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Construction Experience With MQXB Quadrupole Magnets Built at Fermilab for the LHC Interaction Regions

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Abstract—**Fermilab is building eighteen full length cold masses for the LHC Interaction Region inner triplets. One prototype and several production assemblies have been completed. This paper summarizes the construction details. Topics include coil fabrication, ground insulation, collaring, instrumentation, electrical testing, and final assembly. In-process measurements are presented and explained. Problems encountered during construction and their solutions are discussed.**

Index Terms—**Cable insulation, electric variables measurement, mechanical variables measurement, superconducting coils.**

I. Introduction

A SERIES of eighteen 70 mm bore quadrupole cold masses are being constructed at Fermilab in support of the LHC. Four have been completed, and three more are currently in process. The cold masses will be combined, two each, with a corrector coil, into 9 cryostats, and installed as the center component of the eight inner triplets in the interaction regions at the LHC. Eight short models and one long prototype were previously built to prove the viability of the design [1]–[5].

II. Coils

Approximately 100 coils have been fabricated. Inner cable has 37 strands, each 0.808 mm in diameter. Outer cable has 46 strands, each 0.648 mm in diameter. The nominal inner cable insulation system consists of 25 μm thick Kapton with 50% overlap surrounded by 50 μm Kapton with 2 mm gaps. The outer system consists of 25 μm Kapton with 50% overlap surrounded by 25 μm Kapton with 50% overlap. All Kapton is 9.5 mm wide. For both inner and outer coils, the outside surface of the outer layer is coated with a modified-polyimide adhesive.

The coil curing cycle [6] is shown in Fig. 1. Small amounts of azimuthal, radial, and longitudinal pressure are applied to the coils at 190C to set the adhesive and achieve an acceptable inter-strand resistance. Coils are then cooled to 135C, while a higher pressure is applied to set the coil size and Modulus of Elasticity (MOE). Coil size is set by a combination of curing mold cavity size and cable insulation adjustments. Adjustment of cable insulation overlap has proven to be a reliable and accurate method of controlling coil size [7].

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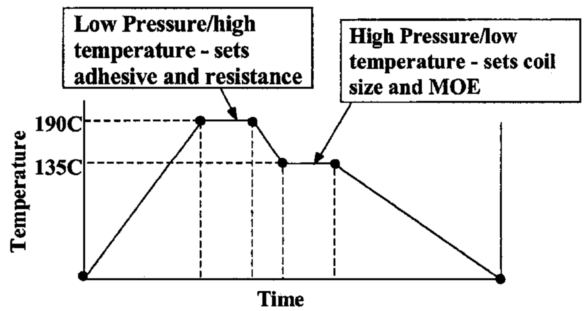

Fig. 1. Coil curing cycle.

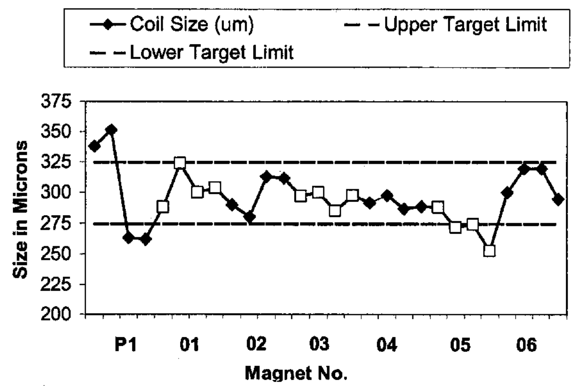

Fig. 2. Inner coil size.

Coil azimuthal size and MOE are taken over a range of pressures between 55 and 100 MPa. The design pressure for both the inner and outer coils at room temperature is 75–80 MPa. Coils are measured with a 76 mm gauge length along the entire straight section of the magnet, while resistance is monitored to ensure that there are no turn-to-turn shorts.

The azimuthal target sizes are +300 μm for inner coils and +250 μm for outer coils, at a pressure of 83 MPa. These values represent a size "with respect to the design size when the magnet is cold and powered." Larger sizes are necessary at room temperature to achieve the correct sizes when the magnet is operating. Figs. 2–5 show inner and outer coil sizes and MOE for the coils used in long magnets to date.

LHC IR coils are wound and cured using steel tooling which fixes the coil to a specific length. When a coil is removed from the tooling after curing, it shrinks longitudinally, relieving the stresses incurred during the winding and curing process.

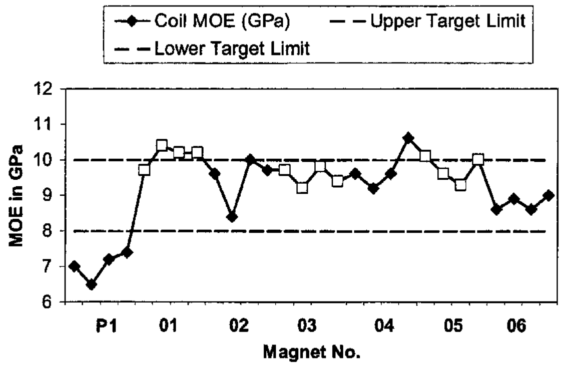

Fig. 3. Inner coil modulus of elasticity.

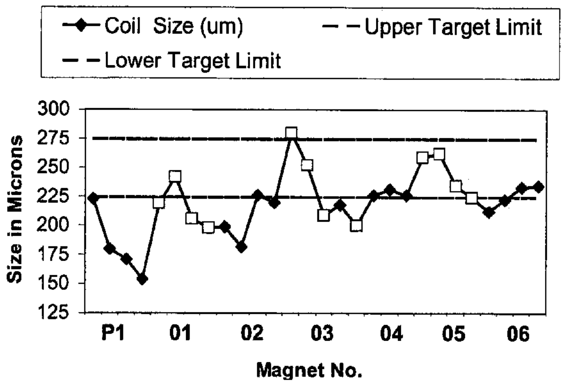

Fig. 4. Outer coil size.

Inner and outer coils shrink by mean amounts of 3.7 mm and 8.2 mm respectively, with peak to peak variations of 1.8 mm and 1.0 mm.

III. Assembly and Ground Insulation

After four inner and four outer coils are chosen for use in a magnet, they are arranged by a method which minimizes preload differences between quadrants. Although mean coil sizes within a magnet may vary by as much as 75 μm, typical differences between quadrants after arrangement are 10–15 μm, and never exceed 25 μm. The coils are then placed on a "rollover" fixture, where quench protection heaters are installed and layers of kapton insulation are placed around the coils and heaters. Quench protection heaters, supplied by CERN, consist of stainless steel strips, 25 μm thick, intermittently copper plated and sandwiched between two 100 μm thick layers of Kapton. They are placed directly upon the outer coil surface.

During production, to improve harmonics, one minor change to ground insulation was considered desirable [8]. The prototype (P1), along with the first three production magnets (MQXB01–MQXB03), showed a significant change in the normal dodecapole with respect to the model magnets, measured at the collared coil stage. Taking into account the systematic warm-cold shift seen in the model magnets and prototype, the dodecapole in these magnets is expected to be about 1/2 unit more negative at operating temperature than the value implied by the model magnets. As a result, the inner coils of magnet MQXB04 were shimmed toward the midplane by 38 μm, reducing the normal dodecapole. Measurements of MQXB04 showed this to be slightly more than necessary, so inner coils on subsequent magnets, beginning with MQXB05, are shimmed 25 μm toward the midplane with respect to the original design.

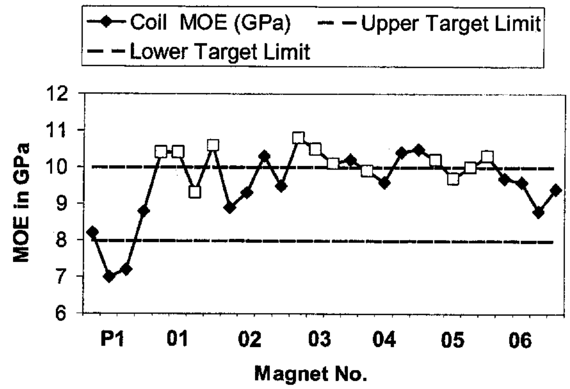

Fig. 5. Outer coil modulus of elasticity.

IV. Splices

All splices are 114 mm long, slightly greater than the longest cable transposition pitch. Areas to be spliced are filled with solder before the coil is wound. The filled, or "tinned" sections are then spliced after the coils are assembled on the mandrel.

The solder/flux combination of splices was changed during the production process. Splices internal to the cold mass (between layers and quadrants) on MQXB01-3 were made with 70/30 lead/tin, using a Kester 1544 flux. Beginning with magnet MQXB04, the solder/flux combination was changed to 96/4 tin/silver with Kester 135 flux. This was done to eliminate the small amount of chloride that is contained in the Kester 1544 flux, and to conform to the solder used at CERN. All splices external to the cold mass, on all magnets, are done with the 96/4 material. Extensive testing was done at Fermilab on the resistance of various splice configurations [9].

V. Collaring and Keying

LHC IR Quads are collared with 1.5 mm thick stainless steel collars, welded into packs 38 mm long. Collars are placed around the assembled coils, then keyed vertically in a hydraulic press as shown in Fig. 6 [10]. 1300 kN is applied to the collars at each of the four poles, while 8 phosphor bronze "keys" are placed into slots in the laminations with 100 kN of force on each quadrant. Hydraulic pressure is then released, and the keys support the coil preload.After keying, collar diameter measurements are taken to determine the coil preload. The amount of preload is determined by calculating the average deflection of the collar radius. A typical collar deflection plot is shown in Fig. 7. Table I shows the average radial deflections of the long magnets in micrometers, including P1 (the prototype) and the last two short models, HGQ08 and HGQ09. Nominal azimuthal preload chosen for the magnet body at room temperature is 75–80 MPa. Strain gauges showed HGQ09 had an average coil preload of 76 MPa, near the target value, while HGQ08, although it had acceptable performance, was 91 MPa,

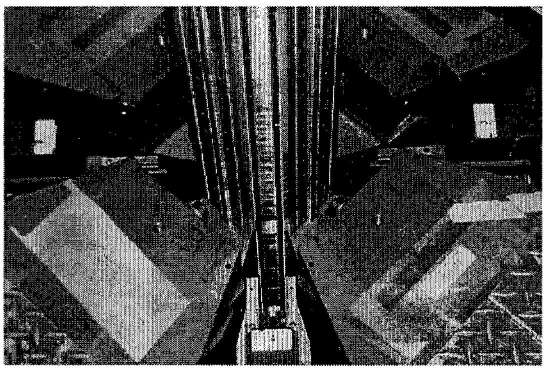

Fig. 6. Keying tooling.

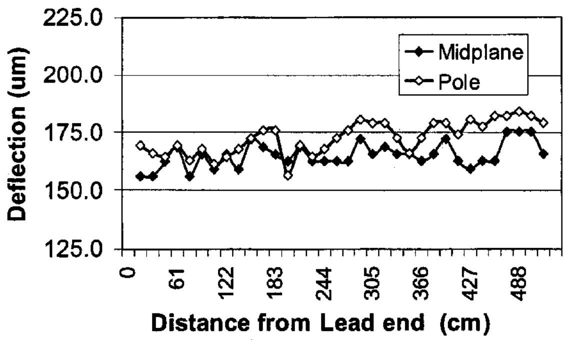

Fig. 7. MQXB05 radial collar deflections.

TABLE I
AVERAGE RADIAL COLLAR DEFLECTIONS OF MQXB COLD MASSES

Magnet No.	Midplane	Pole
HGQ08	222	237
HGQ09	154	159
P1	197	202
MQXB01	176	174
MQXB02	156	160
MQXB03	187	188
MQXB04	N/A	N/A
MQXB05	163	174

significantly above the target. Collar measurements indicate that all the long magnets are within acceptable preload levels.

Only the straight section of the magnet is enclosed in collar laminations. The end areas (including the layer-to-layer splices) are enclosed in collet style "end clamp" assemblies as shown in Fig. 8.

After the collars and end clamps are installed, the cold mass is hipotted to ensure electrical isolation between the coils, strip heaters and ground. Two significant types of electrical failures between these components have occurred during the production of the first few cold masses. They are listed below:

1) Collar-to-strip heater and collar-to-coil failures due to foreign material within the area between collars and coils. Material was observed to be coming from the interior surfaces of the collar packs. Solution was to thoroughly clean all packs in stock and add an additional inspection of collar packs and tooling before assembly to ensure there is no foreign material.

2) Collar-to-coil failures where the collar laminations end. Between keying and end clamp installation, a high stress point

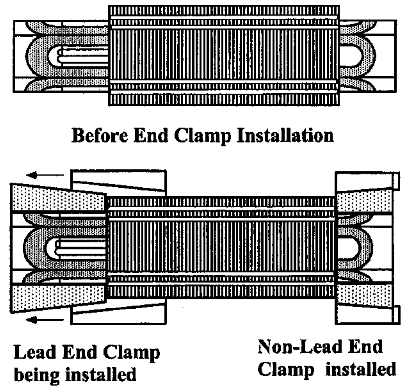

Fig. 8. Collet "end clamp" assembly.

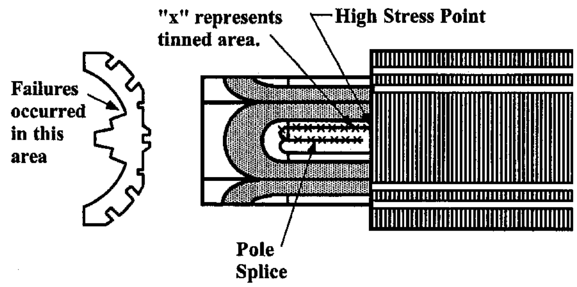

Fig. 9. Insulation failure position.

exists where the collars end (see Fig. 9). Insulation failure between collars and outer coil occurred here. The last lamination on the lead end cut through the ground wrap as the magnet was keyed, contacting the coil on the outer coil pole turn, always on the lead end at the position shown in Fig. 9. Several attempts were made to alleviate this problem, including modifications to the collar laminations as well as the coil assembly and alignment tooling [11]. The root cause, however, involved the pretinned area for the outer coil splice. Solder had, during the tinning process, flowed or "wicked" into the area that is eventually covered by collar laminations. The stiff, tinned cable was not able to freely bend as it exited the uncollared area after the magnet was keyed but before end clamps were installed. The problem was solved by shortening the amount of tinned cable when making the preform.

VI. YOKE AND SKINNING

The collared coil assembly is surrounded by a laminated steel yoke and enclosed in a stainless steel skin. Stainless steel modified yoke laminations surround the end areas. Before yoking, the magnet is compressed in contact tooling with a force of about 225 kN/m of magnet length. This is done to seat the skin and the laminated yoke packs. One fusion pass, then, consecutively, four filler passes with material added are applied. After welding, the skin is cut to a precise length, and the end plates are welded.

Diameter, twist and straightness measurements are taken after yoking. The allowed mean twist for the cold mass is less than 0.2 mrad/m. Twist measurements for MQXB04 are shown in Fig. 10. The twist was measured to be 0.056 mrad/m across the straight section of the magnet. Table II shows the mean twist for magnets P1-MQXB04.

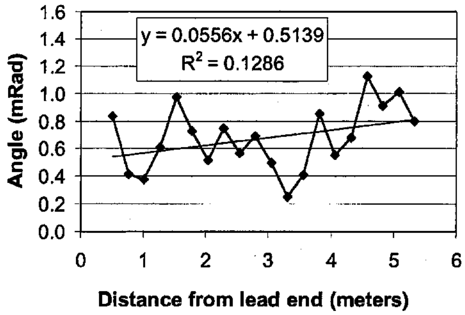

Fig. 10. MQXB04 twist measurements.

TABLE II
MEAN TWIST FOR MAGNETS P1-MQXB04

Magnet No.	Twist (milliradians/meter)
P1	0.141
MQXB01	0.179
MQXB02	0.076
MQXB03	0.073
MQXB04	0.056

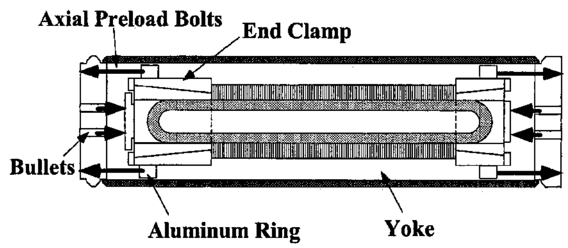

Fig. 11. Axial support system.

VII. FINAL ASSEMBLY

The axial support system of the magnet is shown below in Fig. 11. End load is applied by hand tightening the bullets to the bullet preload plate, then tightening the axial preload bolts to the specified amount. Torque applied to bullets was established from strain gauge readings of short models and P1.

The axial preload bolts are 3/4 inch (19 mm) in diameter. Each is torqued to 135 newton-meters. With that torque, each bolt applies 36 kN longitudinal tension to the magnet. As a result of the loading of the magnet with bolts, the bullets are subjected to a compressive load of 9 kN each. The total force applied to the magnet is therefore 108 kN tension.

Final electrical measurements include coil resistance, inductance, and hipots. Coil to ground, strip heaters to ground, and heaters to coil are hipotted to 5 kV, and coil to coil across midplanes at 3 kV. Maximum leakage requirement for all hipots is 3 μA. All completed cold masses pass these criteria.

VIII. MIDPLANE SPLICES

Midplane splices are made outside the end plate of the cold mass. Leads from 6 of the eight coils are spliced together in three places, formed by hand into their final position and enclosed in G-11. An extra piece of superconducting cable is soldered to each lead for thermal stability. Copper-only cable was initially used for the thermal stabilizer, but was found in practice to be too unstable mechanically to be adequately formed into the proper shape. Superconducting cable, identical to the inner coils, was found to be mechanically as well as thermally adequate, and was tested in P1. The general midplane splice configuration is shown in Fig. 12.

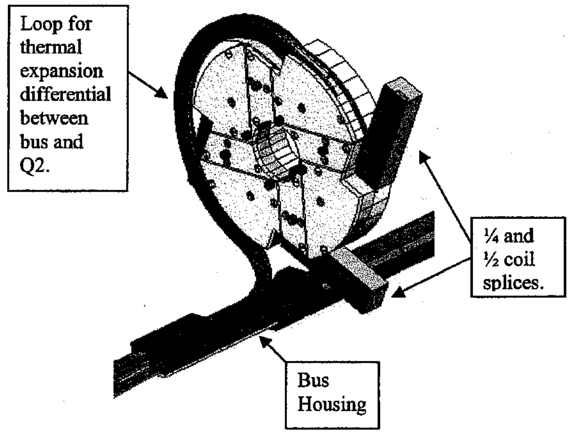

Fig. 12. View of magnet lead end showing splices and expansion loop.

The two power leads, from inner coil quadrants 3 and 4, are formed into a loop before they are attached to the 13 kA bus. This loop was added, after the short magnet program, to allow the necessary 4 cm of longitudinal travel in case of differential thermal contraction between the bus and the cold mass body.

IX. CONCLUSION

Full size production quadrupole cold masses for the LHC inner triplets have been produced successfully at Fermilab. Collaboration with KEK, CERN and LBL has been productive, and is proceeding efficiently. The magnets are operating within the criteria set for the LHC. The project is on pace to complete the magnets on schedule.

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