Development and Test of TQC models, LARP Technological Quadrupole Magnets

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***Abstract*—In support of the development of a large-aperture Nb3Sn superconducting quadrupole for the Large Hadron Collider (LHC) luminosity upgrade, two-layer quadrupole models (TQC and TQS) with 90mm aperture are being constructed at Fermilab and LBNL within the framework of the US LHC Accelerator Research Program (LARP). This paper describes the development and test of TQC01b, the second TQC model, and the experience during construction of TQE02 and TQC02, subsequent models in the series. ANSYS analysis of the mechanical structure, its underlying assumptions, and changes based on experience with TQC01 are presented and discussed. Construction experience, in-process measurements, and modifications to the assembly since TQC01 are described. The test results presented here include magnet strain and quench performance during training of TQC01b, as well as quench studies of current ramp rate dependence.**

***Index Terms*— LARP, LHC IR, Nb_3Sn, quadrupole magnet, collars, yoke, skin.**

I. INTRODUCTION

SEVERAL TQC style models have been built for LARP [1] since the initial testing of TQC01 [2]. TQC01b, made from coils previously used in TQC01 and TQS01 [3], has been built and tested. TQE02 (E stands for “coil exchange”), made from coils previously used in TQS02 [4], and TQC02, made of four new coils, are both currently under construction, scheduled to be tested early in FY08. Construction methods have been refined, instrumentation improved and new in-process measurements have been developed since the fabrication of TQC01.

II. TQC01 EXPERIENCE

TQC01, the first model completed with the TQC style structure (shown in Fig. 1), was tested in FY06 [5]. Quench current plateau at 4.5K was limited to 70% of the critical current limit of the conductor by insufficient preload within the magnet straight section. At 1.9K, after reaching 85% of the critical current limit, quenches appeared at the outer coil mid-plane in two coils, resulting from cable degradation at those positions. Low preload in the magnet body, coupled with higher preload at the ends, allowed longitudinal movement of the coils at the mid-planes, resulting in degradation and limiting the current level.

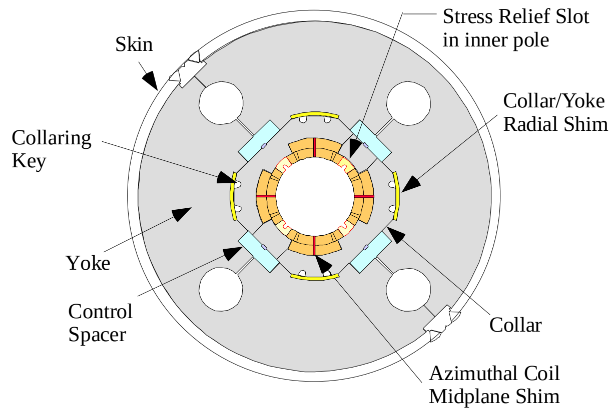

Fig. 1. TQC structure and shim system.

III. CONSTRUCTION IMPROVEMENTS

A. *Refinement of Assumptions about Coil Properties.*

To achieve the proper preload when using the TQC structure, the coils must be shimmed azimuthally at the midplanes and radially between the collars and yoke, at the positions shown in Fig. 1. To establish the shims needed, it is important to know the Modulus of Elasticity and azimuthal size of the individual coils. An elastic MOE of 40 GPa was assumed for both the analysis and readout of instrumentation in TQC01. Preload was inferred during construction from strain gauges mounted to the interior surface of the coils.

Use of a high coil MOE resulted in an underestimation of the shim size needed as well as a misinterpretation of the preload level during construction. Beginning with TQC01b, analysis is based on plastic behavior of coils derived from previous measurements taken at FNAL [6], with an MOE of 20 GPa on the first application of pressure, followed by a permanent change in size and an approximately 40 GPa MOE on subsequent pressings, as shown in Fig. 2. Preload is inferred by strain gauges mounted to the inside surface of the inner poles, which may be made of either bronze or titanium.

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B. *ANSYS Preload Analysis*

All structural analysis for TQC was adjusted based on the revised coil properties. The expected internal coil preloads during all phases of construction and operation are shown in Table 1 at the positions described in Fig. 3. Coil stress after collaring is highest at the inner coil mid-plane. Then, due to force applied by the yoke at the mid-planes, preload reaches a maximum level of approximately 130 MPa at the poles after the yoke is installed. The preload remains increases slightly during cool-down and is then redistributed toward the mid-plane when the magnet is powered.

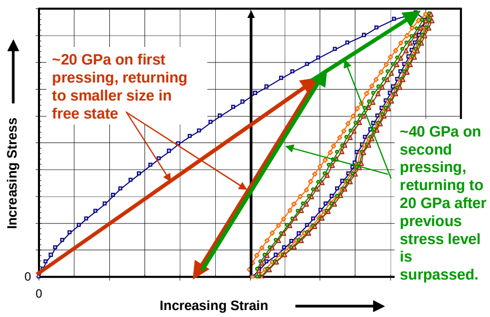

Fig. 2. Nb_3Sn coil Modulus of Elasticity.

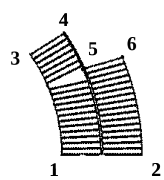

Fig. 3. Key stress points within cross section.

TABLE 1 PREDICTED PRELOADS WITHIN COIL

Collared Coil		Completed Magnet 300K		After Cooldown 4.5K		At Maximum Field	
Pos	MPa	Pos	MPa	Pos	MPa	Pos	MPa
1	70	1	95	1	75	1	150
2	40	2	115	2	110	2	150
3	40	3	130	3	145	3	15
4	40	4	95	4	80	4	0
5	40	5	95	5	80	5	30
6	70	6	115	6	105	6	60

C. *In-process Measurements*

To determine the midplane shim size, it is important to have accurate measurements of the coil cross section. This has been done routinely, at the expected operating pressures, in past programs using niobium titanium magnets [7], but is not easily done with Nb3Sn coils due to possible degradation of the cable when making the measurement. As a result, coil size measurements were not available for TQC01. Beginning with magnet TQC01b, measurements have been taken of each coil cross section in the free-state on a coordinate measuring machine [8] (Fig. 4), then combined with FEA to determine the final mid-plane shim size.

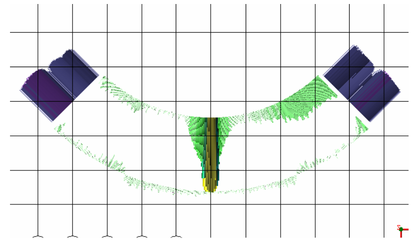

Fig. 4. Coil cross section measurement. Lines on radius and midplane indicate size of coil with respect to nominal. One square is equal to 100 um. Note: The large spike at the center of the inner surface represents deviations in the depth of the slot machined in the inner pole. This dimension is not critical.

After collaring, measurements are taken of both the collar O.D. (manually) and the yoke I.D. (with a CMM) at the positions shown in Figs. 5 and 6. Collar measurements are used to determine average preload in the collared coil assembly. Individual coil preloads are determined by strain gauges mounted to the inner poles. Both collar and yoke measurements, again combined with analysis, are used to determine the size of the radial yoke-collar shim. Although collared coil measurements were available when building TQC01, yoke measurements were not incorporated until the construction of TQC01b.

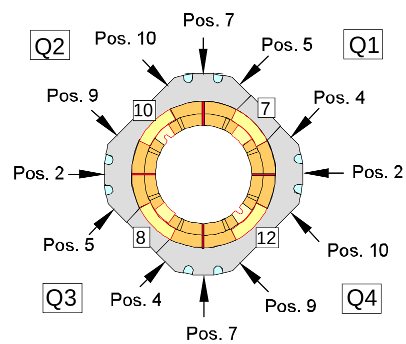

Fig. 5. Collared coil measurement positions (TQC01b shown).

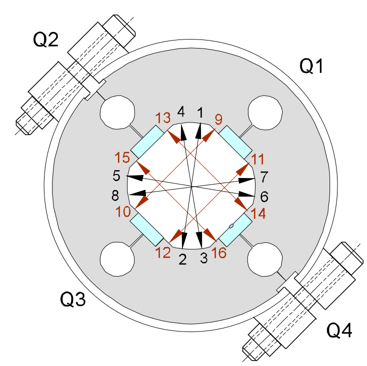

Fig. 6. Yoke interior measurement positions. (Bolt-on skin is used to make measurements. Actual magnets can use bolt-on or welded skin.)

Yoke interior measurements are done with a special bolt-on skin. Actual magnets can use a bolt-on or welded skin. TQC01 was made with a welded skin, but TQC01b and TQE02 use a bolted skin. This allows the skin to be removed to adjust shims during construction if necessary. TQC01b did not require shim adjustment.

After yoking, an axial load of 14 kN is applied to each end through preload bolts attached to 50mm thick end plates. The end loading system is unchanged from TQC01. End load was maintained in TQC01 throughout all construction and testing.

IV. TQC01B Construction

TQC01b contained two coils that were reused from each of the initial TQ models, TQS01 and TQC01, each which have slightly different features. The most significant difference is the existence of a "stress relief slot" (see Fig 1) in the inner pole of the TQC style coils (10 and 12), which does not appear in the TQS coils (7 and 8). As a result, the expected preload is 15-20 MPa lower after yoking for the TQC style coils. Coils of similar styles were placed across from each other, as shown in Fig. 5.

Strain gauges were mounted to the center inside surface of the inner poles of coils 7 and 8, and were used to measure coil preload curing construction and operation, as shown in Table II. Due to the slot at the inner pole, coils 10 and 12 could not accommodate these gauges, so the preload of these coils must be inferred from the coil 7 and 8 measurements.

Preload after collaring varied, possibly due to the imbalance created by the use of two different style coils in the same collars. Average collar deflections (Fig 7) measured at positions 2 and 7 were 70 um, equivalent to an average pole preload of about 35 MPa, consistent with the strain gauge average. The final yoked values are much more evenly distributed, although lower by about 20% than the original TQC goal. This is due to the use of a bolt-on skin, where the final yoked stresses are lower than the values gained when a welded skin is used, due to "springback" after the hydraulic load is released. The inferred preload in coils 10 and 12 is 15-20 MPa lower than in coils 7 and 8, due to the pole slots.

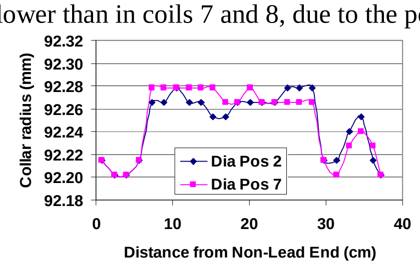

Fig. 7. Collar deflection measurements of TQC01b.

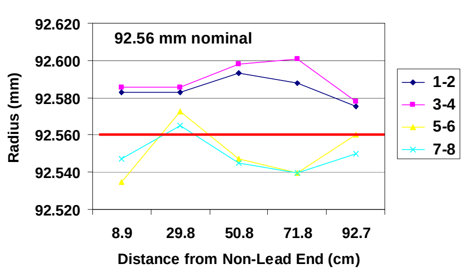

Fig. 8. Yoke measurements of TQC01b.

TABLE II TQC01B PRELOAD (MPa)

Coil No.	After collaring	After yoke	After Cooldown	At Max Field
7	49	110	122	41
8	30	102	108	36

V. TQC01B Test Results

TQC01b was tested in Fermilab's Vertical Magnet Test Facility (VMTF) in July and August of 2007.

A. Quench Performance

Magnet training was done in a liquid helium dewar at both 4.5 K and 1.9 K. Nominal current ramp rate for training quenches was 20 A/s (see Fig. 9). The quench current for the first quench was 8338 A, about 67 % percent of the estimated critical current value of the conductor, ultimately reaching 10528 A after 39 quenches at 4.5 K, about 85% of the original critical current limit of the cable (12400 A). During subsequent training at 1.9K, current reached 11957A, 89% of the critical current limit of 13400A. Finally, after returning to 4.5K, there were three quenches at about 10550 A, about the same current reached previously at that temperature. However, the coils in TQC01b have been used in several previous magnets, and may have been degraded during these tests and construction, so the critical current of these coils is not precisely known.

Peak field for TQC01b was in the end region, although the field in the straight section inner layer pole turn was only about 4% below the peak. Most of the training quenches at 20 A/s, both at 4.5K and 1.9K, occurred in the first turn of the inner layer of coils 7 and 8, with the final 8 quenches all in coil 8. Since both coils 7 and 8 had only two voltage taps on the first turn, it is not known whether these quenches took place in the straight section or the end area. Quench velocity calculations and quench antennae data may reveal the position of these quenches. There were several quenches in both inner and outer layer of coils 10 and 12.

Ramp rate behavior at 4.5K (see Fig. 10) indicates that the current level is close to, but not quite at, the cable critical current. However, training was still taking place when the higher ramp-rate quenches were taken, and some were taken at different times during the training sequence, which introduces several systematic uncertainties in the data.

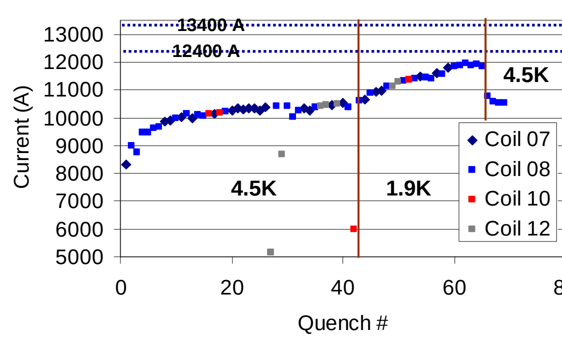

Fig. 9. Quench performance of TQC01b.

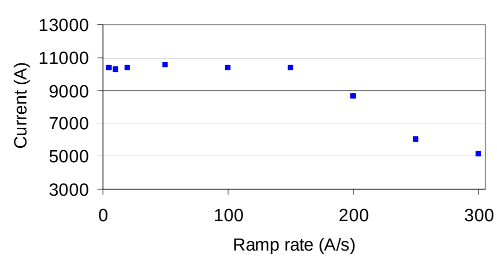

Fig. 10. Ramp rate behavior of TQC01b.

B. Strain gauge results

1) Cool-down: All strain gauges were read during cool-down and excitation. Preload shown by the azimuthal gauges mounted to each bronze inner pole is shown in Table II. Coil azimuthal stresses increased slightly with cooldown as expected. Skin stresses increased during cooldown, from 210 to 320 MPa. Load on control spacers redistributed slightly and increased during cool-down, as expected, taking the load from the skin without overcompressing the coils. End load increased during cooldown from 14 kN to an average of 140 kN.

2) Excitation: During excitation, skin stresses remained about the same, as expected. At 4.5K, stress in the control spacers decreased slightly under the Lorenz forces, indicating that azimuthal load was being transferred from the control spacers to the coils as desired. Also, as Lorenz forces began to increase, the strain read by the azimuthal gauges on the inner bronze poles decreased immediately and linearly with I^2, indicating that the coils remained loaded at all times (Fig.11). Preload at maximum field, shown in Table II, was about 40 MPa at the inner poles. ("Maximum Field", in this case, is recorded at 10500 A during the first thermal cycle at 4.5K.)

Adequate end support was confirmed by bullet gauges, which increased from 140 kN to about 170 kN at 10500 A.

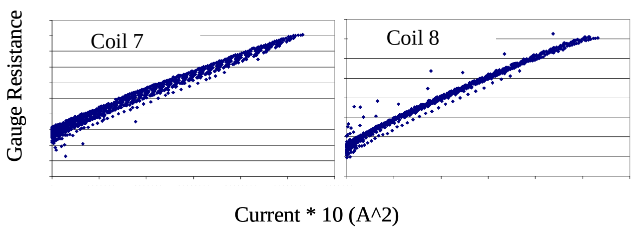

Fig. 11. Current vs. I^2 for azimuthal coil gauges on inner bronze pole..

VI. TQE02 Construction

TQE02 is being built with coils used previously in TQS02. The coils have titanium poles without stress relief slots, and will be arranged identically to the configuration used in TQS02. TQE02 will therefore provide the closest possible technical comparison between the TQS and TQC structures, since no other TQC magnet contains titanium as a pole material. Also, titanium poles without inner coil stress relief slots are the current choice for the LQ magnets [9].

Preloads from gauges on the titanium poles after collaring are shown in Table III, and are close to the expected values. Note: expected pole preloads in TQE02 after collaring were 50-55 MPa, higher than the 40 MPa value shown in Table I for two reasons; TQE02 has coils without slots on the inner pole, and was shimmed slightly higher due to the expected higher field. Collar deflection measurements of TQE02 in the completed collared coil body averaged about 85 um at the midplane radius, equivalent to an average preload of 47 MPa within the collared coil when using coils without pole slots. TQE02 will be completed and tested in the fall of 2007.

TABLE III TQE02 PRELOAD AFTER COLLARING (MPa)

Coil No.	After collaring
20	56
21	59
22	52
23	59

VII. TQC02 Construction

Three of the four coils needed are ready for assembly. The final two (including one spare) are currently being reacted at Fermilab (the first TQ coils to be done at Fermilab since the practice coils). All coils for TQC02 include bronze poles and stress relief slots, similar to the coils for TQC01. TQC02 assembly and testing will be completed in early FY08.

VIII. Conclusion

TQC01b, the second model in the TQC series, has been completed and tested, and construction of TQE02 and TQC02 are in process. Quench performance of TQC01b is consistent with expectations. Both TQC01b and TQE02 have been shown to have preloads and stresses within the internal components that are in agreement with analysis. This series of magnets will demonstrate the viability of the TQC structure for LARP quadrupoles.

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