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In the framework of the LHC superconducting dipole magnet model programme, a 56 mm bore, twin-aperture dipole model 1 m long, using existing cables of the standard SSC type, was launched to initiate studies of lower field magnets with smaller strand size cables for a 7 TeV collider. This model was designed, built, assembled and tested at CERN and reached a peak field of 9.7 T at 1.8 K. The paper reviews the main design principles, presents the fabrication and assembly procedures and finally discusses the overall test results.

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Abstract—In the framework of the LHC superconducting dipole magnet model programme, a 56 mm bore, twin-aperture dipole model 1 m long, using existing cables of the standard SSC type, was launched to initiate studies of lower field magnets with smaller strand size cables for a 7 TeV collider. This model was designed, built, assembled and tested at CERN and reached a peak field of 9.7 T at 1.8 K. The paper reviews the main design principles, presents the fabrication and assembly procedures and finally discusses the overall test results.

I. INTRODUCTION

The Large Hadron Collider (LHC) is an accelerator-collider machine for 7 TeV nominal proton beam energy which will be installed in the 27 km long LEP tunnel at CERN. It consists mainly of a ring of high field superconducting dipole and quadrupole magnets of double aperture having an inner bore diameter of 56 mm. The nominal dipole field is 8.368 T [1]. In the framework of the LHC dipole R&D programme several 1 m and 10 m long 50 mm bore and 17 mm wide cable dipole model magnets were built in industry and tested at CERN [2]. To start tests at CERN of lower field dipoles with larger aperture and smaller strand and cable size within a short time, the construction of a twin-aperture dipole magnet using existing SSC type cable started at the beginning of 1993 [2]. This model, so-called MBTRA, was completed in Autumn of 1994 and cold tested at the end of 1994.

II. CHOICE OF BASIC DESIGN

The studies were oriented towards achieving a high field magnet of required field quality with features allowing to use existing technologies, compatible with the aim of improving performance and lowering costs. Solutions retained for the SSC magnets were scrutinized adopting those which appeared interesting for this model. This analysis led to the following choices:

- Coils in two layers with a layer jump and splice box as developed by BNL [3] which is compatible with a twin aperture configuration.
- Separate collars for each aperture, symmetric with respect to the vertical axis, made of non-magnetic steel.
- Collars that retain the required azimuthal prestress and are in contact with the yoke at 2 K. Separate collars simplify tooling and making them of steel reduces the inner yoke diameter and enhances the field/current transfer function.
- Two yoke versions were studied: either vertically split in three parts as tested in the MTA3/CERN model [2], or horizontally split in two parts. The latter option was finally adopted. The main parameters of the magnet are presented in Table I.

TABLE I
MAIN MAGNET PARAMETERS

Bore aperture	56 mm
Short sample current I_{ss} at 2 K	9700 A
Short sample field B_{ss} at 2 K	9.45 T
Current for nominal field $B_{nom}=8.368$ T	8510 A
B_{peak} (inner layer conductor)/ B_0	1.058
B_{peak} (outer layer conductor)/ B_0	0.892
Turns per beam channel	inner shell: $2 \times (8+7+5)$ outer shell: $2 \times (17+12)$
Distance between aperture axes	180 mm
Inner yoke diameter	164 mm
Outer yoke diameter	560 mm
Overall length of magnet	1.3 m
Stored energy for both channels (at B_{nom})	344 kJ
Self-inductance for both channels (11.4 mH/m)	9.5 mH
Resultant magnetic forces first coil quadrant (at B_{nom}):	
Total horizontal force Σf_x (1.56 MN/m)	1.3 MN
Total vertical force Σf_y (-0.728 MN/m)	-0.60 MN
Axial magnetic force on coils per channel (at B_{nom})	0.16 MN

III. MAGNETIC DESIGN

A. Cable and cable insulation

The cables were supplied by the SSC Laboratory. The main cable parameters are shown in Table II. The critical currents at 4.2 K are derived from strand and cable measurements at BNL and SSC Laboratory of the cables used for the model (ref. SSC-3-S-00036 and SSC-4-0-0101 for inner and outer layer respectively) [4]. At 1.8 K the 4.2 K values are taken with a field shift of 3 T [5]. The insulation of both cables consists of two half lapped layers of polyimide film, the first 25 μ m thick and the second 12.5 μ m plus a third layer of glass-fibre prepregged tape spaced by 2 mm between successive turns. The theoretical cured and compressed insulation thickness is azimuthally 95 μ m for the inner and 105 μ m for the outer layer and radially 175 μ m.

TABLE II
CABLE PARAMETERS

	Inner layer	Outer layer
Strand diameter	0.808 mm	0.648 mm
Filament diam.	6 μ m	6 μ m
Cu:SC ratio	1.5	1.8
Strands/cable	30	36
Cable width (bare)	12.34 mm	11.68 mm
Cable mid thick. (bare)	1.458 mm	1.156 mm
Keystone angle	1.2°	1.01°
Critical current I_c (6 T, 4.2 K)	13807 A	9626 A
Critical current I_c (7 T, 4.22K)	10452 A	7156 A

Fig. 1. Coil cross-section of MBTR model (1st quadrant).

B. Coil and yoke cross-section

In previous designs with 17 mm cable only 6-block geometries fulfilled the field quality requirements. With the increased bore and smaller cable size, the finer discretization of the conductor distribution allowed to optimize a 5-block geometry, shown in Fig. 1, with the required low content in b_7 and b_9 components, using the programme ROXIE [6]. Compared to a 6-block solution, both have nearly the same transfer function of 0.99 T/kA, however the quenching field in the 5-block case is reduced by .09 T due to the 1.5% higher ratio of inner layer peak field to bore field coming from the larger number of conductors in the uppermost block (i.e. 5 turns instead of 3). The 5-block solution was preferred for its simpler construction, fewer Cu spacers and potentially safer quenching behaviour.

The yoke optimization was done with the programme POISOPT [6] minimizing the variations of multipoles with saturation, mainly b_2 and b_3 and maintaining a high dipole field by adjusting the outer yoke radius and the position and radius of the field correction holes in the vertical symmetry plane. For reasons of compatibility with existing tooling and components the outer yoke diameter was made 560 mm and the finally adopted cross-section of the model is shown in Fig. 2. The calculated variations of geometrical multipoles with current are shown in Fig. 3.

Fig. 2. Dipole cross-section (dimensions in mm).

Fig. 3. Calculated variation of geometrical multipoles b_2 , b_3 , b_4 and b_5 with current.

C. Coil end design

The coil end shapes were designed to ensure suitable windability, maintain cable stability and insulation integrity and obtain end spacer geometries adequate for machining on CNC 3-axis milling machines. The approach chosen for the end spacer design was based on shapes of constant perimeter assuming the cable resting on the cylindrical surface of the winding mandrel at the coil ends [7]. The curves defining the edges of the spacers were assumed to be ellipses with those on the inner side of the coils being prolonged by straight lines to satisfy the constant perimeter condition. Winding tests around the first turn end post, which is the most critical one, were made to optimize the ellipse parameters and the inclination angle between the spacer at the vertical symmetry plane. Best results were obtained with 10.5° for the inner and 20.36° for the outer layer inclination. Subsequently, all ellipses on the outer coil surfaces were chosen with the same origin, defining thus the rest of the spacers. Each of them separates a current block as defined in the 2D cross-section. By adjusting their length the error multipoles in the ends can be minimized. Peak field in the coil ends is reduced by replacing the low carbon yoke laminations by non-magnetic steel laminations in this region.

IV. MECHANICAL DESIGN

Initial computations by hand based on previous calculations for similar structures were later refined by FEM calculations with the programme CASTEM [8]. A maximum field of 9.6 T was considered for these computations. The behaviour during assembly, cooling to 1.9 K and energization is described below.

The amount of prestress to be applied to the coils is a basic parameter to compute, to ensure on the one hand sufficient compression under all operational conditions and on the other hand to avoid excessive pressure which will lead to cable damage and too large insulation creep. Collaring is done under a press and once the collars are locked around the coils and the press released, the coils deform the collars and consequently part of the prestress is lost. This relaxation was computed to be 30% of the maximum collaring pressure and depends mainly on coil size and stiffness. By pulling on the collar arms during collaring this loss can be reduced. The minimum average coil prestress after collaring is 70 MPa for the inner layer and 50 MPa for the outer layer which will

ensure a residual level of 10 MPa at the top of the coils at maximum field level.

A rigid structure, required to limit the deformations during energization, was obtained by imposing a closed yoke gap up to maximum field level and a good contact between the iron yoke and the collars at all stages of assembly and operation. Due to the differential thermal contraction of collars and iron yoke a minimum interference of 50 μm in the collar-iron radius must be imposed at room temperature. The external 10 mm thick shrinking cylinder is mounted around the yoke with an average tensile stress of 140 MPa in order to ensure iron gap closure. The force applied by the cylinder loads the collar-coil assembly as well, increasing the average coil prestress by 10 MPa.

During cool-down, the steel collars shrink more than the iron yoke but less than the coils. Consequently the average prestress decreases by about 30 MPa in the inner layer and 20 MPa in the outer. The stress in the outer cylinder increases to 350 MPa. At full field, the compression at the top of the coils reduces to 10 - 15 MPa whereas in the median plane it increases to 140 - 150 MPa. The iron gap remains closed and the stress in the external cylinder does not change.

V. FABRICATION

A. Coil fabrication

The cable was wound on a rotating table around a centre-post fixed to a cylindrical mandrel which can pivot along its longitudinal axis and applying a tension of about 20 daN for both inner and outer layer cables. They were insulated on line with the winding process using Kapton tape supplied by Du Pont (USA) and a glass-epoxy prepreg of type VP1037 supplied by Isovolt (A). End spacers were machined at CERN in G11 using a spherical milling head. The cables fitted well to the theoretical shape of these spacers, except for the end saddles which had to be slightly adjusted by filing. The coils were cured at 160 °C for one hour in a fixed cavity mould which was shimmed according to the results of ten stack tests and closed at around 100 °C at a pressure of typically 7 daN/mm² while the end saddles were restrained by axial bolts fixed to the mandrel. In total six coils of each layer were made and passed successfully the electrical tests. The average size deviations of the coils used for magnet assembly are + 0.02/+ 0.16 mm for the inner/outer layers, measured in both cases at nominal prestress on the falling branch of the pressure cycle, which was taken up to 110 MPa. The average modulus on the rising branch is 12000/11000 MPa for inner/outer layers and respectively 23000/ 14000 MPa for the falling branch at nominal value of prestress. The empty spaces in the coil ends due to the inclined position of the cables were filled with epoxy resin containing an important amount of mineral filler. The coils were assembled by an internal layer jump and splice formed and soft soldered with a precision aluminium alloy fixture and placed in a G11 precision machined box.

B. Collaring

The coils were paired to compensate size variations, provided with voltage taps, quench heaters and spot heaters, the latter being placed between the return end posts and first turn. Ground insulation is composed of six layers of 0.125 mm polyimide sheets, covered by an 0.7 mm thick

stainless steel collaring shoe. The collars were made by fine stamping by Malvestiti (I), of non-magnetic austenitic Mn steel delivered by Ugine (F), having an integrated thermal contraction coefficient of 2.65×10^{-3} and a tensile strength of 480 MPa at room temperature. The nominal pole shims between collars and coils had to be reduced by 0.1 mm for the inner and 0.3 mm for the outer layer, part of which can be explained by the deviation in coil size. During collaring, forces are brought to bear on the top and bottom flat faces of the collars and on the collar ears. To compensate for collar elongation and bending, shims of 0.2 mm are placed on these ears. The total vertical collaring force was 560 tons, at which time the tapered keys were inserted with a horizontal force of 30 tons. No reduction of vertical forces was possible during key insertion. In the standard section this resulted in a maximum inner/outer layer coil stress of 147/104 MPa with a relaxation after release of the press of 35/32% for the inner/outer layers, somewhat higher than the calculated 30%. Between collaring and yoke assembly (about 13 days) 15/10% prestress was lost in average due to creep in the inner/outer layers. The jump and splice region was shimmed to have similar prestress as the standard part whereas over the 180 mm of the coil ends the prestress gradually decreases and vanishes at the saddle ends. The description of the mechanical instrumentation, of collaring tests on short models and of the measurements during assembly and testing are given in a companion paper presented at this conference [8].

C. Yoke assembly

The yoke is split along the horizontal symmetry plane and assembled by a bolted stainless steel cylinder. The central magnetic part of the yoke consists of a 620 mm long stack of 5 mm thick laminations of low carbon steel sheet made by Cockerill (B), and cut by fine stamping by Garçonnet (F). At each end the yoke is terminated by 205 mm long stacks of laminations of identical cross-section of non-magnetic steel of the same grade as for the collars. The collared coils are mounted inside the yoke with a radial nominal interference at room temperature of 0.12 mm extending over $\pm 20^\circ$ around the horizontal median plane. The yoke laminations have triangularly shaped protrusions which provide vertical interference with the collar ears, ensuring correct alignment of both apertures inside the yoke. After insertion of the collared coils and closing of the yoke under a force of 70 tons using the magnet assembly press, the 2 x 33 M20 bolts along the outer shrinking cylinder were tightened with a force of 6.5 tons each, resulting in a azimuthal stress of 140 MPa in the cylinder. As expected, the inner layer prestress increased by about 20 MPa whereas the outer layer prestress remained essentially unchanged. Two instrumented bolts per aperture, screwed into 49 mm thick stainless steel plates support the axial end forces of the coils, and were preloaded with 750 daN each.

VI. COLD TESTS

The magnet was measured in two test campaigns separated by a one day thermal cycle to room temperature. After cooling to 1.8 K the first training quench was at 8 T and the fifth at 9.15 T with a maximum of 9.7 T reached after 22 training quenches. At this field level the training behaviour is somewhat irregular, the quenching field fluctuating between 9.4 and 9.7 T with a bath temperature between 1.7 and 1.9 K. The origin of all these quenches was

Fig. 4. Measured loadline and critical cable currents.

related to mechanical movements, indicating that the short sample limit was not fully reached yet. At 2 K the measured short sample field is 9.65 T, which is 2% higher than deduced from measured cable critical currents (Fig. 4). After the thermal cycle the first quench occurred at 8.9 T indicating a certain retraining. With the measured RRR values of 100/190 for the inner/outer layers, the maximum hot spot temperature with 55% extracted energy reaches 370 °C. The quench current dependence on ramping at higher di/dt indicates a type A behaviour, when compared with SSC type magnets [9]. Further results of the cold measurements of this magnet are given in a companion paper at this conference [10].

VII. CONCLUSIONS

Lessons learned with this model contributed to the further design of the dipole magnets. For instance the high values of coil compression needed during collaring are reflected in material choices for the LHC, i.e. collars made of aluminium alloy. The model trained-up in a similar way as the model magnets of 17 mm cable, showing that the weak spots are located in similar regions of the coils, i.e. mainly in the ends. For this magnet they are in the return end of the inner layer, the end turn just after the splice in the outer layer and also in the inner layer straight part just before the ramp. Quenches were however evenly distributed between the poles and also between the inner and outer layer, showing that

coils are of uniform quality. Improving these regions is therefore one of the important objectives of the present model programme. The large quenching temperatures and voltages confirm the requirement of larger cables for LHC. The magnetic measurements showed also that the 5-block geometry adopted for the LHC dipoles is adequate in producing the required field quality.

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