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Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions

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Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions

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Abstract **– In order to achieve high field quality and low current rating of the 250 T/m quadrupoles for the LHC low-β insertions, a design based on a graded four-layer coil with an aperture of 70 mm, wound from NbTi conductor cooled at 1.8 K, has been proposed. Its mechanical structure is based on the collar-spacer concept, where a thin collar serves for coil assembly only. The iron yoke has both important magnetic and structural functions, since the magnetic forces are taken by the rigidity of the iron lamination pack. The coil and cable parameters are derived for this particular structure, and the results of the structural analysis of the magnet are presented. A one-metre model of the quadrupole is presently under construction; its features are described and some initial cable tests reported.**

I. Introduction

The study of the Large Hadron Collider (LHC) [1], proposed as the future extension of the CERN accelerator complex, has been accompanied by a vigorous superconducting magnet development program [2]. The specific requirements for the LHC insertions quadrupoles, especially those concerning the low random multipole errors of the quadrupole field, have led us to propose a design that is based on a four layer coil with an aperture of 70 mm, wound from two NbTi graded keystoned cables adjusted for the ideal Roman arch windings. The analysis of the design principles and of the magnetic performance of the coil in single and two-in-one quadrupole configurations, conceived for low-β and LHC cleaning and dump insertion quadrupoles, has been presented in ref.[3].

As is well known, the structural design of the magnet and of the tooling, the ease of its assembly, and finally its performance, are closely related to the design concept of the collars, which can be of the spacer type, or may partially or fully support the magnetic forces. It is our opinion that the approach based on a fully supporting collar, although having the advantage of decoupling the coil-collar assembly from the rest of the magnet, is a difficult solution for magnets of the type we are considering, since its disadvantages are emphasized by the extreme forces and the large aperture of the coil. Since the concept of the graded coil was to be tested on a model of the low-β quadrupole, we have decided to investigate a design with a collar-spacer as its basic feature, which has an important advantage of increasing the field and temperature margins of the magnet. We recall that a similar concept has been successfully applied in the D19 dipole at LBL [4], and has been proposed by Caspi et al. for the SSC insertion quadrupoles [5].

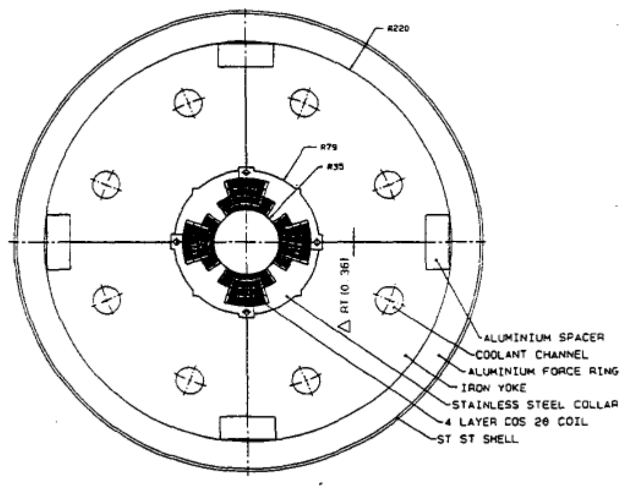

Fig. 1. The cross-section of the 70 mm LHC low-β quadrupole model

The cross section of the LHC low-β quadrupole is shown in Fig. 1. It features a four layer coil wound from two keystoned cables 8.20 mm wide with respective current carrying capacities graded by a factor of 1.5. The coils are assembled using quadrupole type stainless steel col-

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lars 9 mm wide which are locked with four stainless steel rods. A four-fold symmetric yoke is assembled around the collared coils and held by a tight fitting cylinder, so that the stress in the coils reaches the nominal value at room temperature. The Al-spacers serve mainly as an assembly aid, controlling the symmetry of the structure during assembly and cooldown.

Several possibilities concerning the yoke and external cylinder design were considered, including an elegant solution using Al-keys/clamps for yoke compression [6]. For the purposes of the model, we have decided to use the Al-ring and collet technique, since in that case, the compressive force of the Al-ring can be progressively increased and easily monitored. This approach also simplifies the magnet assembly, which can be done with relatively simple tooling.

In this report, the relevant details of the design of the 1-metre model of the LHC low-β quadrupole, based on the collar-spacer concept and four-fold split iron yoke, are presented. The winding technique and coil end design are also described, and some initial tests on the cables reported.

II. Coil and Yoke Optimization and Cable Parameters

On the basis of the initial design of the LHC low-β quadrupole [3], the coil and the cable parameters were further refined taking into account that the inner diameter of the iron is an adjustable parameter in the collar-spacer concept. Using a Monte Carlo code developed for optimization of the coil and cable parameters of graded coil configurations [7], the gain in magnet performance was studied as function of the diameter of the iron hole. The optimum is rather wide, with a minimum for the iron diameter of 140 mm and collar thickness of 9 mm. The resulting parameters of the NbTi cables are given in Table I.

Since the optimization of the coils and cable parameters was performed assuming infinite permeability iron, the laminations were optimized for saturation effects by modifications of the lamination outer diameter and of the dimensions of certain structural details. This analysis indicated that the dimensions of the centering indent, located at the 45 degree symmetry line, have the largest effect on the b_6 systematic error, which decreases by a factor of 2.5 if the indent is convex, as opposed to the situation when it is concave (i.e. pointed towards the magnet center). The field multipoles are much less sensitive to other parameters of the laminations (position and size of the cooling opening, the dimensions of the locking or Al-spacer indents). However, these parameters can be used to shape the variation of the systematic b_6 error in the magnet cycle. The optimized iron lamination geometry is shown in Fig. 1; the field component variation during

TABLE I
PARAMETERS OF THE CABLES FOR THE LHC LOW-β QUADRUPOLE (DIMENSIONS IN mm)

Parameter	Cable 1	Cable 2
Width	8.2	8.2
Minor edge	1.13	0.77
Major edge	1.44	0.92
Keystone angle (deg)	2.16	1.05
No of strands	22	34
Strand dia. (μm)	0.735	0.480
Packing factor	0.91	0.91
Cu/SC Ratio	1.3	1.3
Filament dia. (μm)	10	10
Critical current at 4.2 K	8400 A at 6.5 T	7650 A at 5 T

magnet energizing is given in Table II. At 250 T/m and 2 K the temperature margin is 1.1 K.

TABLE II
MAIN FIELD COMPONENTS AT $r_0 = 10mm$ AS FUNCTION OF MAGNET CURRENT

Current (A)	B_2 (T/m)	b_6 (units)	b_{10} (units)
1000	50.00	0.003	-0.005
2000	99.70	0.010	-0.005
3000	146.55	0.012	-0.005
4000	191.00	0.010	-0.003
5000	234.50	-0.013	0.003
5500	256.00	-0.020	-0.005

III. Coil winding

A. Cable Insulation

A number of different all Kapton cable insulation systems were considered. Finally, a three layer, butt wound system was selected. The first two layers of 6 mm wide, 25 μm thick 100HN Kapton tape are counter wrapped onto the cable. The third layer of 6 mm wide, 20 μm thick Kapton tape has a 5 μm thick layer of un-cured Polyimide on one side. DuPont offered two types of Polyimide bonding systems, CI and XCI, which cure at 220 C and 190 C, respectively. Ten stack bonding tests were performed on both with encouraging results. The XCI was finally chosen due to the lower curing temperature.

The 6 mm tape width design was the result of trials focused on reducing the wrinkle in the insulation when the cable is bent and twisted around tight radius of the inner pole turn. The Polyimide bonding system will only bond to other Polyimide surfaces, therefore it is important that the sides of each cable lay flat against each other to form a strong bond. This configuration of wrapped tape insulation gives a porous structure allowing superfluid helium easy access to the strands in the cable, which is important since the quadrupole will need a high degree of cooling. Voltage testing on this insulation format gave values > 2 KV turn-to-turn.

The main body of the ground insulation consists of four layers of 125 μm thick Kapton sheet, pre-formed in a heated vacuum mold to exactly fit the surface of the coil. The insulation at the ends is provided by the G11 end spacers.

B. Cable Joint

The four layer graded coil design requires a joint to be made between the two types of cable inside the coil end. The insulation is cured at approximately 200 C, at which temperature soft solder will melt. On the other hand, the superconductor will be damaged if its temperature exceeds 300 C. A eutectic lead-tin solder with a melt temperature of 255 C and a re-melt at 290 C will enable the joint to be made and the coil cured at approximately 200 C without damaging the joint or conductor.

C. Coil Ends

A substantial effort during the design of the magnet was spent in optimizing the coil ends. The magnetic performance of the end region was analyzed using the TOSCA package. Each coil was divided in blocks represented by the constant perimeter end coils of the TOSCA library. Although these coils do not adequately model blocks of keystoned cables, nor do they distinguish between the lead and return ends, it is estimated that the geometrical errors are much lower than the disretization errors of the model.

The individual block distribution was initially determined so as to limit the peak field in the coils, which, as expected, occurs in the innermost block of the first layer. The field in outermost blocks being much lower, their position may be chosen so as to minimize the integral field errors. This was done with purpose written routines running on top of OPERA, so that a large number of cases could be examined. A number of constraints were introduced, so as to take into account the requirements of spacer design. The final coil configuration was included in the nonlinear TOSCA model of the magnet, and the peak field and multipole distributions examined in presence of iron. This model also enabled an estimate of the effects of different iron packing factors in the straight section and end part of the magnet, a technique proposed to lower the peak field in the ends. The cross-section of the return end finally adopted is shown in Fig. 2.

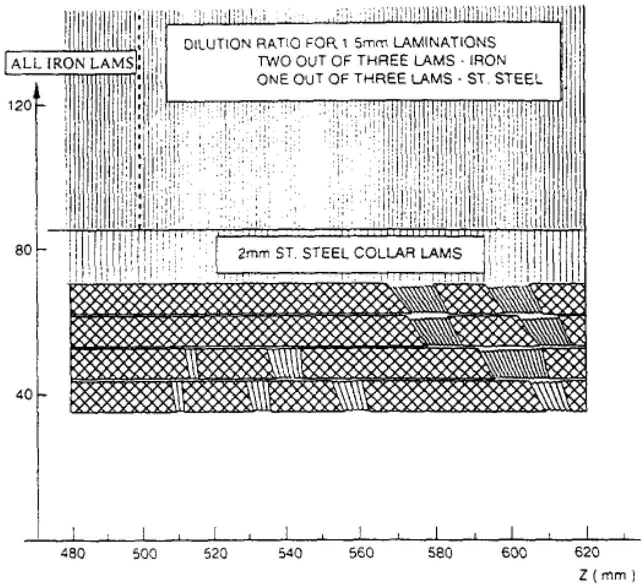

Fig. 2. The cross section of the model quadrupole at the return end

IV. Structural Analysis of the Magnet

The behavior of the magnet under different loading conditions has been analyzed with ANSYS, and is extensively reported in [8]. The main result of this analysis are briefly summarized below.

As the collars are serving only as an assembly aid, the magnet is collared using a small quadrupole type press. Upon introduction of the locking rods and releasing of the press, the coils remain under a compression of around 10 MPa. The four-fold symmetric yoke quadrants are then assembled around the collared coils with the aid of Al-spacers, and the assembly compressed with the Al-ring and collet structure. In the very beginning of this procedure, the gap between the collars and the yoke closes and the locking rods are released. The collar thereafter acts as a spacer, transferring the compressive forces to the coil. The yoke-yoke gap gradually closes from the initial value of 0.36 mm as the compressive force of the Al-ring builds up. For an initial interference between the Al-ring and iron lamination of 0.30 mm, the average azimuthal stress in the coil is 55 MPa. At this stage the yoke is still open, with a gap of 0.16 mm, which is sufficiently regular that tapering is not necessary. The dimensions of Al-spacers are chosen in such a way that the spacers and the yoke are barely touching after the yoking operation.

Due to differential contraction of the structure during cooldown to 2 K, the yoke-yoke gap closes with a contact force sufficiently large to keep the yoke closed under all magnetic loading conditions. The Al-spacers are released completely, while the azimuthal stress in the coils is slightly higher than at RT, and is on the average 73 MPa.

The contact forces between various structure components are summarized in Table III.

The Al-ring-yoke interface and the yoke-yoke gap were chosen such that for the design current of 5200 A, the azimuthal stress at the poles is greater than 10 MPa everywhere in the coil. For this case, the average azimuthal stress in the coil is 34 MPa, while it is about 90 MPa in the median plane. Although the total magnetic radial and axial forces per half pole are large (1126 N/mm and -1348 N/mm, respectively), the gaps between the yoke quadrants are closed with a force of 1820 N/mm. As a consequence, the structure is very rigid so that the maximum coil displacement during magnet energizing is 0.028 mm. This is corroborated by the stress in the Al-ring which changes by less than 1% between the no force and nominal magnetic force loading situations.

TABLE III
GAPS AND CONTACT FORCES
BETWEEN STRUCTURE COMPONENTS

Contact Surface	Initial RT	Yoking RT	2K	Nominal Current
Collar-Yoke				
gap (mm)	0.05	closed	closed	closed
F (N/mm)	-	1030	1875	2175
Yoke-Yoke				
gap (mm)	0.36	0.16	closed	closed
F (N/mm)	-	-	2120	1820
Al-spacer-Yoke				
gap (mm)	0.22	closed	0.10	0.08
F (N/mm)	-	88	-	-
Al-ring-Yoke				
gap (mm)	-0.30	closed	closed	closed
F (N/mm)	-	1100	3720	3735

V. WINDING AND ASSEMBLY TOOLING

A simple 1.5 m long winding machine has been built to wind the model quadrupole coils, wound as two double layers. Sufficient cable to wind two layers is part wound onto two spools, one of the spools is fixed to the winding mandrel while the other is mounted on the tensioner. The first layer wound, the spool that was mounted onto the mandrel is then moved to the tensioner and the second layer wound. In this way, the coil start and end leads are on the outside of the coil, which simplifies the cable runs in the magnet.

The all Kapton bonding system uses temperature and pressure to cure the coil. Each of the two double layers is mounted in a simple mould, which is then placed into an oven. The mould design uses differential thermal expansion to provide the curing pressure, which is continually measured. Initial trials on a short model mould achieved good bonding and dimensional accuracy.

For collaring, the coils are assembled vertically from a frame. The short collar packs are compressed at low pressure onto the coils using a steel collet driven by a hydraulic ram, and locked with rods in place. The same assembly tooling is used to compress the aluminium outer force-ring collet, which in turn squeezes the iron yoke around the collared coil assembly.

VI. CONCLUSIONS

Within the concept of a graded-shell quadrupole, proposed for the LHC insertion quadrupoles, the design of a 70 mm aperture low-β quadrupole has been pursued. The design takes into account the constraints imposed on stand-alone units, which result in a four layer coil design. The support structure is based on the collar-spacer concept, which is considered a better alternative for the large aperture and high gradient quadrupoles, as it reduces the outer dimensions and increases the operating margin of the magnet.

The overall magnet concept is being tested on a 1 m long model, which is presently under construction. The all Kapton insulated cable is wound in two double pancakes which are separately cured, and assembled vertically for collaring and yoking. For the model magnet we adopted the Al-ring and collet structure for magnet assembly, as it is more flexible in applying the compressive force and allows easier disassembly.

It is planned to test the magnet in superfluid helium in early 1994.

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