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LARP NB_3SN QUADRUPOLE MAGNETS FOR THE LHC LUMINOSITY UPGRADE

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ABSTRACT

The US LHC Accelerator Research Program (LARP) is a collaboration between four US laboratories (BNL, FNAL, LBNL, and SLAC) aimed at contributing to the commissioning and operation of the LHC and conducting R&D on its luminosity upgrade. Within LARP, the Magnet Program's main goal is to demonstrate that Nb_3Sn superconducting magnets are a viable option for a future upgrade of the LHC Interaction Regions. Over the past four years, LARP has successfully fabricated and tested several R&D magnets: 1) the subscale quadrupole magnet SQ, to perform technology studies with 300 mm long racetrack coils, 2) the technology quadrupole TQ, to investigate support structure behavior with 1 m long cos2θ coils, and 3) the long racetrack magnet LR, to test 3.6 m long racetrack coils. The next milestone consists in the fabrication and test of the 3.7 m long quadrupole magnet LQ, with the goal of demonstrating that Nb_3Sn technology is mature for use in high energy accelerators. After an overview of design features and test results of the LARP magnets fabricated so far, this paper focuses on the status of the fabrication of LQ: we describe the production of the 3.4 m long cos2θ coils, and the qualification of the support structure. Finally, the status of the development of the next 1 m long model HQ, conceived to explore stress and field limits of Nb_3Sn superconducting magnets, is presented.

KEYWORDS: LARP, Nb_3Sn, quadrupole magnets, LHC Interaction Regions.

INTRODUCTION

In order to maximize the physics reach of the Large Hadron Collider (LHC), a series of upgrades has been envisioned for the experiments, the LHC Interaction Regions (IR), and the injector complex. The first stage of the IR upgrade (Phase I) includes the replacement of the present 70 mm aperture IR quadrupoles, operating at a gradient of 200 T/m, with 120 mm aperture quadrupoles, operating at a gradient of 120 T/m [1]. The new quadrupoles will adopt the same NbTi cable design currently used in the LHC dipoles. The goal of the Phase I upgrade is to increase the luminosity up to $2\text{-}3{\cdot}10^{34}$ $cm^{-2}s^{-1}$. A second stage (Phase II upgrade), foreseen for 2020, is aimed to bring the luminosity up to the 10^{35} $cm^{-2}s^{-1}$ level. It is expected that IR quadrupoles for the Phase II will need to accommodate a larger aperture and to operate at higher fields (>10 T) with increased temperature margins. These new operational conditions will require the use of superconducting materials with improved performance parameters with respect to NbTi. At the moment, Nb_3Sn appears as the best candidate for the Phase II quadrupoles.

The LHC Accelerator Research Program (LARP [2]) is a collaboration between four U.S. DOE National Laboratories, (BNL, FNAL, LBNL, and SLAC), working with the U.S. Department of Energy, and in close collaboration with CERN, on the future upgrade of the LHC. Its Magnet Program [3] is focused on the development of large aperture Nb_3Sn quadrupole magnets for the Phase II luminosity upgrade. Since 2004, several magnets have been fabricated and tested with the goal of demonstrating that Nb_3Sn is a viable option for the next generation IR quadrupoles. We present in this paper an overview of the LARP Magnet Program. Design features, goals, and test results of the magnets tested so far are described, and status and next steps of the quadrupoles under development are discussed.

OVERVIEW OF THE LARP MAGNET PROGRAM

An overview of all the magnets developed by LARP since 2004 is shown in FIGURE 1, where all the cross-sections are depicted in scale and in chronological order from top to bottom. The program has focused on the fabrication and characterization of racetrack and cos2θ coils, with a length ranging from 0.3 m to 3.6 m, and on the development of two different types of support structures for 90 mm aperture models. The first concept (Collar-based, “C” in the magnet acronyms) is derived from the structure of the MQXB NbTi quadrupoles built at Fermilab for the LHC Interaction Regions [4], and it clamps the coils in stainless steel collars contained within a 2-piece iron yoke and an external welded stainless steel shell. The second concept (Shell-based, “S” in the magnet acronyms), is an evolution of support structures developed at LBNL for Nb_3Sn high field dipoles [5-6], and it provides coil support through an aluminum shell pre-tensioned with water-pressurized bladders. In the collar-based concept, the target coil pre-load, required to minimize conductor motion during excitation, is mostly reached at room temperature through the collaring and shell-welding operation, and then maintained during cool-down. In the shell-based concept, the bladder operation at room temperature provides only a fraction of the target pre-load, which is then achieved after cool-down through the contraction of the aluminum shell. Another difference consists in the way the axial support is provided to the coil. In the collar-based design, two end plates, in contact with the coils through pre-loaded bullets, are welded to the shell. In the shell-based design, the end plates are compressed against the coil through four full-length aluminum rods, applying the major fraction the axial load during cool-down.

The first magnet developed by LARP was the subscale quadrupole SQ: tested in 2004, it was the first magnet where the shell-based structure was applied to a quadrupole configuration with 300 mm long racetrack coils and a 110 mm aperture. The goal of SQ was to assess the performance in operational conditions of the conductor to be implemented in the following TQ program, provide feed-back on assembly and loading procedures, and validate 3D finite element models.

Following the test of SQ, the Technology Quadrupoles TQC and TQS were tested for the first time in 2005. The magnets assembled 1 m long cos2θ coils respectively in and collar-based and shell-based structure.

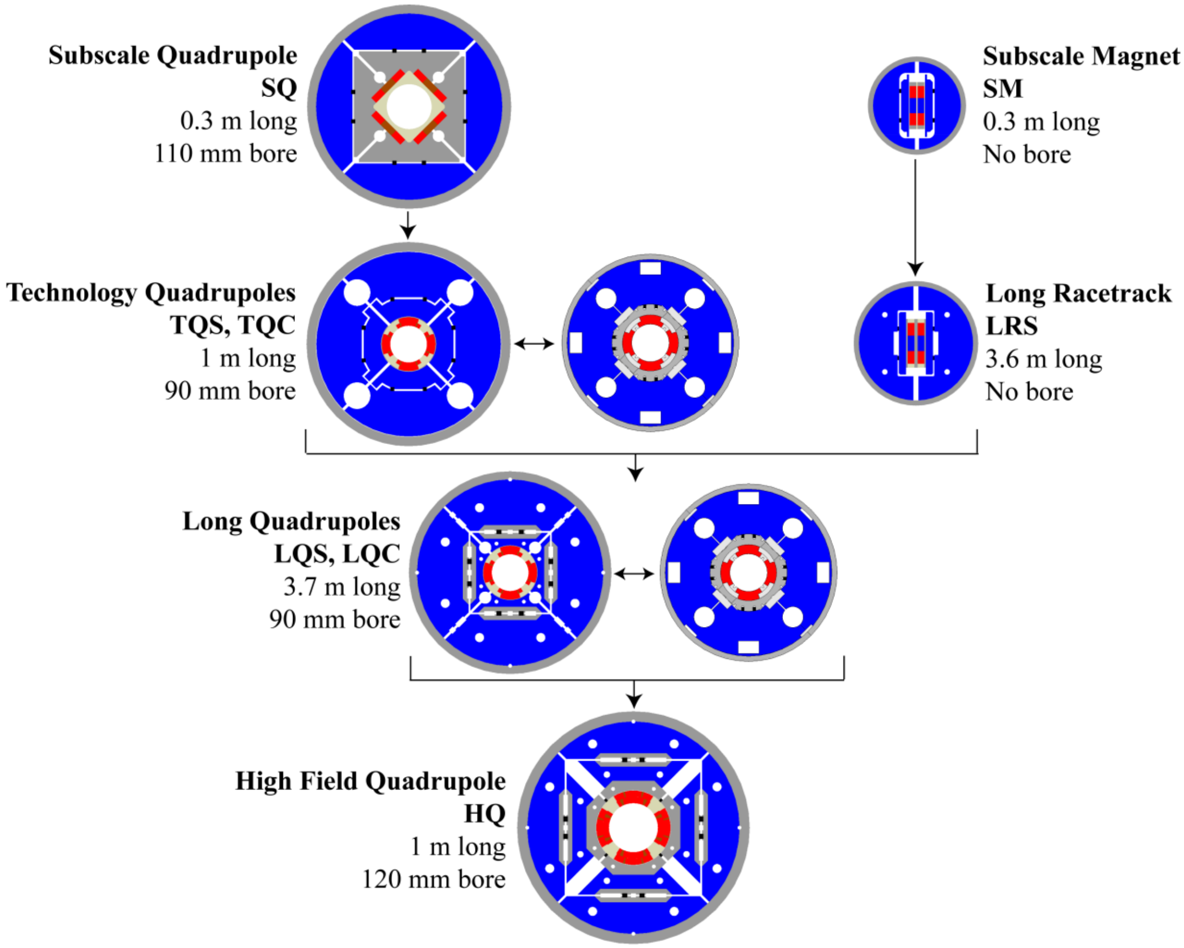

FIGURE 1. Overview of LARP magnets: cross-sections are shown in scale and in chronological order from top to bottom (TQC cross-section by I. Novitsky, FNAL).

With a target gradient of 200 T/m in a 90 mm aperture coil aperture, the TQ tests were aimed at optimizing the fabrication and investigating the performance of cos2θ coils, at the same time comparing the behavior of the two support structures.

In parallel to the TQ program, in 2006 the Long Racetrack Shell-type magnet LRS was fabricated and tested. The goal of LRS was to test for the first time long (3.6 m) Nb_3Sn racetrack coils, and to apply the shell-bladder concept to long magnets. The development of the LRS and TQ magnets paved the way towards the development of the 3.7 m long cos2θ quadrupole magnets LQS and LQC, currently under construction. The structures will be basically an extension of the TQ structures, with additional features to facilitate assembly and pre-loading, and to provide alignment of the structural components. Similarly to TQ, the LQ goal is to reach a target gradient of 200 T/m in a 90 mm aperture, thus demonstrating that Nb_3Sn is a mature technology for long accelerator magnets. Its first test is expected by the end of 2009.

Finally, in 2008 LARP has started the fabrication of the 1 m long high field quadrupole HQ. HQ will increase the conductor peak field towards the 15 T level, thus exploring the limits of Nb_3Sn cos2θ coils and providing a performance reference for the Phase II upgrade magnets. The choice of an 120 mm aperture, the same as the NbTi Phase I quadrupoles, will allow a full qualification of HQ based on the requirements of the Phase I luminosity upgrade. The support structure design combines a collar-type clamping system to provide coil alignment with an aluminum shell pre-tensioned with bladders. The first test is expected in 2010.

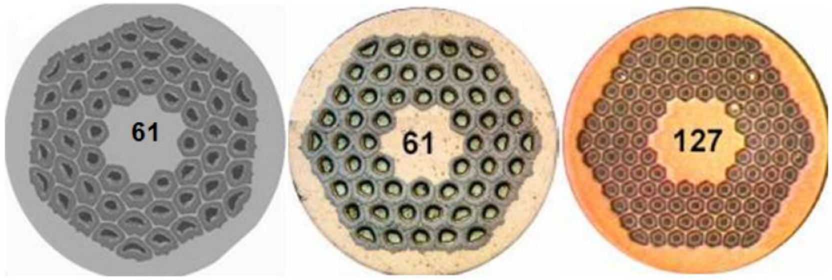

FIGURE 2. LARP strand cross-sections: 0.7 mm OST MJR strand with 54/61 stack (left), 0.7 mm OST RRP strand with 54/61 stack (center), and 0.7 mm OST RRP strand with 108/127 stack (right).

TABLE 1. Conductor and cable parameters for the LARP magnets.

	Unit	SQ	TQ01	LRS	TQ02/LQ	TQ03	HQ
Strand d.	mm	0.7	0.7	0.7	0.7	0.7	0.8
Process		MJR	MJR	RRP	RRP	RRP	RRP
Stack		54/61	54/61	54/61	54/61	108/127	54/61
No. strands		20	27	20	27	27	35
Cu/Sc		0.89	0.89	0.86	0.89	1.17	0.87
Cable width (bare)	mm	7.793	10.050	7.828	10.050	10.050	15.150
Cable inner thick. (bare)	mm	1.276	1.172	1.276	1.172	1.172	1.338
Cable outer thick. (bare)	mm	1.276	1.348	1.276	1.348	1.348	1.536
Insulation thick.	mm	0.092	0.125	0.092	0.125	0.125	0.100

CONDUCTOR AND CABLE PARAMETERS

In TABLE I we provide the parameters of the strands and cables adopted for the LARP magnets. The SQ02 and the TQ01 series used Oxford Superconducting Technologies (OST) strands fabricated with the Modified Jelly Roll (MJR) process (see FIGURE 2, left). The strands where composed by 54 Nb_3Sn sub-elements in a 61 stack billet (54/61). The heat treatment was optimized to obtain a J_c in the superconductor at 4.2 K and 12 T of at least 1800 A/mm^2, at the same time maximizing the strand stability at low field [7]. For the second series of magnets (LRS, TQ02, LQ), a strand with the same design (see FIGURE 2, center) but fabricated through the Restacked Rod Process (RRP) was implemented, with an increase of J_c to about 2800 A/mm^2 [8]. A third strand design, with 108 Nb_3Sn sub-elements in a 127 stack billet (see FIGURE 2, right) will be tested in the TQ03 magnet series. Cable parameters like packing factor and keystone angle were optimized to provide mechanical stability with minimal critical current degradation [9].

SUBSCALE QUADRUPOLE MAGNET (SQ)

In order to gain an early feed-back on conductor performance and mechanical behavior of a support structure similar to the one designed for the TQS quadrupole magnet, the Subscale Quadrupole (SQ) was fabricated and tested [10-12]. SQ consists of 4 racetrack coils, 0.3 m long and based on the design of the coils for the LBNL Subscale Magnet program [13], placed around an aluminum bore with a clear aperture of 110 mm (see SQ cross-section in FIGURE 1). The coils were wound with the same MJR conductor and underwent similar operational conditions as in the TQ01 series.

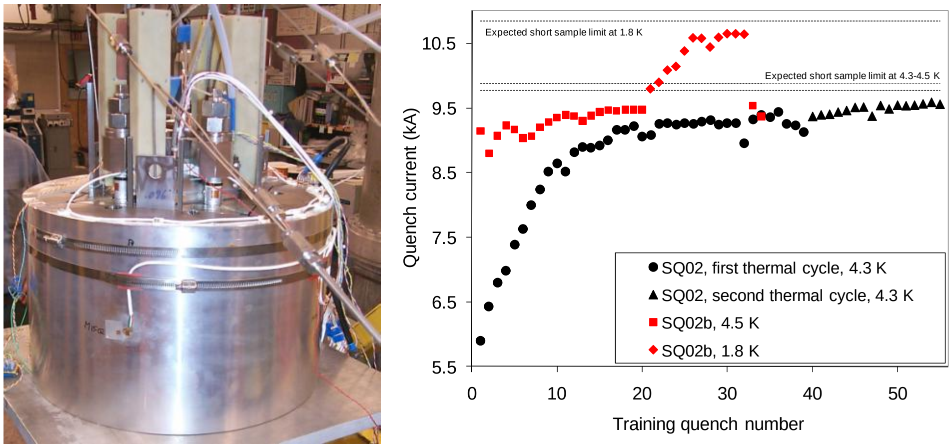

FIGURE 3. SQ assembly (left) and training performance (right) of SQ02 (two thermal cycles at 4.3 K) and SQ02b (at 4.5 K and 1.8 K). The dashed lines in the graph represent the expected current limits based on extracted strand measurements.

The coil pack is surrounded by 4 stainless steel pads, a 4-piece iron yoke and an aluminum shell. The structure is pre-loaded by 4 bladders, inserted in between the pads and the yoke, which generate the force needed to spread the yoke apart, apply tension to the shell and pre-compress the coil-pads subassembly. Once the pre-load is locked by interference keys, the bladders are deflated and removed. The longitudinal support system is composed of four pre-tensioned aluminum rods and two end plates (see FIGURE 3, left).

In the first two tests (SQ02 and SQ02b) the magnet reached a current of 9.6 kA at 4.3 K, corresponding to 97% of the expected maximum current I_{ss} ("short sample" current, based on strands extracted from cables and assuming no strain degradation), and of 10.6 kA (98% of I_{ss}) at 1.8 K, with a conductor peak field of 11.7 T. The results confirmed that the conductor performance was consistent with expectations and the support structure was capable of providing the required coil support. All the training quenches occurred in the pole turn, as reproduced by a 3D finite element analysis, which predicted separation and sliding of the coil with respect to the winding pole. The magnet was used also to investigate the effect of axial support on quench performance [14]: in a third test (SQ02c), the removal of the axial support caused a 5 to 10% reduction of maximum quench current.

TECHNOLOGY QUADRUPOLE MAGNETS (TQ)

In 2004, LARP started developing the quadrupole magnets TQ. Since the beginning of the TQ program, a total of 33 cos2θ coils (1 m long) have been fabricated and tested. The first generation of coils, implemented in the TQ01 series, used 54/61 MJR conductor wound around a segmented winding pole made of aluminum bronze. Gaps were introduced in between the pole segments to prevent excessive strain on the conductor during reaction. Analysis of the TQS01 test results indicated that quench origins concentrated around the pole gaps, which, according to a finite element model of the magnet, tended to open under the action of electro-magnetic forces. In the second generation of coils, implemented in the TQ02 series and wound with 54/61 RRP conductor, the winding pole material was changed to titanium alloy (Ti6Al4V), which, because of its low thermal contraction, resulted in closed gaps during all magnet operations. The coils were assembled in two structures, called TQC and TQS. In the TQC design [15] the coil pre-load is provided by the combined action of stainless steel collars, a 2-piece iron yoke and a welded stainless steel shell.

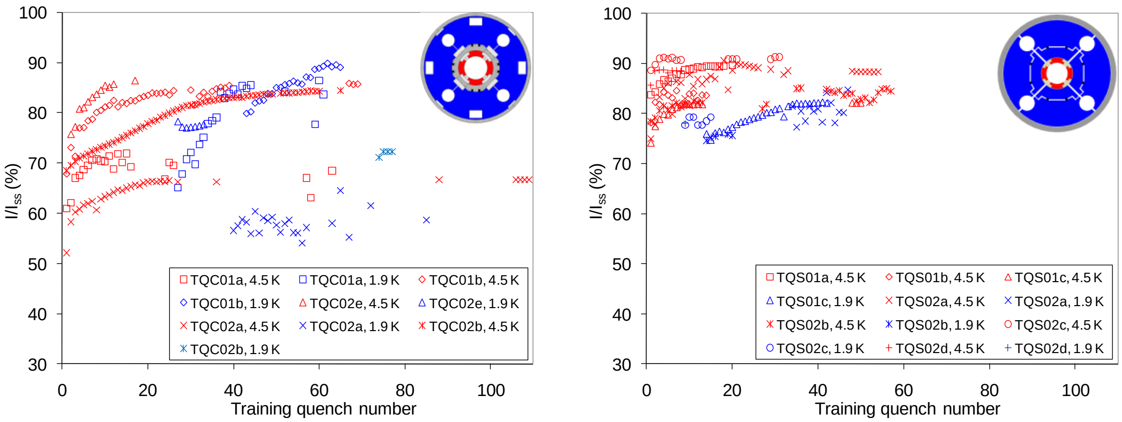

FIGURE 4. TQC (left) and TQS (right) training performance: the percentage of expected maximum current, based on strand measurements, is plotted as function of the number of training quench at a ramp rate ≤50 A/s.

The collar design was modified with respect to the MQX by removing the inner poles (round collar configuration). Stress adjustment is obtained by optimizing the dimension of shims placed at the coil mid-planes and between the collars and the yokes. In addition, aluminum spacers limit the shell and yoke contraction during cool-down and prevent over compression of the coil pack. After yoking, axial load is applied to each coil end through instrumented bolts attached to 50 mm thick end plates. Starting from the TQC01b test, the welded shell was replaced by a bolted shell to facilitate pre-load adjustment. A summary of the TQ test results is given in FIGURE 4 (left) and TABLE 2: a total of 6 TQC tests were performed, with 6 assembly and loading operations [16-18]. The target gradient of 200 T/m was reached in the TQC01a, TQC01b, and TQC02E tests. The TQS design [19-21] applies the bladder and key concept to cos2θ coils (see cross-sections in FIGURE 1). The presence of iron pads in close contact with the coil determines, for the same current, an 8% higher gradient than TQC. As shown in FIGURE 4 (right) and TABLE 2, a total of 7 TQS tests were performed, with 6 assembly and loading operations and 1 re-loading operation [22-25]. The target gradient of 200 T/m was consistency reached in the TQS02 tests, with a maximum gradient of 231 T/m (and a peak field of 11.8 T) obtained in TQS02c.

TABLE 2. TQ test result summary. Quench data are obtained at a ramp rate of 20 A/s, unless specified.

	Training at 4.4 K			Training at 1.9 K			Highest quench	
	G_{start} (T/m)	G_{max} (T/m)	G_{max}/G_{ss} (%)	G_{start} (T/m)	G_{max} (T/m)	G_{max}/G_{ss} (%)	G_{max} (T/m)	G_{max} quench conditions.
TQC01a	134	158	72	153	196	86	200	1.9 K, 100 A/s
TQC01b	144	178	86	179	200	90	200	1.9 K
TQC02E	178	201	86	198	198	78	201	4.4 K
TQC02a	127	158	67	147	165	64	170	1.9 K, 50 A/s
TQC02b	145	175	84	161	175	78	177	3.6 K, 50 A/s
TQS01a	181	194	90	n/a	n/a	n/a	200	3.2 K
TQS01b	169	183	85	n/a	n/a	n/a	183	4.4 K
TQS01c	160	178	82	177	192	82	192	1.9 K
TQS02a	182	220	91	215	223	85	224	2.2 K
TQS02b	191	207	85	197	200	76	207	4.4 K
TQS02c	216	222	91	205	209	79	231	2.7 K
TQS02d	208	216	89	206	206	78	227	2.7 K

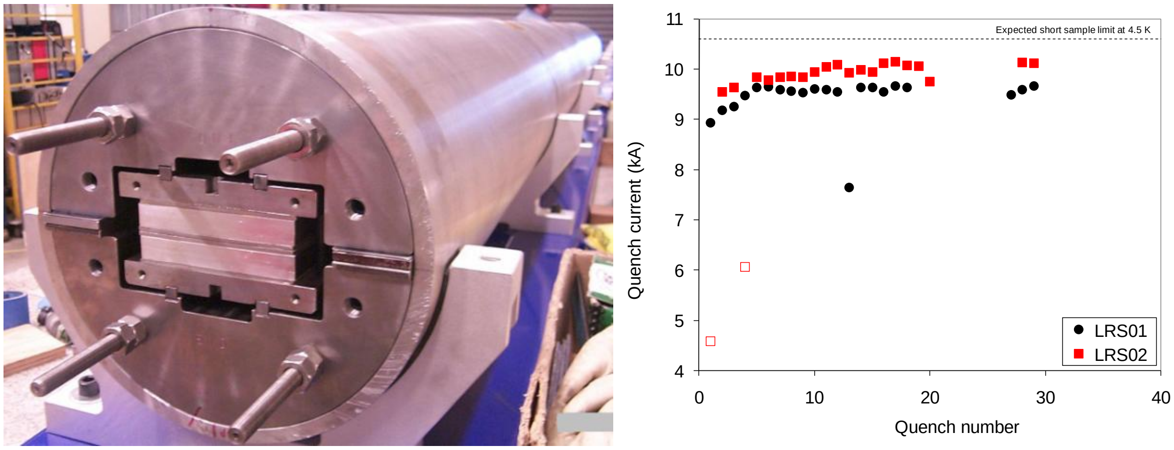

FIGURE 5. LRS assembly (left) and training performance (right) of LRS01 and LRS02 at 4.5 K. The dashed lines in the graph represent the expected current limits based on strand measurements.

All the TQ02 magnets showed a degraded performance at 1.9 K with respect to 4.5 K. Possible causes, like conductor damage during fabrication coupled with self-field effects in magneto-thermal instabilities of Nb_3Sn strands [26], are under investigation. Field quality measurements were taken during both TQC and TQS magnet tests [27]: although field quality was not among the goals of the TQ program, the measured homogeneity of the field along the axis was comparable to the standards values observed in NbTi magnets [28].

LONG RACTERACK SHELL-TYPE MAGNET (LRS)

In order to demonstrate that Nb_3Sn coils and shell-based support structures can be extended to 3.6 m, the LRS magnet was built and tested in 2007. The design of LRS [29,30], shown in FIGURE 1, is based on the lay-out of the LBNL Subscale Magnets [13]. Two double-layer racetrack coil modules, 3.7 m long, are contained in a shell-based structure composed by a full-length aluminum shell (see FIGURE 5, left). The first magnet of the series LRS01 [31,32], reached 91% of I_{ss} (see FIGURE 5, right), corresponding to a current of 9.6 kA and a computed conductor peak field of 11.0 T. A mechanical analysis of the support structure, performed through a 3D finite element model and confirmed by strain gauge data, showed that the contact friction with the iron yoke induced an increasing tensional strain in the shell from the ends towards the magnet center, resulting in variation of coil pre-stress along the length. In order to reduce the axial strain and improve coil stress uniformity, the shell was segmented in 4 parts 0.9 m long for a second test (LRS02 [33]). The new magnet achieved 96% of I_{ss} with a conductor peak field of 11.50 T (see FIGURE 5, left), confirming that magnets made with Nb_3Sn racetrack coils and support structures with segmented aluminum shells can perform successfully when extended in length.

FIGURE 6. LQ coil after winding (left), in the reaction tooling (center), and after impregnation (right).

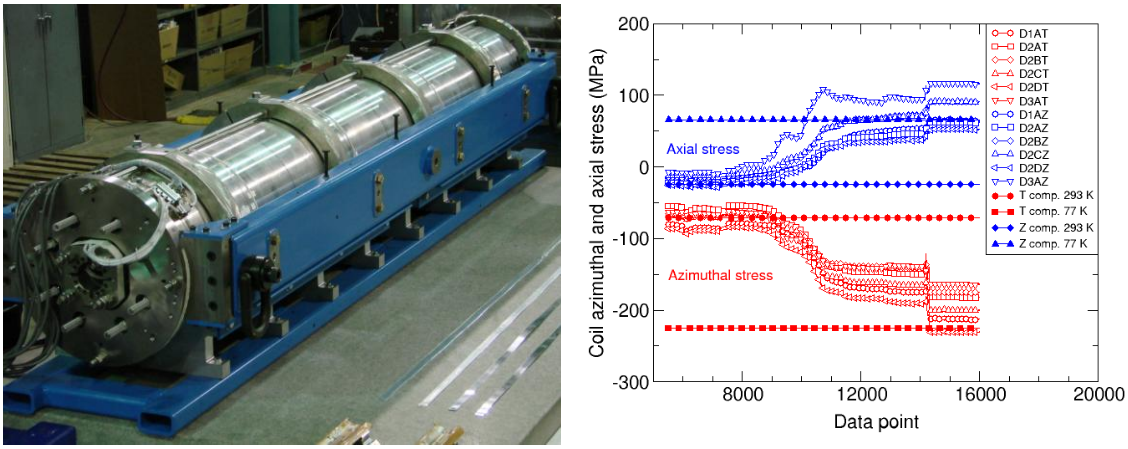

FIGURE 7. LQS at the end of the assembly with dummy coils (left) and strain gauge measurements of azimuthal and axial stress (MPa) in the dummy coils and comparison with computed values.

LONG QUADRUPOLE MAGNET (LQ)

By extending the TQ magnets from 1 m to 3.7 m, LARP is currently progressing towards a length scale-up demonstration for cos2θ magnets [34]. These magnets, called LQS or LQC depending on support structure design, use TQ-style cos2θ coils with a length of 3.4 m [35,36]. Similarly to TQ, the target gradient is 200 T/m. The LQ coil fabrication process (see FIGURE 6) follows the one applied to the TQ coils, with the following modifications: 1) in order to reduce asymmetries, coil are processed in single-cavity reaction and impregnation fixtures (the TQ fixture contained two coils); 2) gaps are re-introduced in the Ti alloy winding pole parts to minimize axial strain in the conductor resulting from winding and heat treatment; 3) a layer of mica is used to reduce friction between the coils and the reaction fixture. Coil instrumentation and protection heaters are provided by flexible circuits called traces, based on a kapton sheet and a 0.025 mm foil of stainless steel impregnated with the coils [37]. Strain gauges are mounted on the coil after impregnation. At the time of the submission of this paper, 9 coils have been fabricated.

Both a shell-based (LQS) and a collar-based (LQC) support structures are being developed. The LQS structure (see cross-section in FIGURE 1) is a scale-up of the TQS structure [38], where long trapezoidal plates, called master keys, provide alignment between yoke and pads and facilitate coil-pack insertion. Keys and pins are added to provide alignment among all the structure components, with the exception of the coil. In addition, the load keys have been moved towards the mid-plane to improve coil stress distribution. Similarly to LRS02, a segmented shell was adopted: this choice required the implementation of a new assembly procedure where four yoke-shell sections 0.85 m long are pre-assembled individually and then combined together with tie rods. In order to validate the assembly procedure, qualify the mechanical behavior of the structure, and practice shipping and insertion in the vertical cryostat, LQS has been assembled with aluminum dummy coils at LBNL (see FIGURE 7, left) and sent to FNAL for a cool-down test to 77 K. The aluminum shell and the dummy coil were equipped with respectively 20 and 12 strain gauges: as shown in FIGURE 8 (right) the strain measurements were consistent with the predictions of a 3D finite element model. The LQC structure will be a 3.7 long version of the TQC structure; the only modification currently under investigation involves the geometry of the collars. TQC used quadrupole-like collars and the collaring procedure was performed by partially inserting keys in individual 40 mm long collar packs, complete the operation for the entire length and repeating the process up to the target load.

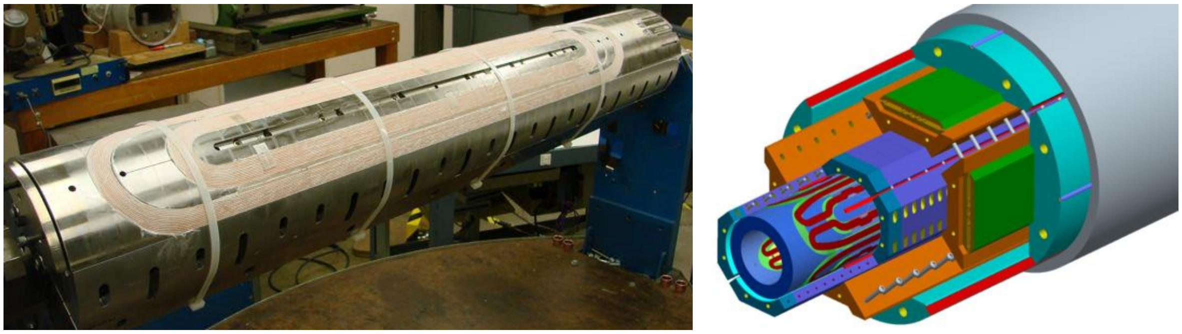

FIGURE 8. First practice coil after curing (left) and exploded view of the HQ design (right).

The LQC may implement dipole-like collars, which would allow a collaring operation carried out in a full-length press in a single pass, eliminating degradation risk and reducing construction time. The first LQ test is expected by the end of 2009 using the LQS structure. Additional tests with both structures are expected in 2010-2011.

HIGH FIELD QUADRUPOLE MAGNET (HQ)

In 2008, LARP has started the development of the High Field Quadrupole HQ. The magnet will feature the same 120 mm aperture of the Phase I upgrade, and will explore the field and stress limits for Nb_3Sn coils [45-48]. HQ (see cross-section in FIGURE 1) utilizes 1 m long double-layer cos2θ coils wound with a 15 mm wide cable. The support structure combines an LQS-type design (aluminum shell, yoke, pads, and masters) with aluminum bolted collars, included to provide alignment between the coil and the structure (see FIGURE 8, right). The maximum expected gradient is 219 T/m at 1.9 K, at a current of 19.5 kA and with a conductor peak field of 15.1 T. Coil and iron designs have been optimized to minimize conductor stresses, keep allowed harmonics below 0.5 units at 120 T/m at a R_{ref} of 40 mm, and limit the variation of b_6 from 0 to 19.5 kA within ± 1 unit. Assuming a coil pre-load for a 219 (180) T/m gradient, the computed peak stress on the conductor reaches 180 (150) MPa. At the time of the submission of this paper, the first practice coil has been wound and cured (see FIGURE 8, left), and it is ready for reaction. The plan is to assemble the magnet by the end of the 2009 and test in 2010.

CONCLUSIONS

The LARP Magnet Program is developing Nb_3Sn magnets for the Phase II LHC luminosity upgrade. In the last four years, the program has successfully fabricated and tested the magnets SQ, LRS, and TQ. With a length ranging from 0.3 m to 3.6 m, these magnets have proven the coil fabrication process and the mechanical behavior of the containment structures. LARP is now focused on the next milestones: the development of the 3.7 m long cos2θ quadrupole LQs and of the 1 m long cos2θ quadrupole HQ, aimed at demonstrating that Nb_3Sn is a mature technology for long accelerator-quality magnets.

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