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***Abstract*—In support of the development of a large-aperture Nb_3Sn superconducting quadrupole for the Large Hadron Collider (LHC) luminosity upgrade, two-layer quadrupole models (TQC and TQS) with 90 mm aperture are being constructed at Fermilab and LBNL within the framework of the US LHC Accelerator Research Program (LARP). This paper describes the construction and test of model TQC01. ANSYS calculations of the structure are compared with measurements during construction. Fabrication experience is described and in-process measurements are reported. Test results at 4.5 K are presented, including magnet training, current ramp rate studies and magnet quench current. Results of magnetic measurements at helium temperature are also presented.**

***Index Terms*—LARP, LHC, IR, Nb3Sn, quadrupole magnet, collars, yoke, skin.**

I. Introduction

One of the primary objectives of the US LHC Accelerator Research Program is to develop Nb_3Sn quadrupole technology for a future LHC upgrade [1]. Technology quadrupole models using two different structures [2][3], each with identical coils, are being constructed in collaboration between Lawrence Berkeley Lab (LBNL) and Fermilab (FNAL). The TQC01 structure, developed and built at Fermilab, consists of stainless steel collars surrounding the coils supported by an iron yoke and stainless steel skin [3].

II. Magnet Design and Analysis

A. Magnet Design

The TQ coils (common to TQC and TQS) are manufactured using a 2-layer cos-2θ configuration with a 90 mm bore and one wedge per octant in the inner layer. TQC coil and structural design and 2D analysis have been previously discussed [3].

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B. Instrumentation

TQC01 is instrumented with strain gauges at various locations to measure preloads and stresses within structural components during assembly and testing. Coil instrumentation included azimuthal gauges on the inner coil and axial gauges on the inner surface of the bronze pole pieces, both in the straight section and at the pole on the lead end. Control spacers, skins and end preload bolts (bullets) were also instrumented. Shims were placed at specified locations to provide coil design preload. Fig. 1 shows the TQ structure with the main structural components labeled, and the positions of strain gauges and shims noted. Fig. 2 shows the lead end of a coil with positions of strain gauges shown.

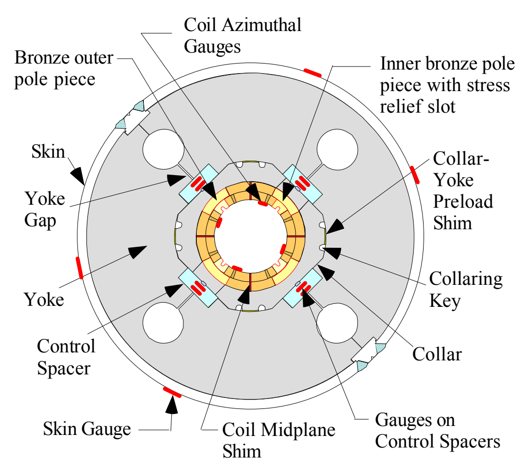

Fig. 1. TQ structure with positions of instrumentation.

Fig. 2. Inner surface of instrumented coil.

C. Analysis

2D and 3D analysis for TQC01 has been completed [3] [4]. Table I shows expected stresses within the structure according to the 2D analysis. End load was chosen based on 3D analysis and previous experience with Nb_3Sn dipoles and NbTi quadrupoles at Fermilab [5][6].

TABLE I
EXPECTED STRESSES WITHIN TQC01

Gauges	Units	After keying	After assy
Coil Azimuthal (peak)	MPa	-70	-140
Coil Azimuthal (at gauges)	MPa	-50	-100
Control Spacer	MPa		-50
Skin	MPa		160
Bullets	KN		-14

III. MAGNET FABRICATION

A. Mechanical Models

A series of mechanical models were completed to test the production processes and to compare stresses within the structure to the analysis. A preliminary mechanical model using an aluminum tube to represent the coils demonstrated that coil azimuthal pre-stress along the magnet length can be controlled to within 15 MPa, allowing the keying process to take place without degrading the Nb_3Sn cable. The models 2 and 3 consisted of collared coils only, and were used to understand coil size and preload levels after collaring, by measuring stresses within the completed collared coil assembly and comparing them to expected values. Due to moderate variations in preload between coils in TQC mechanical model a "full round" collar was used for TQC01 as shown in Fig. 3. The tabbed collar may be reintroduced later, depending on the results of measurements of coil size variations and the TQC01 test.

The final two mechanical models 4 and 5 included yokes, and were used to establish the coil mid-plane and collar-yoke shims needed for TQC01. Results indicated similar preload of about 70 MPa in both the inner and outer layers, after keying. Increase in strain of coils during yoke assembly was about a factor of 2, similar to the values derived from the 2D analysis.

Fig. 3. Collar laminations, 'with pole tab" and "full round"

B. Magnet Construction

Four coils were wound and cured at Fermilab, reacted and impregnated at LBNL, then shipped back to FNAL, by a process described in [3]. TQC01 assembly was completed at FNAL. Readings of gauges at various stages of assembly are shown in Table II.

Assembly begins with coil arrangement and application of ground insulation. Collaring and keying is done in a hydraulic press, as shown in Fig. 4. Initial pressure is applied by main cylinders, after which key cylinders are energized. Multiple passes are applied, with key depth controlled and incrementally increased with each pass. TQC01 was keyed twice, first without mid-plane shims and the second time using a 50 µm shim at each coil mid-plane. Inner layer coil azimuthal preload after each keying was determined by strain gauges on coils as shown in Fig. 2 and by collar deflection measurements, shown in Fig. 5. Measurements agree that preload in the magnet body was ~50-55 MPa after keying with a 35 µm mid-plane shim. Collar deflection "low points" appear at the positions where the cable is turning around the ends. "High points" occur where the cross section is made completely of bronze end parts.

After completion of the collared coil assembly, TQC01 was yoked and the skin was welded longitudinally at four positions using automatic weld heads. A 425 µm collar-yoke shim was used. Average coil preloads from azimuthal gauges during collaring and yoke welding is shown in Fig. 6. Weld is typically applied in several (4-6) passes, with increasing stress applied to the coils from skin stretching during each pass. The initial two passes yielded higher than expected coil stresses, but in subsequent passes the force from the skin was diverted to the control spacers, as expected from the analysis. Some asymmetry between coils occurred, due to uneven side-to-side application of load by the press, to be corrected with shimming in future assemblies. End plates were installed and total end load of 14 kN was applied to each end by mechanically tightening the end preload bolts (bullets).

TABLE II
STRESSES WITHIN TQC01 COMPONENTS DURING CONSTRUCTION

Gauges	Units	Position	After keying		After assembly	
			end	center	end	center
Coil Azimtl	MPa	Average	-39	-37	-78	-96
Coil Axial	MPa	Average	15	15	30	30
Cont Sp	MPa	Average	-----		-80	
Skin	MPa	Average	-----		140-170	
Bullets	kN	LE Avg.	-----		-14	
Bullets	kN	NLE Avg.	-----		-14	

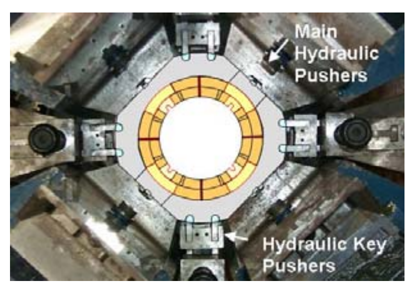

Fig. 4. Illustration of TQ collared coil in collaring press

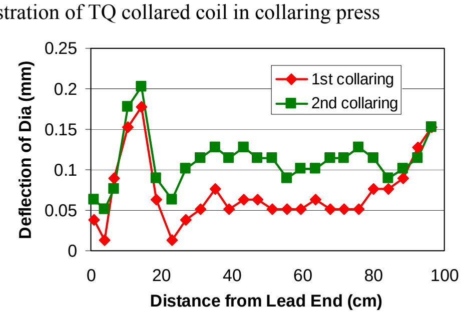

Fig. 5. Collar deflection measurements.

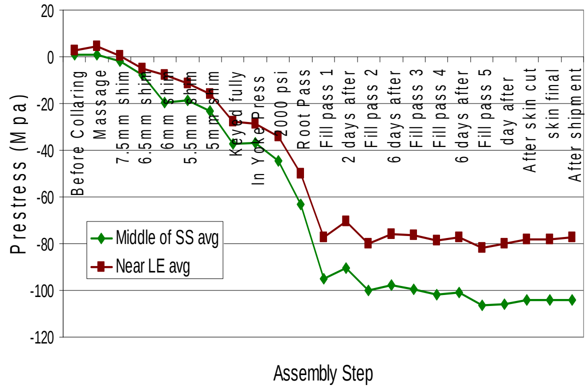

Fig. 6. Coil azimuthal stresses during construction as read by coil gauges. (based on coil E-modulus of 40 GPa)

IV. Test Results

TQC01 was tested in Fermilab's Vertical Magnet Test Facility (VMTF) in August 2006.

A. Quench Performance

Magnet training was performed first in a liquid helium bath at a temperature of 4.5 K. Current ramp rate for training quenches was 20 A/s (see Fig. 7). The quench current for the first quench was only 7681 A, about 60 % percent of the estimated critical current value of the conductor. The magnet exhibited very slow training, reaching 8995 A after 11 quenches, still only 70 % of the critical current limit. Quench current did not significantly increase over the next five quenches, even falling back 3 times.

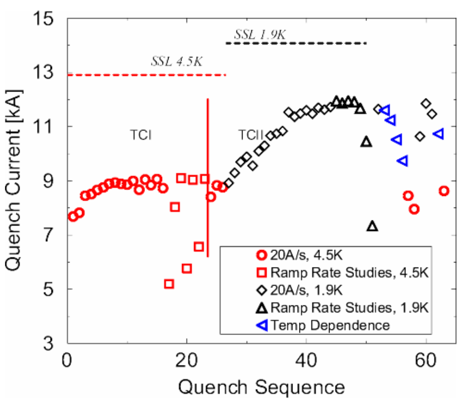

Fig. 7. TQC01 training curve. The magnet critical current limit is 12900A.

Quench locations were generally in the pole turn region of the inner coils, which is the highest field region of the magnet. Longitudinal locations were not concentrated in a particular section of the coils, although few end region quenches were observed (see Fig. 8.).

Due to difficulties in cooling the magnet to superfluid temperatures the magnet went through a full thermal cycle up to 300 K before cooling back down to 4.5 K. After three quenches at 4.5K, the magnet was cooled to 1.9 K and the test program continued with 20 A/s quench training. It took eleven quenches to reach the 1.9 K quench plateau of ~11700 A. At this current level the magnet exhibited erratic behavior and the quench locations moved from the inner pole turn region to the section of the outer coil which was not instrumented with voltage taps. Even if the exact locations of these quenches are not known the pole turn section of the coil can be excluded.

The 1.9 K quench current ramp rate dependence was similar to that taken at 4.5 K. The highest quench current corresponding to a gradient of ~200 T/m, was reached whole ramping at a ramp rate of 100 A/s.

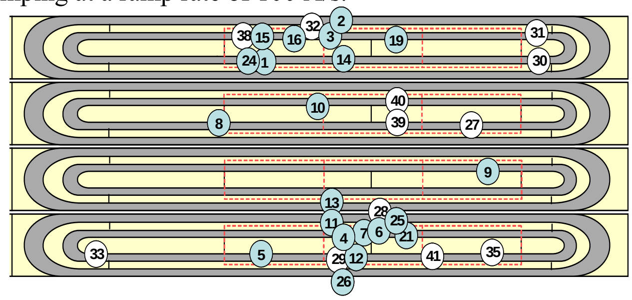

Fig. 8 TQC01 quench positions at 4.5 K (grey) and 1.9 K (white). Figure is shown looking at the inside surface of the inner coils, with the lead end on the left and Quadrants 1 through 4 positioned from top to bottom. All training quenches were in the inner coil pole area, except quenches 37 and 42-45, which occurred in the multi-turn sections of the inner layer (37) and outer layer (42-45). High ramp rate, multi-turn quenches, and quenches of unknown location (34,36) are not shown.

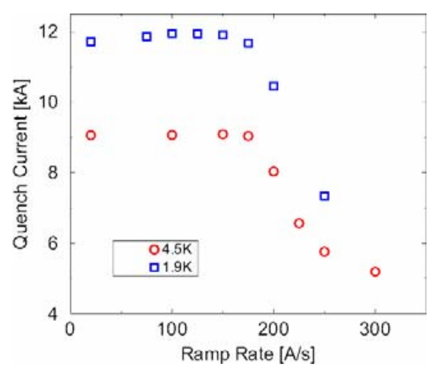

Fig. 9. TQC01 Quench current ramp rate dependence.

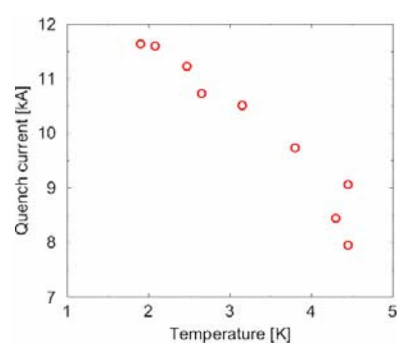

Fig. 10 TQC01 quench current temperature dependence.

Quench current temperature dependence is shown in Fig. 10. The quench current falls as the temperature increases, however the slope of the current change is much steeper than one would expect. It is interesting to notice that the 4.5 K quench locations after the 1.9 K quench test have changed from the inner coil pole turn to the outer coil midplane region and the quench current has reached a low value of 7953 A. To check whether the magnet has permanent degradation, it was cooled to 1.9 K again. Interestingly, the first quench current was about 1000 A less than the previously obtained 1.9 K quench plateau and with the quench location in the same coil as the previous quench at 4.5 K (Q1). The second 1.9 K quench current, however, returned to 11843 A with the origin in a different coil.

B. Strain gauge results

1) Cool-down: All strain gauges were read during cool-down and excitation. Strain gauges mounted to the skin showed increasing stress during cool-down, as expected by the analysis. Load on control spacers increased during cool-down, as expected, taking the load from the skin without transferring it to the coils. End preload bolts stayed in contact with the coils at 4.5 K, with the amount of force increasing slightly. Axial gauges on the bronze inner pole tip, in tension at room temperature, showed a decrease in tension when cold.

2) Excitation: During excitation, skin stresses increased slightly as expected. At 4.5K, stress in control spacers decreased slightly under the Lorenz forces, indicating that azimuthal load was being transferred from the control spacers to the coil mid-planes, as expected. This behavior revealed that at the 9000 A force level (about half of the designed value at full current), the yoke and skin structural rigidity is consistent with the analysis.

Adequate end support was confirmed by bullet gauges. The increase in end load under the Lorenz forces was about 15 % of the level calculated for total end force from Lorenz forces. This shows that the coil axial support through radial force from the collar, yoke and skin structure is utilized. Also, as Lorenz forces began to increase, load increased immediately and linearly, indicating that the ends remained loaded at all times.

Azimuthal gauges showed unloading of the coils near 9000 A (Fig. 11). This indicates that the azimuthal pre-stress of the coils was not sufficient. Low pre-stress might be a reason for the poor training behavior of the magnet. Also, strong asymmetrical loading with current appears near the center of the magnet. This phenomenon is less pronounced in the end area where the outer pole is glued. Detailed mechanical analysis of the magnet will be presented later.

TABLE III
MEASURED HARMONICS AT 7 KA AND 1.9 K (R_{REF}=17 MM)

	TQC01	MQXB		TQC01	MQXB
b3	1.3997	-0.04±0.59	a3	-1.4883	0.01±1.00
b4	-0.9871	0.13±0.13	a4	0.4655	-0.22±0.40
b5	0.4377	0.00±0.17	a5	-0.0296	0.01±0.18
b6	-0.3028	0.11±0.29	a6	-0.0155	-0.10±0.18
b7	0.0533	-0.00±0.04	a7	0.0679	-0.00±0.03
b8	0.0005	-0.01±0.01	a8	0.0106	-0.00±0.03
b9	0.0015	0.00±0.01	a9	0.0128	0.00±0.01
b10	-0.0048	0.02±0.01	a10	-0.0032	-0.00±0.02

C. Magnetic measurements

Magnetic measurements were also performed. Harmonic measurements are summarized in Table III, where the data for the first generation LHC IR quads (MQXB) [7] are also presented. It is important to notice that the presence of a relatively large b4 is another indication that the coils are asymmetric, which could be related to their uneven preload.

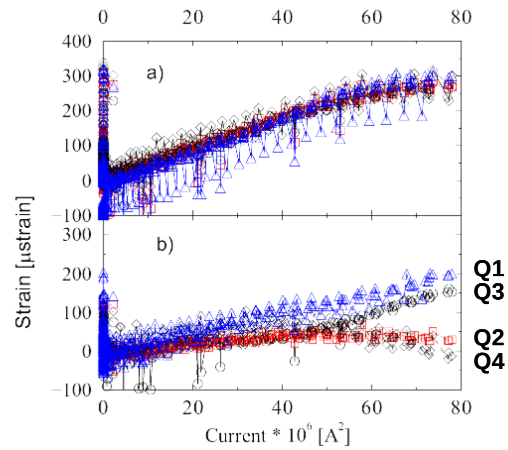

Fig. 11. Strain from azimuthal gauges near center of magnet (bottom plot) and near lead end (top plot) vs. I^2.

V. CONCLUSION

TQC01, the first Technology Quadrupole in a series of 2-layer Nb_3Sn quadrupoles for LARP, has been completed. Construction steps were performed successfully, with most parameters during construction in agreement with the mechanical analysis.

Testing has been completed at 4.5 K and 1.9 K, demonstrating that primary goal to build a 200 T/m, 90 mm bore magnet was achieved. However, the magnet quench performance indicates that the design and fabrication procedure needs further optimization. Although there are clear signs of low preload in the straight section, lead damage at the outer midplane, which began at higher current values achieved at superfluid helium temperatures, cannot be excluded. Further analysis, to unfold the complex quench behavior of this magnet, is required.

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