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Abstract - A twin-aperture superconducting dipole model has been designed in collaboration with Finnish and Swedish Scientific Institutions within the framework of the LHC R&D programme and has been built at CERN. Principal features of the magnet are 56 mm aperture, separate stainless steel collared coils, yoke closed after assembly at room temperature, and longitudinal prestressing of the coil ends. This paper recalls the main dipole design characteristics and presents some details of its fabrication including geometrical and mechanical measurements of the collared coil assembly.

I. INTRODUCTION

The Large Hadron Collider (LHC) which is the new approved project at CERN will use high field superconducting magnets assembled in a common yoke and cryostat following the "two-in-one" concept [1]. Twin aperture short and long models have been constructed and tested [2]. Magnetic fields up to 10.5 T at 2 K using NbTi conductors were reached in a 1.3 m long, 50 mm twin aperture dipole. A review of the requirements for beam optics of the collider has led to a change of the diameter of the coil aperture from 50 to 56 mm and also a change of the magnet length so that the specified energy of 7 TeV per beam is now obtained with a dipole central field of 8.4 T. An R&D programme searching for the possible strongest magnetic field in 56-mm-twin-aperture dipoles has nevertheless been maintained and in the wake of close co-operations with industries and scientific institutions, a collaboration programme was set up with the Helsinki University of Technology (Finland), the Uppsala University (Sweden) and CERN to design and build the magnet model called MFISC. The main tasks have been shared in the following manner: a group of engineers and draftsmen, coming from the aforementioned institutions was constituted at CERN to design the magnet; the orders for all the magnet pieces were placed with Finnish and Swedish industries, the cable supplied by CERN, the tooling built at CERN and the magnet built and assembled at CERN. The fabrication of the magnet is now completed and the first tests have started in summer 1995 (about one year later than the date previously announced). This delay is due to some difficulties encountered in the course of the magnet construction and a change of priorities established later for the CERN model magnet workshop (dipole model magnet with coils wound with SSC cable to be made first [3]). The problems occurred in the magnet manufacturing were mainly located in the ends of the coils. Since the mathematical optimization of the ends was done mainly considering magnetic field aspects, the shape of the end pieces had to be fine-tuned experimentally.

Moreover, electrical short circuits between coil end turns happened during the collaring phase, leading to coil repairs and also to the fabrication of a new coil.

II. DESCRIPTION OF THE MAGNET

The main parameters of the magnet [4] are listed in Table I and its cross-section is shown in Fig. 1. This model is a 56 mm twin-aperture, 1.3 m long superconducting dipole using 16.7 mm wide NbTi superconducting cables and operating at superfluid helium temperature ($T < 2.16$ K). The collared coils are centered and aligned by means of collar bulges placed in grooves made in the yoke. The yoke is vertically split and made in three parts (as shown in Fig. 1, the yoke is composed of a centre piece conically-shaped and left and right lateral laminations). At room temperature, the yoke gap is closed at the yoke periphery after assembly. The collared coils and the yoke have a *line-to-line fit* contact extended over a ± 45 degree angle on both sides to ensure both a good force transmission and a good collared coil geometry (round shape) to maintain a good field quality in all working conditions. The welding of the stainless steel cylinder applies to the yoke a force of about 450 N/mm. In this final assembly phase, the coil azimuthal stress increases by 20 MPa.

A. Coils

Each coil is composed of two concentric shells wound with trapezoidal cables of different dimensions to adapt the current density to the maximum magnetic field seen by the

TABLE I
MODEL DIPOLE PARAMETERS

Coil turns per beam channel	inner shell	28	
	outer shell	54	
Quenching field at 2 K		10	T
Stored energy for both channels		760	KJ/m
Current at quenching field		14370	A
Self-inductance for both channels		7.35	mH/m
Coil aperture diameter		56	mm
Magnetic length		840	mm
Iron length		670	mm
Collared coil length		1080	mm
Overall length		1320	mm
Intra-beam distance		200	mm
Collar diameter		182	mm
Inner yoke diameter		183	mm
Outer diameter		600	mm
Resultant of e-magnetic forces in first coil quadrant			
	$\sum F_x$	2.50	MN
	$\sum F_y$	- 1.22	MN
Axial e-magnetic force on magnet ends		760	kN

Fig. 1. Cross Section of the Magnet Model.

superconducting cable. The strand material is a Nb47Ti/Cu composite with 5 μm diameter filaments. The main cable parameters are listed in Table II.

Both type of strands have a 1 μm thick Sn5Ag coating. To avoid sharp edges on the thin side of the cables, the compaction ratio (91%) has been decreased with respect to that adopted for the 50 mm aperture LHC superconducting dipole magnets. Critical current measurements made on strands extracted from the cables indicate that the cable degradation is lower than 3%. Both cables are insulated with two 25 μm thick polyimide tapes and a 120 μm thick pre-impregnated epoxy tape (resin content between 19 and 23%). The polyimide layers are wrapped around the cables in the same direction with a 50% overlap while the prepreg is helically wound on the polyimide tapes and spaced by 2 mm to set up channels for superfluid helium. To improve the field quality, special care was taken in designing the conductor placement to keep the relative multipoles b_7 and b_9 as small as possible ($b_7 = -0.009$ and $b_9 = 0.002$). There are three copper wedges in the inner layer and one in the outer.

The coil ends are of approximate constant perimeter profiles with big end spacers machined from epoxy-impregnated fibre-glass tubes and small ones made of epoxy-preimpregnated fibre-glass foils. For the first time in the dipole models, the small spacers (*chips* and *wedge tips*), distributed between turns in the ends, have been cast in machined aluminium moulds. During the winding tests, hand-made spacer mock-ups were made and their surfaces translated into digital files to be read by a numerically controlled machine tool to manufacture the aluminium moulds. The foils (57% fibre-glass and 43% epoxy resin) were cut in strips of appropriate shape and size, piled up in the mould cavity and pre-polymerized following a curing cycle at 130 $^{\circ}\text{C}$ with a long dwelling at the gel point temperature (around 95 $^{\circ}\text{C}$) of the resin. Since the complete polymerization of the chips and wedge tips is done during the curing of the coil, the shapes of the spacers still have the

TABLE II
CHARACTERISTIC DATA OF THE CABLE

	Inner Layer	Outer Layer
Diameter of strand (mm)	1.1	0.87
Cu/Sc ratio	1.6	1.87
Filament size (μm)	5	5
J_c at 8 T and 4.2 K (A/mm^2)	1070	1108
Number of strands	30	38
Mid thickness bare (mm)	1.965	1.560
Width bare (mm)	16.7	16.7
Keystone angle	1.20	0.83
Number of filaments	20328	9438
dJ_c/dB ($\text{A}/\text{mm}^2/\text{T}$)	487	609

possibility to adapt their geometries to modifications of cable placements to better mate the cable surfaces. This mating would prevent cable movements during energization. The inner and outer layer coils are electrically connected in series and separated by a 450 μm thick epoxy-impregnated fibre-glass spacer composed of 200 μm thick fibre-glass sheets, glued in a grid pattern and moulded together at 120 $^{\circ}\text{C}$ for two hours (see Fig. 2). This design allows a good cable radial support and an optimal helium wetting between layers. To have a good sliding between the inner and outer coils during the assembly, the external surface of the grid has been covered with a low friction product. A quench protection heater is inserted between the outer coil layer and the innermost foil of ground insulation. The heater consists of 15 mm wide, 25 μm thick copper clad stainless steel strips with clad areas 250 mm long and 250 mm apart. These strips are placed between two polyimide foils of different thickness, one of which is adhesive. In order to avoid any wrinkles and thicknesses built-up, the strips were positioned on the 25 μm thick sticky polyimide layer, pressed and covered with the 125 μm thick polyimide foil. The resulting sandwich is easy to handle and mechanically robust to punching through. The ground insulation is composed of several layers of 75 and 125 μm thick polyimide foils.

B. Collars

The insulated coils are surrounded by 2 mm thick EDM machined austenitic stainless steel collars. The room temperature stainless steel yield point is 700 MPa and the integrated thermal expansion coefficient between 2 K and 300 K is 2.6×10^{-3} . The magnetic permeability of the collar material is rather good (1.004) and tests done at CERN (temperature cycles) show that it does not change between cool and room temperature. Figure 2 shows the *shim retainer* where the inner coil collaring shims are inserted. This is a thin stainless steel foil formed in a hairpin like shape. This sheet has the function of preventing the collaring shims from sliding into the bore during collaring and then possibly avoid the use of the collaring mandrel.

Collars and floating collars, spaced with 100 μm aluminium washers, are joined in packs by means of stainless steel rods. The collar pack rigidity was enhanced by gluing the collars with a given quantity of epoxy resin of air-cure type that was deposited on the external collar pack surface. By capillarity, the resin flowed into the interstices and filled the spaces between collars, leaving the collar pack external

Fig. 2. Intercoil Spacer and Shim Retainer.

surface proper and clean. Since the collars are glued together, the *quench pressure venting* is obtained by spacing the collar packs by 1.5 mm. The collared coils are longitudinally restrained by stainless steel rings (*backing rings*).

To obtain a better end turns compaction, the coil ends are axially prestressed by means of bolts housed in the end collar packs and the backing ring. From the magnet training point of view, the magnet ends represent an area where there is a high probability of quench development. In previous models, the quench zone is located in the first end turns of both the inner and outer layers of the coil ends. In these locations, the field gradient is high and the cable is bent the hard way. Differences of azimuthal prestress (less prestress in the magnet ends than the straight part) seen by the turns in the region where the cables start bending, different compactness with respect to the straight part and spacially distributed magnetic forces along the length of the coil end might explain the weakness of this magnet area. After curing, due to cable elasticity, at the beginning or at the end of the bending, adjacent turns may present some little misplacements which can be enhanced by electromagnetic forces during excitation. To limit and possibly eliminate these misplacements the chosen solution was to compact the ends by applying a longitudinal force greater than or equal to the sum of the magnetic force seen by the first cables. This mechanical end assembly is called the "*cage*". Figure 3 shows a picture of the collared coil end where the cage is located. The longitudinal force is applied by means of bolts fixed in a collar pack laying in the straight part of the magnet. After collaring, by screwing the corresponding nuts, the bolts are

Fig. 3. Collared Coil and Cage.

tightened and their force transferred to the coil ends. To assure a good force transfer between bolts and coils the end collar packs should have a longitudinal spring constant lower than that of the coil ends.

C. Yoke and Assembly

The 5 mm thick EDM machined yoke laminations are assembled with a packing factor of about 95% in packs which are riveted by means of stainless steel tubes flared at one end. Shims are introduced between the collared coils and the yoke pieces to ensure the 45 degree angle line to line fit and obtain the specified preload on the collared coil after the welding of the 10 mm thick shrinking cylinder (azimuthal stress in the shell of about 220 MPa). The collared coils are longitudinally loaded by means of screws (one per coil assembly) placed in 50-mm-thick, non magnetic, stainless steel end plates. Each screw is set to apply a 20 kN axial pre-load. The stainless steel end plates are fixed to the shrinking cylinder with a non continuous ring bolted to the plates and located in grooves made in the stainless steel shell.

III. FABRICATION OF THE MAGNET

A. Coil mechanical characteristics

The measurements of the coil mechanical characteristics have been made both on separate coil layers and on assembled poles (inner and outer coil layers joined together). To measure the elastic modulus of the single layers assembled together, the pressing apparatus schematically shown in Fig. 4 has been used. The upper portion of the apparatus reproduces the collar internal shape. This means that the ground insulation and pole shims can be inserted during the measurements. The opportunity of playing with pole shims of different thicknesses combined with the good mechanical interaction between coil layers is essential to calculate the most appropriate collaring shim arrangements. The forces in the coil layers and the dimensional variations are measured with calibrated strain gages and dial indicators respectively. Figure 5 shows an example of the coil mechanical characteristics. These data are utilized to calculate the final thickness of the collaring shims inserted between coils and collars at the coil layer upper angle, taking into account the loss of coil prestress after collaring due the collar elasticity.

B. Collaring

During collaring, the press force is only counteracted by the coils. When the collars are locked and the force of the press removed, the collars start reacting until the mechanical equilibrium between coils and collars is reached. Obviously, an increase of the rigidity of the collars would reduce the coil peak stress under the press. By gluing the collar packs, the gain in stiffness with respect to unglued collars is 15% and 30% in vertical and horizontal directions respectively.

Table III shows the mean measured radial displacement of the two collared coils at various positions. The indicated

TABLE III
VERTICAL AND HORIZONTAL COLLARED COIL DISPLACEMENTS

Angle	Collared Coil 1 Radial Displacements (μm)		Collared Coil 2 Radial Displacement (μm)	
	Ends	Straight Part	Ends	Straight Part
0	-10	30	-10	40
30	-10	40	-10	40
45	-10	40	0	40
90	40	120	60	120

radial displacements correspond to an average azimuthal prestress of 65 MPa in the coil straight part and 15 MPa in the ends. Due to the geometries of the inner and outer coil windings, both layers have the same azimuthal prestress.

C. Instrumentation

The instrumentation of the MFISC model includes a total of 27 voltage taps. Eighteen of these are placed on the coil turns, while the remaining are external and fixed to the connections. The coil layers are also equipped with spot heaters to study the behaviour of the magnet by provoking quenches in the two coil layers at different magnetic fields. To better understand and investigate the mechanical dipole behaviour in all working conditions, the magnet has been instrumented with calibrated strain gage transducers. These were mounted and glued to expressly machined collars and screws (bullet gauges). The collar transducers read the variations of the coil azimuthal stress while the bullet transducers read the change of the longitudinal coil force.

Fig. 4. Coil Elastic Modulus Apparatus

Fig. 5. Example of Coil Stress-Strain Curve (100 bar correspond to 27.7 MPa azimuthal stress).

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NOTE: FIRST TEST RESULTS

The magnet reached the short sample limit of 10 T at the third quench, after quenching at 89% and 95% of the short sample limit.