LARP Long Nb_3Sn Quadrupole Design

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***Abstract*—A major milestone for the LHC Accelerator Research Program (LARP) is the test, by the end of 2009, of two 4m-long quadrupole magnets (LQ) wound with Nb_3Sn conductor. The goal of these magnets is to be a proof of principle that Nb_3Sn is a viable technology for a possible LHC luminosity upgrade. The design of the LQ is based on the design of the LARP Technological Quadrupoles, presently under development at FNAL and LBNL, with 90-mm aperture and gradient higher than 200 T/m. The design of the first LQ model will be completed by the end of 2007 with the selection of a mechanical design.**

In this paper we present the coil design addressing some fabrication technology issues, the quench protection study, and three designs of the support structure.

***Index Terms*—LARP, Long magnets, Magnet design, Nb_3Sn,**

I. INTRODUCTION

THE LARP Long Quadrupole (LQ) is going to be the first 4-m long Nb_3Sn quadrupole magnet ever built. With an aperture of 90 mm, and a gradient of 200 T/m, the LQ is a "Proof of Principle" magnet aiming at demonstrating that Nb_3Sn technology is mature for use in high energy particle accelerators. The LQ is thus a fundamental step toward the LARP goal of developing Nb_3Sn quadrupole prototypes for the LHC (Large Hadron Collider) [1] interaction regions for a possible luminosity upgrade.

The Long Quadrupole R&D builds upon other LARP tasks (such as the Technological Quadrupoles (TQ) [2],[3], and the Long Racetrack [4]), and upon tasks performed by other programs (such as the Long Mirror under development at Fermilab [5]). The present plan includes the fabrication of three LQ models by the summer 2010. The fabrication of the coils for the first LQ will start at the beginning of 2008 with the assembly of the first LQ in fall 2008. The first Long Quadrupole, based on the first two series of LARP TQ magnets, is not going to have coil alignment features. These features will be introduced in subsequent LQ models after successful test in short models.

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II. MAGNETIC DESIGN

The design of the Long Quadrupole is based on the present design of the Technological Quadrupoles. In the TQS (Technological Quadrupoles with Al shell) the iron is closer to the coil than in the TQC (Technological Quadrupoles with Collars). The main parameters of both designs are summarized in Table I (assuming a critical current of 2400 A/mm^2 at 4.2 K, 12 T). A recent proposal of an "hybrid design" using collars and stainless steel shell preloaded by bladders and keys has magnetic features similar to TQC.

Presently the baseline strand for the LARP program is the Nb_3Sn Restacked Rod Process (RRP) strand with 54 subelements in a stack pattern of 61 being produced by Oxford Superconducting Technology (OST). This strand has been successfully used in the TQS02 magnet and is going to be used in the upcoming TQC02. Other high critical-current strands with more subelements are in development at OST and will be considered for future LQ magnets.

To balance the needs of a Jc (12 T, 4.2 K) of about 2,800 A/mm^2 and a RRR greater than 100 (to assure stability at low field) the present TQ02 coil heat treatment schedule is 72 h at 210 ˚C, 48 h at 400 ˚C, and 48 h at 640 ˚C. Strands with this heat treatment have a stability current greater than 1,000 A at 4.2 K. This current meets the LARP program target of having the stability current double the strand short sample current in a magnet. The cable parameters to be used in LQ are identical to those that have been developed for TQ magnet program and are reported in [6].

TABLE I
LONG QUADRUPOLE MAGNET PARAMETERS BASED ON TQ DESIGNS

Parameter	Unit	TQC	TQS
N of layers	-	2	
N of turns	-	136	
Coil area (Cu + nonCu)	cm^2	29.33	
4.2 K temperature			
Quench gradient	T/m	221.4	234
Quench current	kA	13.34	13.2
Peak field in the body at quench	T	11.48	12.0
Peak field in the end at quench	T	11.94	11.8
Inductance at quench	mH/m	4.56	5.03
Stored energy at quench	kJ/m	405.7	438
1.9 K temperature			
Quench gradient	T/m	238.43	252
Quench current	kA	14.44	14.4
Peak field in the body at quench	T	12.37	12.9
Peak field in the end at quench	T	12.87	12.7
Stored energy at quench	kJ/m	472.1	511

III. Coil Design and Fabrication

The main features and fabrication steps of the LQ coils, presented in [6], are summarized and updated in the following.

The LQ coils consist of two layers without inter-layer splice, fabricated using the Wind-and-React method. The coils of the first LQ model (LQ01) are insulated by a ~0.1 mm thick S-glass sleeve. The sleeve is reinforced by palmitic acid sizing applied after burning the original sizing. The use of S-glass insulation braided on the cable is under development for subsequent models. A ceramic binder (CTD-1202 [7]) is applied after winding the inner coil layer. The layer is subsequently cured under pressure in a precise mold at 150 ˚C in air. The outer layer is wound above the cured inner layer and the curing operation is repeated. The coils are heat treated in argon atmosphere, and then vacuum impregnated with CTD-101k.

Based on the successful experience of TQS02, LQ coils have a pole (sometimes referred to as an "island") made of Ti-Al-V. The use of this material avoids the need of gaps in the pole during the heat treatment, and is more compatible with the longitudinal thermal contraction of a TQS-style structure. The LQ coils don't have the groove in the center of the pole used in the TQC01 coils. This groove reduces the peak stress on the coil pole turns, but doesn't allow a precise measurement of the coil stress in the same region. The ground insulation is made of overlapping layers of polyimide (Kapton®) sheets (5 mil = 127 µm thick) as in present TQC coils (Fig. 1). The amount of ground insulation is equivalent to that used on the present LHC IR quadrupoles [8]. Protection heaters cover the whole inner and outer coil surfaces. Together with the wiring for the voltage taps, they are glued between two layers of Kapton (the resulting sandwich is called a "Trace"). After tests at 1.9 K the inner surface of TQ coils presented several "bubbles" (local detachment of the insulation from the conductor) possibly caused by vaporization of helium that had penetrated through the epoxy impregnated insulation. These bubbles reduce the efficiency of protection heaters located on the coil inner surface. The placement of protection heaters (without Kapton) between the coil layers is a possible solution to this problem. Otherwise, the first LQ could be tested at 4.5 and 2.3 K avoiding superfluid helium.

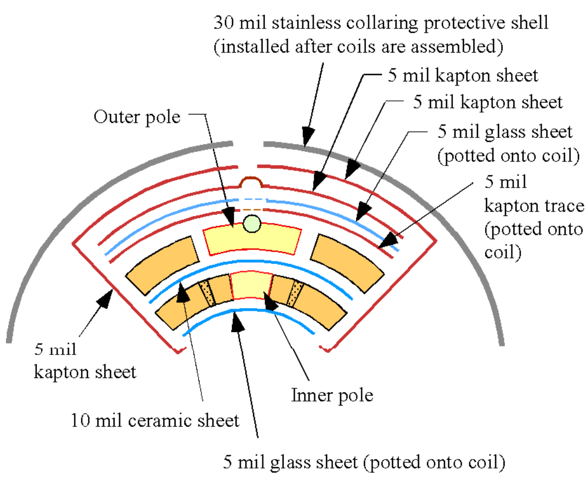

Fig. 1. Cross section of LQ coil with TQC ground insulation system

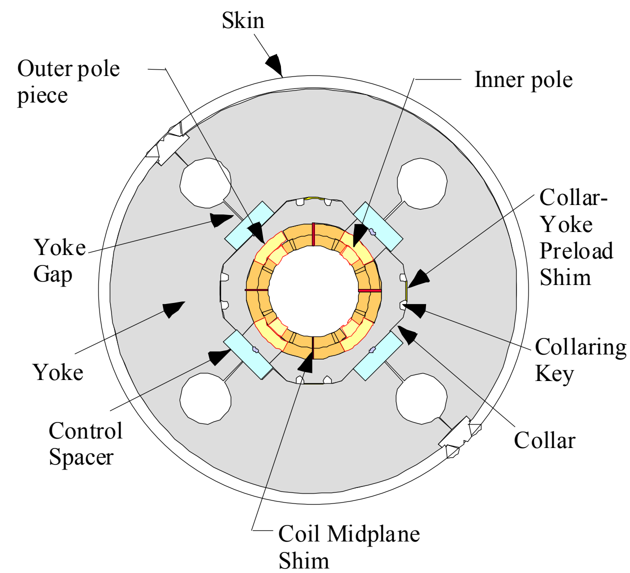

Fig. 2. Cross section of TQC support structure

IV. Mechanical Design

Three mechanical designs based on the present TQ magnets have been developed. The design for the first LQ will be selected in fall 2007.

A. LQ support structure based on TQC magnets

The shell structure used for the TQC short models is shown in Fig. 2. It is easily extended to lengths in excess of 4 meters. Components are very similar to those used for the LHC IR quadrupole [8] as well as earlier cos-theta magnets built at Fermilab in lengths up to 17 meters [9]. Alignment to the outer skin, splicing of coils at the ends, and attachment of the ends to the cryostat are straightforward extrapolations of the LHC IR quadrupole design.

The structure consists of stainless steel collar laminations, control spacers, laminated iron yoke and stainless steel skin. Azimuthal coil preload is shared by the collars and the yoke, and is limited by the control spacers.

The collars are hydraulically pressed onto the coils, applying radial pressure, and are held in place by collaring keys. The amount of pressure applied by the collars is controlled by coil midplane shims. The midplane shim thickness is determined by a combination of analysis, coil cross section measurements and past experience. Pressure is then increased by a 12-mm thick stainless steel skin, welded in place longitudinally. The skin force is applied to the collars radially through the yoke by the collar-yoke preload shims. The thickness of these shims is determined by a combination of analysis, collared coil deflections, measured component sizes, and past experience. The final preload applied to the coils by the yoke is limited by stainless steel control spacers. These components intercept any preload beyond the design limits applied during construction as well as cool-down, preventing over-compression of the coils. Target peak pre-stress is 135 ± 10 MPa at 300 K (pole turn), 145 ± 10 MPa at 1.9 K (pole turn), and 160 ± 10 MPa at maximum gradient (midplane).

A 0.75-mm thick stainless steel "protective shell" prevents possible coil damage from the laminated collar packs. A round rod (Fig. 1) can be used for coil alignment to the collar pack.

A "minimal" axial loading system is applied, similar to that used on LHC IR quads and identical to Nb_3Sn dipoles built at Fermilab [10], both of which have been successful. Load to the ends is applied by a combination of radial force through the collars by the skin, and end force applied by four preload screws, or "bullets", through 50-mm thick stainless steel end plates. A total force of 14 kN is applied to each end. The system is designed to ensure that the magnet ends are in contact with the bullets during all phases of cool-down and operation.

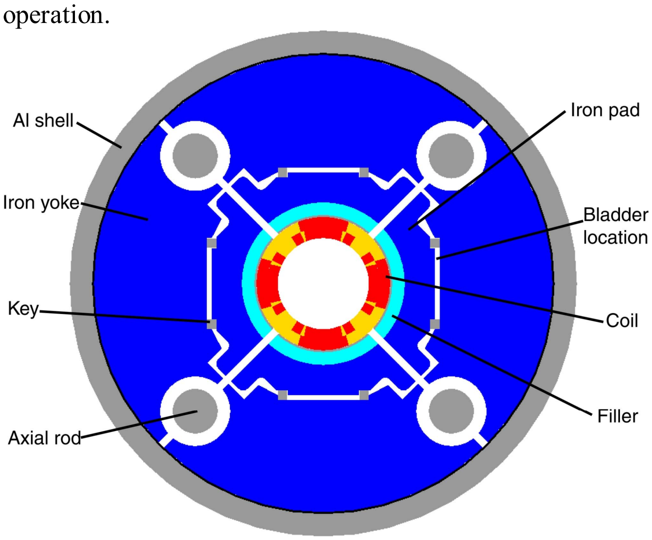

Fig. 3. TQS02 cross-section.

B. *LQ support structure based on TQS magnets*

The structure for the first LQ could be a simple extension of the 1-m long TQS magnet [3]. The TQS program has shown, through analysis and in four separate tests that a shell structure, assembled with keys and bladders, could successfully deliver 150 MPa pre-stress to the coils and meet the minimum required 200 T/m LQ target. The TQS02 cross-section (Fig. 3) is a design based on an iron yoke surrounded by a 22 mm thick aluminum shell, and includes four iron pads, four iron fillers and four coils wound around Ti-Al-V poles. Between each pad and yoke two interference keys are used to balance the azimuthal tension in the outer shell with the azimuthal compression in the inner coils. The space between keys, 68 mm, is wide enough to allow using a single low pressure bladder during assembly. With coils under 40 MPa of azimuthal compression at room temperature and 150 MPa on the inner layer after cool-down, the magnet is assembled under well controlled and predictable conditions. Strain gauges mounted on the outer shell and coil islands are a reliable and unambiguous way to measure strain needed to establish the stress condition in the coils and structure.

For an LQ shell-base supporting structure, a number of improvements will have to be considered to the TQS cross-section. First, it appears that the location of the keys with respect to the mid-plane is a sensitive parameter that plays a major role in the stress distribution in the coil [11]. The mechanical analysis of TQS shows that the cold peak stress in the coil outer layer is of the order of 170 MPa. Preliminary computations have also shown that by reducing the span between keys from 68 mm to 28 mm the outer layer peak stress could be reduced to 140 MPa. However, such an improvement has the drawback that, by reducing the bladder size, the applied bladder pressure will have to increase by a factor of 2. This is a possible threat to the bladder integrity. A possible way of reducing bladder pressure could consist in the use of two bladders per quadrant instead of one, placing both bladders outside the keys span.

Due to the potential modification of the bladder locations, including their size and number, an optimization of the shell thickness will also be required. In addition, the test of the LR magnet [12] demonstrated that in long magnets (over ~ 2m) cool-down forces between the shell and the yoke could overcome the axial friction force between them, resulting in a sudden axial slippage. Although such a slippage may have little affect on the coils, segmentation of the long shell may be required to preserve its expected mechanical integrity as well as improve its manufacturing tolerances.

Other improvements, such as moving the locations of the axial aluminum rods, will also be considered in order to reduce the end-plates thickness. The fillers between the coils and the pads will be eliminated or significantly reduced in size. Finally, the issue of helium containment will be addressed later in the program, for example, by placing a thin stainless steel outer skin over the shell. Preliminary computations show that such a skin does not impact the overall mechanical performance of the structure.

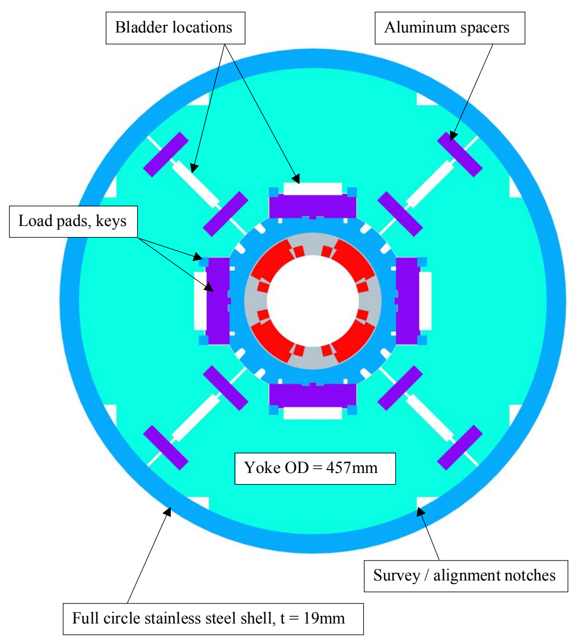

Fig. 4. LQ Hybrid Support Structure Cross-Section

C. *LQ Hybrid Support Structure*

An alternate support structure for the LQ is presently being studied. The design utilizes the attractive features of both the TQC and the TQS support structures. Namely, the hybrid structure incorporates the alignment features and reliability inherent in the collar style assembly, while avoiding distortions by welding. The hybrid structure also reduces the peak coil stresses required during assembly by using the assembly methods developed in bladder-and-key based shell support systems.

The design presently under consideration uses a 457-mm inner diameter, 19-mm thick full circle stainless steel shell and an iron yoke split into four parts for quadrupole symmetry. Yokes are aligned to external fiducials via a series of holes in the stainless steel shell. The yoke quadrants are loaded against each other via aluminum control spacers, which permit the necessary increase in coil stress during cool down. The yoke quadrants provide coil support and alignment through load pads which bear on the outside surface of the collars. Fig. 4 shows a cross section of the proposed assembly.

The design utilizes a two-step assembly process. First, collaring of the coils is performed using collars identical or nearly identical to those used in TQC assemblies. In a variant from TQC, the coils are assembled to a lower, intermediate stress, providing greater margin for safety against conductor damage. The coil stress is controlled using undersized keys in the collar keyways, which allow for continued collar closure later in the assembly process. Separately, the yoke and shell are prepared into a subassembly, using bladders between the yoke quadrants to pretension the shell. Control spacers made of aluminum are installed to retain the load. Next, the collared coil assembly is inserted into the yoke-shell subassembly and preloaded using a second set of bladders between yokes and load pads. The load is retained by keys installed between load pads and yokes. The aluminum yoke control spacers allow for the load to increase during cool down to a level greater than the load which will be imposed by the coils during operation, thereby providing the most rigid support possible, while maintaining a closed yoke midplane after cool down and during operation.

Preliminary finite element analysis indicates that the proposed structure is capable of providing the required coil preload after cool down. The maximum coil stress will be kept relatively low during collaring. Assembly into the support structure will provide a moderate increase in coil load. Cool down will provide the required increase in load to prevent the coil from separating from the pole during coil excitation.

The 2-dimensional design of the hybrid structure will be validated using a short (15-30 cm) mechanical model, to be instrumented and assembled, then cooled to liquid nitrogen temperature.

Support structure end design is presently being planned. The initial concept consists of thick end plates attached to the stainless steel support shell, from which coil end bullets will extend to the coil end saddles to provide a rigid axial coil restraint.

V. Quench Protection

A preliminary analysis of the quench protection of the Long Quadrupole was presented in [6]. It showed that in order to keep the hot-spot temperature within acceptable values the quench protection system needs: large heater coverage, energy extraction, and short detection and heater-delay times (the latter is the time between natural-quench detection and heater-induced-quench start). A series of tests was subsequently performed on TQs in order to measure the detection and heater-delay times, and to fine tune the hot-spot temperature estimates (affected by the amount of insulation included in the computation) and its correlation with MIITs.

Tests aiming at high hot-spot temperatures could easily result in coil failures, therefore it was decided to perform most of them on TQS01c (the third reassembly of TQS01). At the end of the TQS01c regular test, a series of "high-MIITs" quenches was performed by increasing firstly the dump delay time, secondly the protection heater delay time, and thirdly by increasing the detection threshold. Details of this study and results can be found in [13]. The results (Fig. 5) show that up to 7.5 MIITs the quench current didn't change. After a quench with 7.95 MIITs the quench current increased by 3.3%. The following quench with 8.16 MIITs caused a detraining of 7.2% completely recovered in two quenches (i.e. the magnet reached a plateau with quench current 3.3% higher than before starting this study). Subsequent quenches showed another small increment of the quench current (+0.6%) and detraining after quenches with MIITs in the range 7.5 to 8.1. Finally quenches with 8.7 and 9.5 MIITs caused irreversible degradation of 8% and 25% with respect to the quench current before the MIITs study.

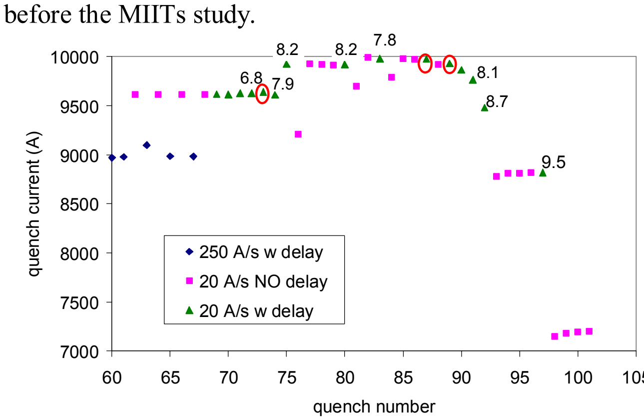

Fig. 5. Quench history during TQS01c MIITs study. The marker of each quench shows the kind of quench (diamond: quench with delays after 250 A/s ramp; square: quench without delays after 20 A/s ramp; triangle: quench with delays after 20 A/s ramp). The numbers close to some quenches at 20 A/s with delays show the MIITs generated during that quench. A circle around a marker indicates a quench that generated 7.5 MIITs.

Since the spot heater planned for this test wasn't operational, spontaneous quenches were used. Unfortunately the length of the segment where the quenches started didn't allow a precise measurement of the hot-spot temperature. Computations using the adiabatic approximation and assuming all cable cross-section (metal, epoxy and insulation) at the same temperature estimated the hot-spot temperature to be 380 K at 7.5 MIITs. It took less than 200 ms to deposit all energy in the hot-spot during a quench that generated 7.5 MIITs at current higher than 9.5 kA.

A test performed on TQC01 [14] using a spot heater showed that TQ coils can withstand 9 MIITs in a low field area (some local degradation could be hidden by the large margin due to the low field). This quench was induced by firing the spot heater at moderate current (5000 A) with a high detection threshold and a long dump delay. The hot-spot temperature was estimated to be 340 K based on resistance growth (assuming that the spot-heater segment had the same RRR of the whole coil). Computation of the hop-spot temperature estimated 370-390 K for 9 MIITs in low field areas. It took about 600 ms to deposit all energy in the hot-spot during this quench, therefore some cooling may explain the difference between estimated and measured temperatures.

From this study it was concluded that the maximum acceptable level for the LQ quench protection should be 7.5 MIITs. Quench simulations performed using QuenchPro [15] showed that MIITs can be limited to 7.5 during 4.5 K tests by using a 60 mohm dump resistance (allowing the extraction of about 1/3 of the energy), full heater coverage (i.e. both inner and outer layers), heater delay time shorter than or equal to 12 ms, and very short detection time (5 ms). The complete heater coverage also avoids voltage unbalances keeping the maximum voltage to ground below 1 kV and the maximum turn to turn voltage below 100 V. Simulations were performed with current at the short sample limit (SSL). Quench propagation velocities, detection and heater delay times were measured on TQ01-series and SQ (Small Quadrupoles) magnets operating at 80-90% of the SSL, providing conservative estimates. Quench-back was not included.

Recent tests of TQS02a [16] (a TQS magnet using RRP conductor with 54/61 sub-elements) showed very large voltage spikes (up to 4.5 V) in the channels used for magnet quench protection [17]. These voltage spikes (induced by conductor flux jumps) forced the use of quench detection thresholds incompatible with the LQ requirement of very short detection time. A detailed analysis of the voltage spike distribution versus current has shown that the highest spikes occurred between one and two kA, with a rapid decay after 2 kA. Above 5 kA all spikes were below 300 mV. Presently the Vertical Magnet Test Facility (VMTF) [18] at Fermilab, where the LQs will be tested, requires fixed quench detection thresholds. An upgrade is planned in 2008 to allow the use of current-varying detection thresholds. This upgrade will make it possible to test an LQ made with 54/61 RRP strands.

Every coil surface will be covered by two 2-m long quench protection heaters (each one extending from the magnet center to an end), providing full coverage and options for redundant circuits (two or four).

VI. Conclusion

The design of the first LARP 4-m Long Nb_3Sn Quadrupole, aiming at 200 T/m in a 90 mm aperture, is almost complete. Coil design and fabrication process have been finalized. Three mechanical designs have been developed based on LARP Technological Quadrupoles (1-m long models). The final design is going to be selected by the end of 2007. Coil fabrication is starting in early 2008, and magnet assembly in fall 2008. Work supported by DOE DE-AC02-05CH11231.

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