Quench Performance and Mechanical Behavior of the First Fermilab-built Prototype High Gradient Quadrupole for the LHC Interaction Regions

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***Abstract*—As part of the US LHC program to provide high gradient superconducting quadrupoles for the LHC interaction regions, a 5.5 meter long prototype magnet has been built and tested horizontally in a production type cryostat at Fermilab. This prototype magnet was used to validate the mechanical and magnetic design, production fabrication and assembly tooling. The first prototype magnet has met the LHC requirements of operating at 215 T/m with excellent magnetic field harmonics. This paper summarizes the test results of this magnet, including quench tests and mechanical behavior over several thermal cycles.**

***Index Terms*— Magnets, Quadrupole, Superconducting**

I. Introduction

THE final focus triplets in the interaction regions at the Large Hadron Collider (LHC) require high gradient quadrupoles. Each triplet consists of four quadrupoles with 70 mm bore and peak operating field gradients of 215 T/m.

Fermilab is providing half of the Interaction Region inner triplet quadrupoles and KEK the other half. Final assembly and cryostating of all magnets will be done by Fermilab. To develop the design and fabrication procedures for reproducible manufacturing of superconducting magnets that perform with sufficiently high quench current, adequate temperature margin and required field quality at the nominal field gradient, a 2 m long model magnet program was started in 1998 and successfully completed in 2000 [1]. Following the successful conclusion of this model program, the first full scale prototype has been fabricated using the production tooling and tested horizontally in a production type cryostat. The major differences between the prototype and production magnets are the diagnostic instrumentation present only in the prototype, and the correction elements present in the production magnet assembly.

This paper summarizes the test results of the first prototype magnet focusing on quench performance and mechanical behavior.

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II. Cold Mass Design

The cold mass design of the Fermilab built superconducting quadrupoles is shown in Fig. 1. Details of the base line design and fabrication features are described elsewhere [2]-[4].

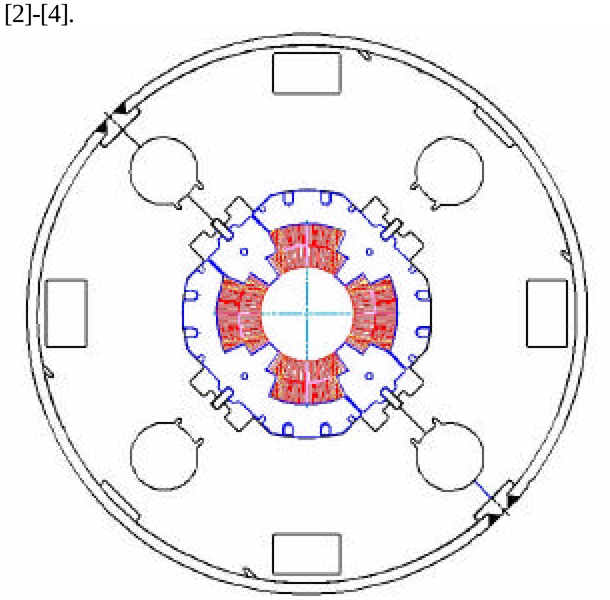

Fig. 1. Prototype magnet cross-section. The coil bore diameter is 70 mm and the skin outside diameter is 416 mm.

These 5.5 m long cold iron superconducting quadrupoles consist of two layer shell type coils. The inner (outer) coils are made from 37 (46) strand Rutherford cable. The uncoated and unannealed SSC type strands are 0.808 mm (0.648 mm) in diameter for the inner (outer) coil; both contain 6 μm NbTi filaments. The inner cable is insulated with a 61% overlap wrap of 25 μm Kapton tape followed by a wrap of 50 μm Kapton tape with 2 mm gaps between turns to increase the liquid helium wetted surface. Both layers of the outer cable are wraped with 50 % overlap wrap of 25 μm Kapton. In both coils, the outer Kapton layer is coated on one side with QIX polyimide adhesive. The coils are cured in two steps cure cycle, which sets both the interstrand resistance and the coil size properly. The end parts are made of G11CR.

The coils are supported in the body and the non-lead end by free-standing Nitronic 40 collars which are stamped, and pre-assembled into 37 mm long packs providing the required rigidity and cooling channels. The collars are keyed with 8 phosphor bronze keys. The coil ends are clamped with a 4 piece G11CR collet assembly enclosed in a tapered aluminum cylinder. Iron yoke laminations surround the collared coil and a welded 8 mm thick stainless steel skin surrounds the yoke. At both ends 35 mm thick stainless steel endplates are welded to the skin to provide support for longitudinal Lorentz forces. The aluminum end cans are anchored to the magnet endplates as a positive means of controlling the magnetic length.

Azimuthal prestress as measured with strain gauges at room temperature for inner (outer) coils was 68 (70) MPa. Longitudinal end preload was 13 kN per quadrant.

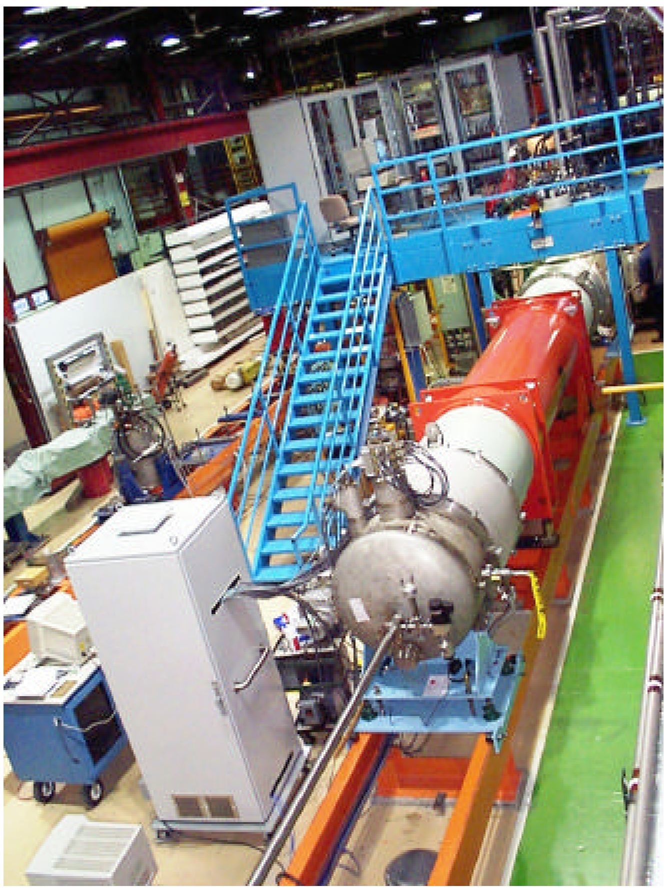

Fig. 2. Horizontal Magnet Test Facility at Fermilab.

III. Test Stand

The cold mass was installed in a cryostat and attached to the Horizontal Magnet Test Facility which (see Fig. 2) was recently built for testing these LHC IR quadrupoles. The cryostat design is described elsewhere [5]. The test stand has some unique features. The middle assembly (Q2) of the inner triplets contains two cold masses. This new test stand was designed with three 15 kA power leads which will allow testing of either cold mass or both cold masses in the Q2 assembly without warming up in order to modify cable splice joints. The test stand is capable of providing forced-flow 4.4 K helium for magnet tests as well as stagnant, pressurized superfluid. The top plate and lambda plate are removable, like those for a vertical test dewar [6], allowing replacement or modification of current leads and instrumentation. However, an imperfect lambda plate seal during these first tests limited temperatures to the 2.0 to 2.1 K range, rather than 1.9 K. The seal will be fixed prior to production magnet testing.

A vacuum insulated warm bore was inserted in the beam tube region extending through the magnet, to allow insertion of probes for making field strength, harmonics, and alignment magnetic measurements. This beam tube was fabricated with special quench antenna detector panels installed in the vacuum space of the warm bore, to capture quench location information on production magnets which will lack quench characterization voltage taps. The system was instrumented to handle 128 characterization voltage taps, and has another 64 channels of fast data logger channels devoted to monitoring voltages and currents used to protect the magnet and power leads. The scan system architecture and quench protection system have been described elsewhere [7]-[10].

IV. Test Program

The prototype magnet has been tested at the Fermilab Horizontal Magnet Test Facility in normal and superfluid liquid helium in the temperature range of 2.0-4.5 K. During quench studies about 50 % of the stored energy was extracted and dissipated in an external dump resistor. Although the prototype magnet was instrumented in the same manner as the short model magnets, with voltage taps and strain gauges to monitor mechanical stresses, the test plan was tailored for production magnets. The magnet training was defined to be acceptable if the number of quenches at superfluid temperatures required to reach a field gradient of 230 T/m was low (≤ 10) and, after warming the magnet to room temperature and re-cooling to superfluid temperature, the magnet reaches 220 T/m field gradient before the first quench occurs.

V. Mechanical and Quench Performance

Coil azimuthal stresses and longitudinal end force measurements were made on each excitation cycle. These data indicate that the azimuthal support of the coils is adequate (See Fig. 3). No unloading of the coils was observed at the highest operating current applied to the magnet and positive coil stress was maintained.

Fig. 4 shows the longitudinal coil force measurement. After cool down the magnet the preload was unchanged which was expected due to anchoring the magnet end can to the endplate. Data for azimuthal and longitudinal stress/force dynamics under various operating conditions are summarized in Table I.

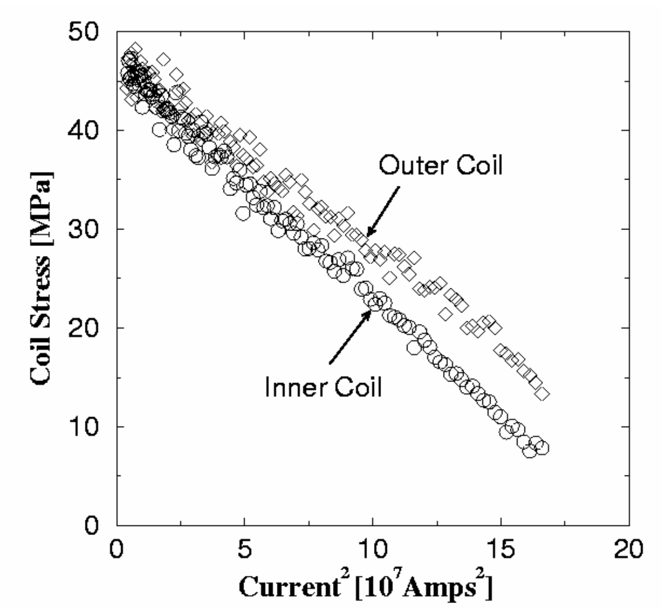

Fig. 3. Azimuthal coil stress change due to Lorentz forces as measured by strain gauges.

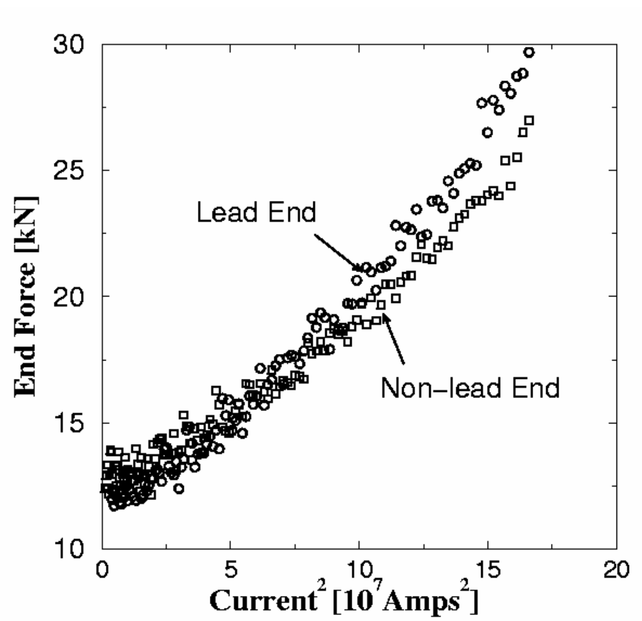

Fig. 4. Longitudinal coil force measurement.

All the values obtained for the prototype magnet are in good agreement with previously measured mechanical properties of the model magnets [11].

The training history with quench locations is presented in Fig. 5. The magnet was trained in normal and superfluid helium and went through two test cycles (TC). At 4.5 K it was few percent within the short sample limit (the estimated critical current value of the conductor based on measurement of cable sample) after modest training. The first quench in superfluid helium was higher than the nominal 205 T/m field gradient value and took only ten quenches to reach 230 T/m field gradient. The magnet exhibited some re-training after the first test cycle, but had its first quench at 212 T/m and

TABLE I
MECHANICAL PERFORMANCE OF COILS

Inner Coil Cool-down Stress Change	20 MPa
Outer Coil Cool-down Stress Change	22 MPa
Inner Coil Lorentz Loss (Azimuthal)	-0.24 MPa/kA^2
Outer Coil Lorentz Loss (Azimuthal)	-0.19 MPa/kA^2
Lead End Longitudinal Lorentz Force	0.1 kN/kA^2
Non-lead End Longitudinal Lorentz Force	0.076 kN/kA^2

the second quench was already higher than 230 T/m. At the end of the quench test, we initiated several trips where the external resistor was bypassed and all the stored energy was deposited in the magnet. Following these heater induced quenches, we successfully ramped the magnet up to 220 T/m field gradient without spontaneously quenching. The quench performance of the prototype magnet meets requirements for LHC operation.

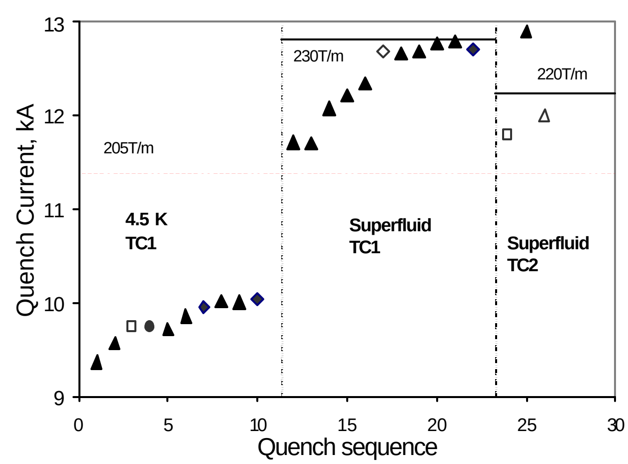

Fig. 5. Quench training of MQXP01. Quench location: Inner coil turn 11 next to wedge (triangles), Inner coil (open square), Outer coil (square), Inner coil pole turn straight section (diamond), Inner coil pole turn non-lead end (open diamond), spot heater induced quench with full energy deposition (open triangle).

TABLE II
QUENCH LOCATION SUMMARY

		Inner Layer		Outer Layer	
		body	end	Body	End
MQXP01	pole	1	1	1	0
	wedge	10	0	0	0
HGQ06	pole	9	5	0	0
	wedge	19	0	0	0
HGQ07	pole	1	5	2	0
	wedge	11	5	0	0
HGQ08	pole	4	1	1	0
	wedge	10	0	8	0
HGQ09	pole	3	1	1	0
	wedge	7	0	2	1

Table II summarizes the quench locations for the prototype and model magnets as well for 1.9 K quenches. The quench locations which are divided into eight regions, defined by body, end, pole and wedge areas of the inner and outer layers. The body of the magnet terminates where end cans take over support of the coil from the collar laminations. Fig. 6 shows

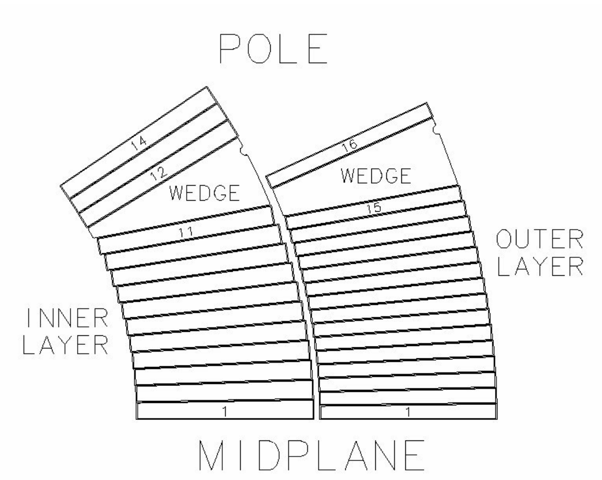

Fig. 6. High Gradient Quadrupole coil octant cross-section.

an octant of the coil cross section. The wedge location for outer layer quenches corresponds to quenches that occur in turn 15 on the midplane side of the wedge. For inner coil quenches wedge location means quenches in both turns 11 and 12, however, most of these quenches were in turn 11.

The quench origins for the prototype magnet (MQXP01) were similar to those of the model magnets: the majority of the quenches appeared in the wedge region. However the quench origins at the wedge region for the model magnets appeared only at higher force levels (~235-240 T/m). This might be related to the lower coil modulus and greater than the nominal coil size variation of the prototype magnet. Lower coil modulus and larger coil size variation could result in reduced mechanical support of the coil under Lorentz force, particularly in the region of the wedges. Although the prototype magnet performance was satisfactory further tuning of the new production tooling could result in further improvement of the magnet performance.

VI. SUMMARY

Test results of the first prototype quadrupole magnet developed for the inner triplet LHC Interaction Regions are presented. Quench performance was satisfactory for LHC operations. Its quench performance was similar to the model magnets leading to the conclusion that the production procedure is well controlled and that the production tooling is adequate for the production.

VII. ACKNOWLEDGMENT

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