Design and Construction of a 1 m Model of the Low Current Superconducting Quadrupole for the LHC Insertions

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Abstract—**About one hundred individually powered low current superconducting quadrupoles will be installed in the LHC insertions. One of the design requirements was to keep the excitation current of the magnet below 6 kA in view of minimizing the costs of the powering circuits. The design of the quadrupole is based on a 8.2 mm NbTi cable, and is designed for a nominal gradient of 200 T/m at 1.9 K. In this paper we present the design of the quadrupole and discuss the construction details of the 1 m single aperture model which has been recently completed.**

I. Introduction

In contrast with the LHC arc quadrupoles which are powered in series, the insertion quadrupoles are individually powered magnets. In view of their specific location in the tunnel, and in order to reduce the costs of the powering infrastructure, one of the design requirements is to keep the excitation current below 6 kA. A similar constraint was assumed in the case of the 70 mm aperture quadrupole developed for the LHC low-β insertions [1]. The optimal configuration for this magnet was a coil wound using 8.2 mm NbTi cables. To date, three 1 m long 70 mm aperture quadrupoles have been built and tested [2], giving particularly important results for development of other low current quadrupoles using the same cables.

A design study of a 56 mm aperture quadrupole using a 8.2 mm cable has shown that such a quadrupole could operate with a gradient of 200 T/m at 1.9 K and 160 T/m at 4.5 K, at 5200 A and 4200 A, respectively [3]. It became therefore conceivable to introduce these magnets as part of the LHC insertions, in particular in the dispersion suppressors and matching sections. With the individual control of each magnet and of the two rings separately, the flexibility and performance of the collider could be substantially improved. This proposal is the basis of the current LHC optics version 6.

Three low current quadrupoles, with identical cross-section but different lengths, are foreseen in the LHC insertions: 2.4 m (MQMC), 3.4 m (MQM) and 4.8 m (MQML) magnets. Besides being used as single units, cold masses housing two MQM units, and a MQM+MQMC units are also envisaged. In the RF insertion, the MQM and MQML collared coils are used in single aperture yokes to accommodate the 420 mm beam separation. The total number of MQM magnets to be installed is close to one hundred.

In this report we present the design of the 56 mm aperture low current quadrupole for the LHC insertions. We also describe the construction procedures, initial tests performed on the prototype coil and on the short mockup, and the final assembly of the 1 m single aperture model of the quadrupole which has been recently completed.

Submitted on the 26 September 1999

II. Quadrupole Design

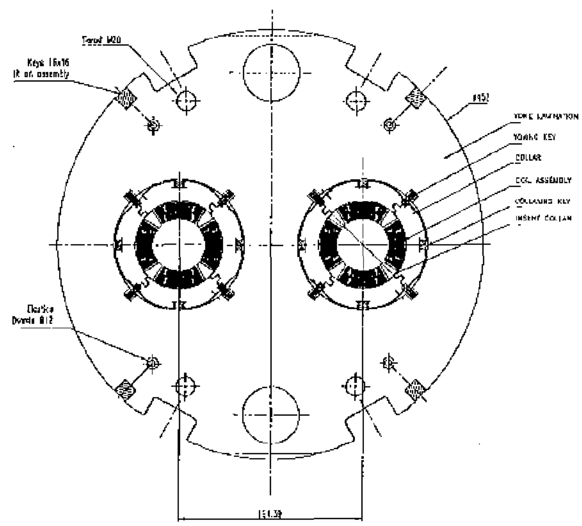

Fig. 1. Transverse cross section of the MQM quadrupole

The MQM quadrupole consists of two identical, independently powered apertures, which are assembled together as shown in Fig. 1. The coils are made using 8.2 mm wide cable wound in two layers and cured in a single cycle. They are assembled using 21 mm wide collars, which cover 180 degrees, and are mounted so that each successive collar is turned by 90 degrees. The collars give the necessary compressive stress in the coils and withstand the magnetic forces. They are locked using four full length keys which are welded onto the coil end plates, giving longitudinal stiffness to the assembly. The pole leads are joined in the connection box mounted on the lead end plate, so that each aperture can be handled as an independent unit.

Two collared apertures are assembled together in a two-in-one magnet using single piece iron laminations, very similar in design to the LHC arc quadrupole. This is an important feature of the design, as the MQM quadrupoles are part of the dispersion suppressors, where the cooling and busbar systems have already been defined on the basis of the LHC arc quadrupole. Besides solving the integration issues, this approach decouples the magnetic and mechanical design of the magnet.

A. Coil

The MQM coil is designed on the basis of the 8.2 mm cable of the 70 mm aperture quadrupole [1]. The cable is made of 34 strands (0.48 mm dia.), and its mid-thickness and keystone angle are 0.845 mm and 1.05 degrees. The filament diameter is 10 μm, and the cable critical current density is 2960 A/mm^2 at 4.2 K and 5 T.

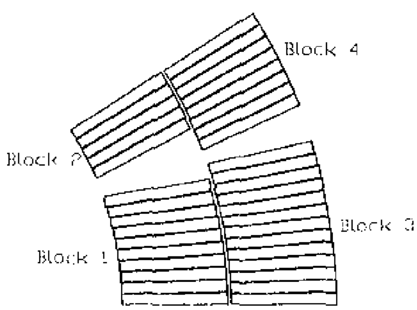

Fig. 2. Cross section of the quadrupole coil

The cable insulation consists of two polyimide layers. The first insulation layer is a 25 μm dry polyimide tape with a 50 % overlap. The outer layer is a 50 μm tape with an uncured adhesive layer on the outer surface, wrapped with a 2 mm gap. The bonding and sizing is achieved by curing the coil at 185°C.

Similarly to the 70 mm aperture quadrupole, we propose a coil design based on curing both layers in a single curing cycle. This technique requires that the layers are aligned at the pole. In addition, winding trials have shown that for correct positioning of the pole turn, the pole angle should be greater than 26 degrees. Furthermore, the coil design should be such that the geometrical b_6 multipole partially compensates the b_6 term due to persistent currents. With the cable parameters and these requirements in mind, the cross-section of the coil was optimised with *Roxie* [4] for highest transfer function and operational margin. The resulting coil section is shown in Fig. 2, and the operating parameters of the magnet listed in Table I.

TABLE I
Operating parameters of the MQM quadrupole

	1.9 K	4.5 K
Nominal gradient	200 T/m	160 T/m
Nominal current	5165 A	4132 A
Peak field in coil	6.31 T	5.05 T
Current density in SC	2349 A/mm^2	1851 A/mm^2
Current density in Cu	1350 A/mm^2	1089 A/mm^2
Quench field	7.86 T	6.13 T
Percentage of the load line	80.3 %	82.4 %
Percentage of the short sample	60.9 %	64.13 %
Temperature margin	1.7 K	1.1 K
Stored energy	60.65 kJ/m	38.8 kJ/m
Inductance	4.55 mH/m	4.55 mH/m
F_y per octant	-427 kN/m	-273 kN/m
F_x per octant	306 kN/m	196 kN/m

The expected multipole errors due to coil geometry and filament magnetisation for the LHC injection gradient (12.5 T/m) and MQM nominal gradients are given in Table II. The transfer function of the quadrupole is 38.76 (T/m/kA) at 160 T/m and 38.74 (T/m/kA) at 200 T/m.

TABLE II
Systematic multipole errors of the MQM quadrupole (units of 10^{-4} at R_{ref}=17 mm)

b_n	Geometric	Magnetisation (12.5 T/m)	Geom.+Sat. (160 T/m)	Geom.+Sat. (200 T/m)
b_2	-	-19.6	-	-
b_6	1.29	-5.69	1.29	1.33
b_{10}	-0.17	0.29	-0.17	-0.17
b_{14}	-0.12	-0.031	-0.12	-0.12

B. Design of the Coil Ends

The coil ends were designed using the isoperimetric method. The goal was to keep the peak field in the ends below that in body of the magnet while using the same yoke laminations everywhere. Also, we tried to keep the ends as compact as possible, to maximise their magnetic length, and to reduce the integrated end harmonics. The resulting peak field is very close to the 2D value (6.3 T), and in case non-magnetic laminations are used over the ends, it is lower by 0.4 T.

The lead end is made of three sections: the layer jump, the end spacer section and the connection box, Fig. 3. The layer jump is designed such to move the cable away from the inner layer, align it to the outer layer, and finally bring it in the position of the first turn of the outer layer. The cable path and the components of the layer jump guarantee mechanical stability of the cable and its electrical integrity.

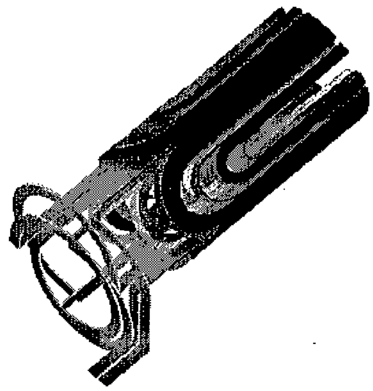

Fig. 3. Computational model of the lead end

C. Quench Protection

Although the inductance and stored energy in the MQM quadrupole are small, the high current density in copper, 1300 A/mm^2, is a major concern for magnet protection. Assuming a strip heater on the outer coil layer and a heater delay of 50 ms, the adiabatic conditions predict a peak temperature of 330 K for the nominal current of 5200 A. As at least 20 ms are required for filtering and detection, the heater reaction time should be less than 30 ms. Test results of the 70 mm quadrupole [2], which uses the same cable and insulation system, have shown that the heater delays for these conditions are typically 15-20 ms. The corresponding quench load number is 3 MIITs, and the expected maximum voltage to ground for the longest magnet chain is below 150 V.

Better protection can be obtained if both layers are heated simultaneously. In order to do so, a quench heater has to be mounted on the outer surface of the inner layer during winding, and has to survive coil curing without loss of electrical integrity. For the model magnet, we have decided to include both quench heaters, so as to test the production aspects of the inner heater, and to check their relative efficiency. Further improvement, particularly in view of relaxing detection times, could be obtained if the cable were modified from 34 to 36 strands. This possibility has been studied thoroughly and adopted for the final magnet design.

III. Construction of the 1 m Model

A. Coil winding

Five 1 m quadrupole coils were wound in ACCEL Instruments, including a prototype coil which was used to test the new winding features, in particular winding over the inner quench heater and curing both layers simultaneously with the heater in place. Separate tests have shown that the inner heaters, consisting of two 75 μm polyimide sheets with a 25 μm thick stainless steel strip glued in between, can withstand temperatures of over 185°C without apparent damage. Nevertheless, the main concern was the integrity of the insulation under the combined effect of high pressure and temperature during curing.

The width of the inner heater used in the prototype coil was identical to the first layer at nominal compression, and it did not cover it fully during winding. As a result, the mid-plane turns of the two layers were not separated by the heater, and when compressed in the curing mold, pushed the heater inwards so that it wrinkled in the inter-turn spaces and developed shorts. To remedy this deficiency, a 25 μm polyimide tape was added on each side of the heater so that the tapes protruded over the inner layer by about 5 mm. This proved very effective as the electrical integrity of the inner heater in the four production coils was fully satisfactory. The oversize of the insulation between the layers was removed after curing.

The prototype coil ends were impregnated in resin and several sections were made to inspect the quality of fit of the cable to the end spacers. A detail of the return end of the coil can be seen in Fig. 4. We found that the fit was very good in all sections, so that no further modifications of the end spacers were necessary for the production coils.

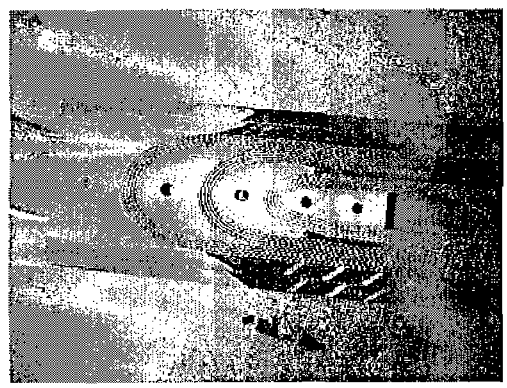

Fig. 4. Detail of the return end of the inner coil. The inner heater connections can be seen on the left.

The coils were measured after curing in order to obtain their size and modulus of elasticity. The measurements of the straight section of the coil were made separately for the two arcs in steps of 100 mm. The average size of the coil was 0.33 mm larger than nominal, with a rms of ±0.13 mm. The average incremental modulus at 50 MPa was 10 GPa. These values were used to determine the shim size necessary for achieving the target average stress in the coils of 60 MPa after assembly.

B. Collaring

In order to verify the collar design, the tooling and procedures, a 200 mm mockup of the magnet straight section was made, Fig 5. For the coil arches, we used sections of the prototype coil. Very encouraging results were obtained, as the collaring proceeded smoothly, without any particular problem during assembly, compression or keying. The azimuthal stress in the coils was recorded with capacitive gauges [5]. The stress after keying was 70 MPa, and 50 MPa after cooldown to 77 K, in very good agreement with the design values. At subsequent warmup, the stress of 60 MPa was recorded, very close to the value before cooling. After disassembly, the collars and keys showed no sign of deformation.

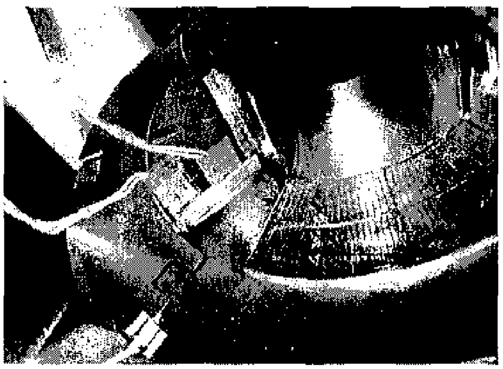

Fig. 5. Short mockup of the collared coil.

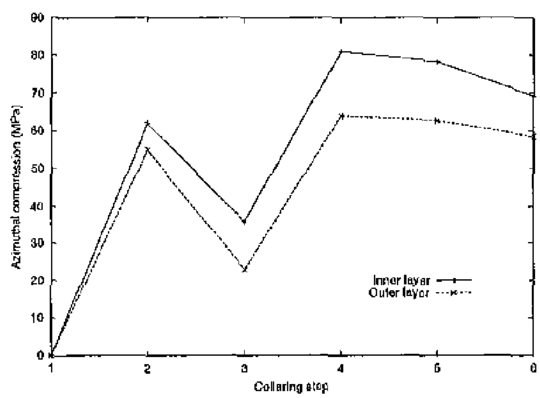

Fig. 6. Azimuthal stress during collaring: (2) Main press at 40 MPa; (3) Keys inserted half way, press released; (4) Keys fully inserted; (5) After 1 hour; (6) After 1 day.

The assembly of the full aperture proceeded with fitting the coils with instrumentation wires (voltage taps and spot heaters), and installing a set of outer quench protection heaters. Also, eight capacitance gauges were placed in the grooves of the pole face shims on the inner and outer coil layers. A non-collapsible mandrel was used, and after fitting the ground insulation, the coils were lightly compressed with pole sections, which were taken out as the collar stack was built. In this way, the two collar arms were partially locked and held in place by friction. Subsequently, the assembly was compressed over the full length by pushing bars, and the 1 m long collaring keys inserted half way. At this point, in order to extract the assembly mandrel, the collaring press was released, and the pressure dropped by about 30 MPa, Fig. 6. The collaring keys were finally pushed in the nominal position by compressing in 100 mm steps in two passes, giving the final stress in the coil of 70 MPa. After one day, the pressure decreased due to creep to 65 MPa. The assembly of the collared coil was completed with quadrant jointing, and the magnet, Fig. 7, made ready for testing.

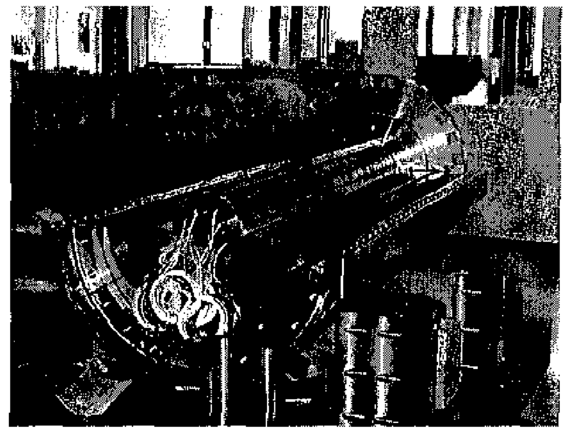

Fig. 7. Collared quadrupole assembled in a single aperture yoke.

IV. Conclusions

A 56 mm aperture low current quadrupole for the LHC insertions has been designed on the basis of the existing 8.2 mm cable for a nominal gradient of 200 T/m at 1.9 K. A 1 m model of the quadrupole has been recently completed. During construction, the mechanical design and assembly procedures have been verified, in particular the possibility of winding and curing two coil layers at a time with the quench protection heater in between. In spite of previous concerns, the heaters have kept a high level of dielectric insulation in all production coils. The magnet, suitably instrumented with spot heaters and pressure sensors, will give valuable information for the final design of the quadrupole.

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