconducting 17 mm wide cables. Fields up to 10.5 T at 2.1 K have been recently achieved.

A review of the requirements of the machine has led to a change in the coil aperture from 50 mm to 56 mm. Even if the operational field of the main dipoles is now 8.65 T, it has

been decided to maintain an R&D program searching for the strongest possible field in the 56 mm twin aperture dipoles. A collaboration has been set up between the Helsinki University of Technology (Finland), the Uppsala University (Sweden), and CERN in order to design, fabricate and test a high field, 56 mm aperture, model dipole (MFISC). The main features of the design are (see also Table I):

A. Coils consisting of two layers of windings in separate stainless steel collars. The stainless steel has an elastic limit of 800 MPa at 300 K. The conductor distribution is optimized to cancel the higher field components in particular b_7 and b_9 .

B. Inner layer cable made with thinner strands with respect to earlier models, which eases coil winding.

C. Iron yoke made in three parts with only one vertical gap. The gap will be closed at the iron periphery during the assembly at room temperature. Special care has been taken in the design of the yoke shape to handle the saturation effects in yoke iron located close to the coil.

D. Compressive stresses in the coils limited to 120 MPa (at 11 T) as in the previous models.

Initially it was envisaged to use NbTiTa alloy in the superconducting cables. A ternary alloy should give a higher current density than NbTi in the range 10-11 T for temperatures lower than 2 K. A development program has been launched in two European firms. The results obtained so far with the alloy containing 25 % Ta have shown that the final current density is not improved (1100 A/mm², 11 T, 2 K). The development is going on with other NbTiTa alloys and modes of fabrication, but the magnet under construction will use NbTi alloy as superconductor. The mechanical structure has been designed nevertheless for forces corresponding to 11 T, which could be achieved with improved NbTiTa alloy (1650 A/mm², 11 T, 2 K). The present report describes the magnet and the main construction features. The first coil has been wound and the magnet should be tested in May 94.

II. THE SUPERCONDUCTING CABLE

The cables of the model are trapezoidal of the Rutherford type and are arranged in the magnet in two layers. The strand material is a NbTi/Cu composite. The cable parameters are shown in Table II. To improve the flexibility of the inner

TABLE I
PARAMETER LIST FOR MAGNET MFISC

Turns per channel		
inner layer	28	
outer layer	54	
Quenching field at 2 K	10	T
Stored energy	760	kJ/m
Main current	14370	A
Inductance	7.35	mH/m
Model magnetic length	0.84	m
Iron length	0.67	m
Coil/collar length	1.08	m
Total length	1.32	m
Intra-beam distance	200	mm
Beam tube diameter	56	mm
Collar diameter	182	mm
Inner yoke diameter	183	mm
Outer diameter	600	mm

TABLE II
CHARACTERISTIC DATA OF THE CABLE

Layer	Inner	Outer	
Outer width, bare	2.12	1.68	mm
Inner width, bare	1.78	1.47	mm
Height, bare	16.7	16.7	mm
Diameter of strands	1.10	0.87	mm
Number of strands	30	38	
Ratio Cu/Sc	1.6	1.87	
J_c at 8.0T and 4.2K	1070	1108	A/mm ²
dJ_c/dB	487	609	A/mm ² T
Filament diameter	5	5	μ m
Number of filaments	20328	9438	

cable during winding, compared to the cable used for the 50 mm aperture LHC dipole [2], the strand diameter has been reduced from 1.29 mm to 1.1 mm and the number of strands has been increased. Both cables have a SnAg coating on the strands. Critical current measurements have been performed on strands extracted from the cables. Results are given in Table II. The measurements indicate that the critical current degradation in the cable is lower than 3 %.

III. THE COIL BLOCK OPTIMIZATION

For the optimization of the dipole coil the program package ROXIE (routine for the optimization of magnet X- sections inverse field calculation and end region design) has been developed at CERN using analytical integration for computing the coil contributions in a yoke which first is considered having infinite permeability. Mathematical optimization techniques by means of a penalty function method and the application of the search routine EXTREM by Jacob [3] have been applied in order to find a coil block arrangement with low multipole errors and high dipole field.

The cross section of the optimal design for the cable used with an aperture of 56 mm is shown in Fig. 1. The relative multipoles (in units of 10^{-4} for 1 cm radius) are $b_3 = 0.03$, $b_5 = 0.001$, $b_7 = -0.009$ and $b_9 = 0.002$. Nominally as the inner layer is at 95.0 % on the load line, the outer layer is at 91.6%.

Fig. 1. Coil cross section.

If the saturation is taken into account the quenching main dipole field is 10.0 T at 14370 A. In this situation the maximum field in the inner cable is 10.3 T and in the outer 9.1 T (94.5 % on the load line of the outer cable).

IV. COIL END DESIGN

As the properties of the cable may degrade during the winding process, the maximum fields to which the cable is exposed in the end sections must be reduced. The objective was to provide a peak magnetic field 5 % lower than in the straight section.

The end turns were modeled with elliptical constant perimeter bends. The magnetic fields were computed using the Biot-Savart law and line current discretization of the conductors. The radial variation of the current density is taken into account. The coil ends are placed outside the yoke in order to lower the field and the design optimization was carried out by adjusting the axial positions of cable blocks in order to have short ends. Both inner and outer layers were made to start bending at the same axial position to reduce the number of collar types.

The peak fields of the optimized coil ends for the inner and the outer layer are 91.5 % and 94 % of the peak fields at the straight sections, respectively.

V. OPTIMIZATION OF THE IRON YOKE

Mechanical requirements primarily dictated the iron yoke design, but some design parameters could be adapted in order to optimize the field quality. Field homogeneity was optimized, both at nominal current and as a function of the excitation. The FE program package POISOPT [4] is applied and allows automated minimization of the saturation induced effects. The package is an extension of CERN's POISSON version. The resulting yoke geometry is shown in Fig. 2. Details indicated numbers 1-4 result from the magnetic optimization. The yoke-collar interface deviates from its original circular shape and 12 holes are added to guide the flux in the yoke. These structures improve the balanced building up of the saturation around the coil.

The void 1 in Fig. 2 is needed because it minimizes the variation of the sextupole relative term Δb_3 ($\Delta b_3 < 0.1$ in units of 10^{-4} for 1 cm radius as the field varies from zero to 9.5 T). It causes, however, a constant sextupole term, $b_3 = 3.5$ units. Thus, the dipole coils were modified, with only minor block displacements, such that a negative b_3 offset is achieved and the sextupole becomes about zero at nominal operation. Holes 2, 3 and 4 are added to diminish the quadrupole relative term b_2 and its variation Δb_2 ($\Delta b_2 < 0.2$ units as field varies from zero to 8.7 T). These details also assist in keeping Δb_3 small. The yoke design did not effect the higher order multipoles ($b_7 - b_{11}$). The void 1 has some effect on b_5 .

Fig. 2. Magnet design. Flux and field lines are calculated for a central field of 9.5 T. For details and labels see text.

($\Delta b_3 = -0.015$ units), however, this is small compared to the effect induced by the permeability of the stainless steel in the collars ($\Delta b_3 = 0.060$ units for $\mu = 1.003$). Fig. 2 also shows flux lines and a field strength map. Contour lines of 1 T, 2 T and 3 T are indicated.

Fig. 3 shows the effect of the yoke optimization. b_2 and b_3 are given for the optimized case and for a simplified case. In the simplified case the inner surface of the yoke is circular and only one hole is used to balance b_2 . The figure demonstrates the possibility of controlling b_3 despite saturation for the whole field range of the twin aperture dipole.

VI MECHANICAL DESIGN

The mechanical structure of the dipole is designed to withstand the huge electromagnetic forces (3.0 MN/m in a coil quadrant at 11 T) and to limit the deformation of the coils as much as possible. The coils must work under compressive stress when the magnet is excited in order to avoid any cracks in their structure [5]. The necessarily rigid geometry can be realized if the gaps between the iron yoke parts are closed at low temperature before and after energizing [6].

Fig. 3 Effects of yoke iron optimization on multipoles b_2 and b_3 .

TABLE III
OPTIMIZED GAP PARAMETERS OF MECHANICAL ANALYSIS

Vertical gap size	0.10	mm
Inclined gap size	0.05	mm
Collar-yoke contact up to		
right side	68	deg.
left side	45	deg.
Yoke-shrinking cylinder		
radius interference	-0.41	mm

The magnet structure is designed in order to keep a good contact between the collars and the iron yoke for all working conditions. Particular care has been paid to ensure a good alignment of the collars and the iron.

A slot has been introduced at the center of the collar post. This element prevents the inner coil from over compression during the assembly. A finite element analysis of the structure has been carried out considering the four cases: after collaring, completed magnet at room temperature, cooled to 1.8 K and excited to 11 T.

Table III gives the optimized gap parameters. In Table IV and Table V the computed forces, displacements and stresses for the different working conditions are listed. Labels in tables refer to Fig. 2. It is important to note that the coils are still under compression when the electromagnetic forces are loading the structure. The elongation of the horizontal diameter of the bore is small (0.07 mm). Since the gaps are still closed at 11 T, there is practically no difference in the azimuthal stress of the cylinder at 1.8 K with or without magnetic forces.

TABLE IV
CHARACTERISTIC DATA OF THE MECHANICAL DESIGN

Load step	293 K 0 T	1.8 K 0 T	1.8 K 11 T	
Vertical gap F_g	122	3769	2122	N/mm
Inclined gap F_i	993	682	1312	N/mm
Collar-yoke				
F_{r4} (45°-68°)	1454	0	0	N/0.5mm
F_{r3} (24°-45°)	422	0	176	N/0.5mm
F_{r2} (12°-24°)	203	0	506	N/0.5mm
F_{r1} (0°-7°)	416	225	687	N/0.5mm
F_{r1} (353°-360°)	136	39	341	N/0.5mm
F_{r2} (336°-348°)	0	0	128	N/0.5mm
F_{r3} (135°-156°)	1468	122	143	N/0.5mm
F_{r3} (156°-168°)	281	31	481	N/0.5mm
F_{r1} (173°-180°)	322	144	722	N/0.5mm
F_{r1} (180°-187°)	83	4	359	N/0.5mm
F_{r2} (192°-204°)	0	0	129	N/0.5mm
Shrinking cylinder stress	216	421	425	MPa
Force in right coil quadrant				
F_x	0	0	3025	N/mm
F_y	0	0	-1481	N/mm

TABLE V
DISPLACEMENTS AND STRESSES IN SOME SIGNIFICANT POINTS

Load step			293 K		1.8 K		1.8 K	
Collaring			0 T		0 T		11 T	
Displacement (mm)								
Points	U _x	U _y	U _x	U _y	U _x	U _y	U _x	U _y
A			0.370	0.000	-0.292	0.000	-0.233	0.000
B			0.000	0.341	0.000	-0.251	0.000	-0.283
D _o			-0.100	-0.061	-0.100	-0.619	-0.100	-0.651
D _i			-0.051	-0.051	-0.100	-0.285	-0.092	-0.317
E _r			-0.026	0.000	-0.474	0.000	-0.402	0.000
K _r			-0.033	0.030	-0.254	0.030	-0.149	0.030
M ₁ [*]	0.000	0.136	-0.014	0.141	-0.241	-0.130	-0.211	-0.193
M ₂ [*]	0.000	0.149	-0.014	0.159	-0.242	-0.118	-0.211	-0.182
E ₁			-0.002	0.000	-0.016	0.000	-0.020	0.000
K ₁			0.009	0.030	-0.233	0.030	-0.271	0.030
Stress (MPa)								
Points	radial	azim.	radial	azim.	radial	azim.	radial	azim.
5	-0.2	-97.3	-0.6	-112.3	-0.8	-92.1	-4.2	-52.9
6	-5.8	-98.9	-13.5	-111.8	-4.8	-89.6	3.9	-70.3
7	-20.2	-102.8	-23.8	-119.6	-19.9	-101.1	-9.8	-41.3
8	-39.2	-45.5	-64.4	-51.7	-9.0	-35.1	-13.3	-9.4
9		-91.1		-103.8		-81.6		-116.1
10		-72.4		-83.4		-66.6		-115.0

* Collars are divided into two layers: fixed (M_1) and floating (M_2).

ACKNOWLEDGMENT

The authors wish to thank, for their continuous support and encouragement, E. Byckling (Helsinki University of Technology), T. Ekelöf (Uppsala University) who are the promoters of the collaboration and G. Brianti, responsible of the LHC activities at CERN.

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