Design of Nb_3Sn Coils for LARP Long Magnets

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***Abstract*—The LHC Accelerator Research Program (LARP) has a primary goal to develop, assemble, and test full size Nb_3Sn quadrupole magnet models for a luminosity upgrade of the Large Hadron Collider (LHC). A major milestone in this development is to assemble and test, by the end of 2009, two 4 m-long quadrupole cold masses, which will be the first Nb_3Sn accelerator magnet models approaching the length of real accelerator magnets. The design is based on the LARP Technological Quadrupoles (TQ), under development at FNAL and LBNL, with gradient higher than 200 T/m and aperture of 90 mm. The mechanical design will be chosen between two designs presently explored for the TQs: traditional collars and Al-shell based design (preloaded by bladders and keys). The fabrication of the first long quadrupole model is expected to start in the last quarter of 2007. Meanwhile the fabrication of 4 m-long racetrack coils started this year at BNL. These coils will be tested in an Al-shell based supporting structure developed at LBNL.**

Several challenges have to be addressed for the successful fabrication of long Nb_3Sn coils. This paper presents these challenges with comments and solutions adopted or under study for these magnets. The coil design of these magnets, including conductor and insulation features, and quench protection studies are also presented.

***Index Terms*—LARP, long coils, Nb_3Sn, superconducting magnet.**

I. Introduction

THE beginning of the development of Nb_3Sn magnets for particle accelerators goes back to the 1960's [1]. But only very recently this development has started facing the challenges of fabricating accelerator size Nb_3Sn magnets.

LARP (LHC Accelerator Research Program) [2] is leading this effort aiming at a full size model of the Interaction Region quadrupole for a possible luminosity upgrade of the Large Hadron Collider under installation at CERN [3]. The model will have the same length (almost 6 m) as the longest quadrupole in the present inner triplet, the same gradient (larger than 200 T/m), and larger aperture (90 mm or more).

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LARP is planning to assemble two 4 m-long cold masses to be tested in a vertical cryostat by 2009, and the first full size model in 2012. Fabrication of the first 4 m Long Quadrupole (LQ) will start in the last quarter of 2007. Presently several R&D lines are contributing to the development of the LQ design and fabrication technology. The most relevant are:

- LARP Technological Quadrupoles (TQ) [4], [5]: two 1 m-long quadrupole models using the same coil design, but different mechanical structures, with a 90-mm aperture and a gradient greater than 200 T/m. Contributions to the LQ: development of coil design and mechanical structure.
- LARP Long Racetracks (LR): 4 m-long racetrack coils tested in an aluminum shell. The design, presented in the following, is based on the LBNL Small Magnet series [6]. Contributions to the LQ: development of long Nb_3Sn coil fabrication technology, tests of a long, shell-based support structure.
- LARP LQ Design Study: study of length related design issues (such as quench protection), collecting results from all other tasks for the generation of the LQ conceptual design proposal.
- FNAL Long Mirror magnets (LM): 2 m and 4 m long dipole coils [7] tested in a magnetic mirror configuration based on FNAL HFDM series [8]. Contributions to the LQ: development of long Nb_3Sn coil fabrication technology exploring options complementary to those used in the LR.

II. Long Nb_3Sn Coil Issues

The successful development of long Nb_3Sn magnets will require resolution of several issues. Those related with coil length are listed in the following with comments about their present status:

1) Cable and insulation: long coils without an interlayer splice require the fabrication of cable units of several hundred meters (380 m for the LR), and therefore need kilometer length strand pieces (in order to minimize losses) and an adequate insulation technique. Presently Oxford Superconducting Technology (OST) has produced unit lengths of several kilometers of the 54/61 RRP (Restacked Rod Process) strand with 54 sub-elements. Other high critical-current strands with more sub-elements are in an advanced state of development at OST and Shape Metal Innovations (Powder In Tube strand). There is no length related problem if the cable insulation consists of a tape (ceramic or S-glass) wrapped around the cable. But the need to overlap the tape results in thick insulation ($\sim$ 200 μm). S-glass sleeves ($\sim$ 100 μm thick) are presently used for the TQs and the first LR (300 m cable), but the application to long cables is very time consuming.

Braiding the insulation on the cable is being explored and presently seems to be the best method to provide thin insulation easily applicable to long cable units.

2) Coil winding and handling: By using the Wind-and-React method, coil winding should be as simple as that of short models. However, the handling of reacted coils will require special care in order to keep the maximum handling-induced strain in the coil to acceptable values. The maximum nominal coil deflection allowed by the LR tooling is 0.01%.
3) Heat treatment: The Nb_3Sn superconductor is formed during a heat treatment with maximum temperatures in the range 640–675°C over several days in vacuum or inert atmosphere. The fabrication of long coils requires ad-hoc furnaces with high temperature uniformity and sophisticated control systems. The design of coil and reaction tooling has to take into account the conductor volume increase during the Nb_3Sn formation, and the different thermal expansion coefficients of the materials involved (conductor, pole and wedges, reaction fixture). The first series of TQ model uses segmented Al-bronze poles with gaps to accommodate pole expansion (larger than the coil expansion) without stretching the coils. The coils are pre-shaped before reaction (by curing a ceramic binder applied on the insulation) in a mold slightly undersized in the azimuthal direction. During heat treatment the conductor expands to fill the reaction mold (with nominal dimensions) without causing excessive coil stress.
4) Impregnation: the impregnation of long coils may be more challenging than the impregnation of short coils due to the need to find the right balance between viscosity, pot life and flow of epoxy. Both viscosity and pot life decrease with increasing temperatures. CTD-101K [9] is presently used for the vacuum impregnation of TQ coils at 60°C (resulting in 100 Cp viscosity, and 20 hours pot life).
5) Quench protection: the linear growth of the inductance with coil length makes quench protection more and more difficult, most of all because of the high critical current densities and the low copper fractions presently used in conductor for high-performance Nb_3Sn magnets. For instance, the current density in the copper of the second generation of TQs (with RRP conductor) is expected to be about 2700 A/mm^2. The quench protection of the Long Racetrack and the Long Quadrupole are presented in the following.

III. LARP Long Magnet Design

The design of the LARP full size quadrupole model will start after the test of some LR and LQ models with additional inputs from short model tests, and studies of radiation damage and dissipation of the heat caused by interaction debris.

A. Long Racetrack

The design of the first Long Racetrack (LRS01) is presented in [10], [11]. The Long Racetracks will be assembled and tested at BNL using a support structure made of an Al shell preloaded by bladders and keys designed and assembled at LBNL [11]. BNL has recently assembled and tested a short racetrack (33 cm long) with the same coil design and fabrication technology that will be used for LRS01 [12]. A cross section of LRS01 is shown in Fig. 1.

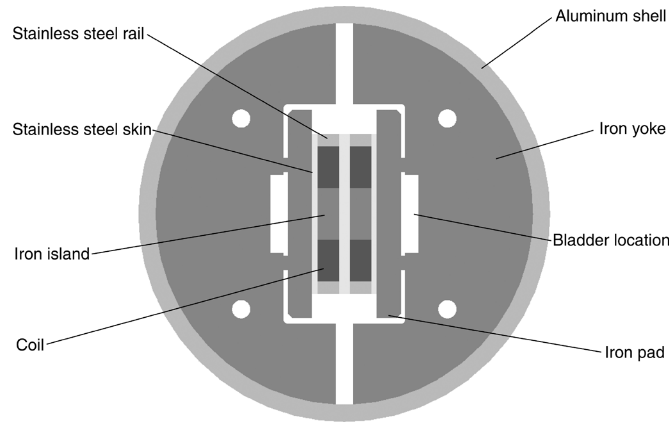

Fig. 1. Cross-section of LRS01.

TABLE I
Long Racetrack and Quadrupole Cable Parameters

Parameter	Unit	LR	LQ
N of strands	-	20	27
Strand diameter	mm	0.7	0.7
Bare width	mm	7.793	10.050
Bare inner edge thickness	mm	1.275	1.172
Bare outer edge thickness	mm		1.348
Keystoning angle	deg.	0	1.0
Radial insulation thickness	mm	0.092	0.125
Azimuthal insulation thickness	mm	0.092	0.125
Copper to non-copper ratio	-	0.89	0.9 - 1.0

The coils consist of two flat double-layer pancakes wound without an interlayer splice. Each layer has 21 turns. The cable parameters are given in Table I. LRS01 will use RRP strands, with 54 sub-elements and 47% copper, fabricated by OST. These strands, when reacted at 650°C/48 hrs, have a RRR greater than 200. Low field stability measurements show that strands reacted with the following schedule (used for strand acceptance): $48\ \mathrm{hrs}/210°\mathrm{C} + 48\ \mathrm{hrs}/400°\mathrm{C} + 48\ \mathrm{hrs}/650°\mathrm{C}$ have a stability limit of 975 A. Once a cable has been fabricated, the heat-treatment will be optimized using extracted strands to ensure adequate critical current (J_c) and stability limit. LRS01 short sample limit is 10.8 kA at 12.2 T (with $J_c = 2800\ A/mm^2$ at 12 T 4.2 K).

LRS01 uses the insulation scheme and fabrication technology adopted for LBNL small magnets. The cable insulation is a $\sim$0.1 mm thick S-glass sleeve. The original sizing is removed through heat treatment in air at 454°C for 2 hours. Palmitic acid sizing is applied to the cleaned glass by passing the sleeve through a Palmitic-acid/Ethanol solution. The insulation is slid over $\sim$10 m length of TFE tubing with the cable inside, and finally the cable is slid through the stationary TFE tube while treated insulation is slid on the cable. The insulation thickness measured on the cable at the end of this process is 0.92 mm.

A long Racetrack with some new features (LRS02) is planned to follow a successful test of LRS01. The new features include the use of a ceramic binder (CTD 1008x [13]) applied on the coils after winding. The coils with the binder are cured before heat treatment in a precise mold under pressure

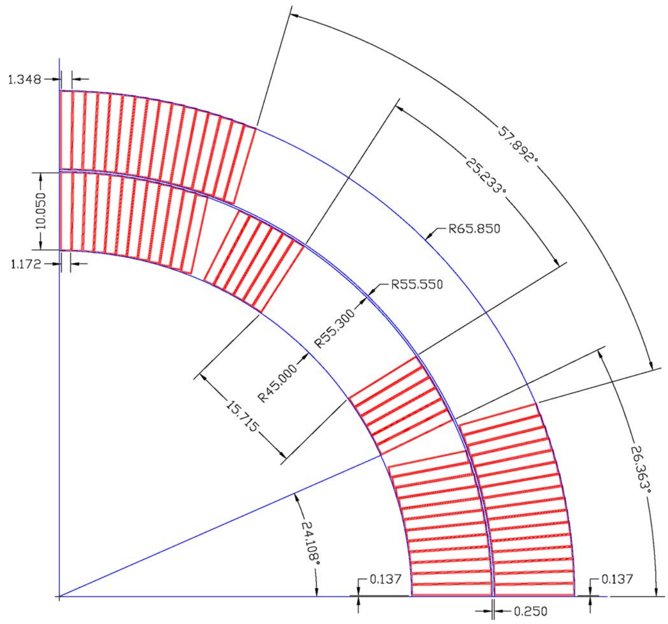

Fig. 2. TQ and LQ coil cross section.

at 150°C in air. During curing the binder becomes a strong bonding agent and the coils can be easily handled, inspected, measured, and prepared for the heat treatment which follows. During the heat treatment, the binder becomes porous but still provides good bonding. The coils are then vacuum impregnated, using CTD-101k. The mechanical properties of the resulting composite have been presented in [14]. The use of this binder, developed by CTD in collaboration with Fermilab and successfully adopted in several Fermilab dipole and mirror magnets [15], offers several advantages: it makes the Nb_3Sn coil fabrication and handling much easier; it provides a way to repair insulation damages that may occur during winding; it allows precise setting and control of the coil dimensions, and it allows accommodation of the coil volume increase (due to Nb_3Sn formation during heat treatment) by curing in a slightly undersized mold. This binder is presently used for all TQ coils and is planned to be adopted for the LQ coils. LRS02 (and FNAL LMs) will provide an opportunity to verify the advantages and possibly debug this technology for its application to long Nb_3Sn coils.

B. Long Quadrupole

The coil design of the Long Quadrupole is based on the coil design of the Technological Quadrupole (TQ) magnets, which is the same for the TQC (TQ with collars) [4] and TQS (TQ with Al-shell) [5] series. It consists of two layers, made of 27-strand cable, without an interlayer splice. The main cable parameters are shown in Table I and the coil cross-section in Fig. 2. The mechanical design will be based on analysis of the results from the TQ magnets with further input from the LR program. Table II shows the magnet parameters computed assuming $J_c = 2400\ A/mm^2$ at 12 T 4.2 K, $copper = 50\%$ and the TQC mechanical structure (the gradient is slightly higher in the TQS configuration since the iron is closer to the coil).

TABLE II
LONG QUADRUPOLE MAGNET PARAMETERS

Parameter	Unit	LQ
N of layers	-	2
N of turns	-	136
Coil area (Cu + nonCu)	cm^2	29.33
4.2 K temperature		
Quench gradient	T/m	224
Quench current	kA	13.5
Peak field in the coil at quench	T	11.6
Inductance at quench	mH/m	4.17
Stored energy at quench	kJ/m	207
1.9 K temperature		
Quench gradient	T/m	241
Quench current	kA	14.6
Peak field in the coil at quench	T	12.5
Stored energy at quench	kJ/m	240

Sleeves braided on the cable are presently under development and evaluation. The sleeve presently used for the TQ coils is a back up solution that could be used for the first LQ. In fact, it has been applied to an LR cable unit length (380 m) that is longer than an LQ unit length (300 m). The coil fabrication technology will be the same as that of the TQ coils (summarized in the previous section of this paper and described in [4]) if its applicability to long coils is successfully demonstrated by the LARP-LR and the FNAL-LM programs. A few minor modifications under evaluation are: (i) the use of a new ceramic binder (CTD-1202) which should have the same properties as CTD-1008, a lower cost, and easier procurement; (ii) the introduction of mica between the coils and the pole in order to allow sliding (presently in TQS, the pole is glued to the coils; in TQC, only the inner layer pole is glued).

The electrical strength of the TQ insulation scheme has been measured in order to assess the voltage breakdown and current leakage under transverse load. The test was performed on sections of TQ practice coils that went through all steps of the fabrication procedure [16]. Results show that the turn-turn insulation can withstand almost 1 kV at 190 MPa pressure.

IV. QUENCH PROTECTION

The quench protection of the LR, performed using the code QUENCHS [17], is presented in [10]. The analysis shows the need for energy extraction and strip heaters. A novel heater configuration has been designed to provide both maximum coverage and redundancy, and without the use of copper shunting. The heater scheme consists of eight 3 cm wide, 0.025 mm thick stainless steel strips, one for each straight section of all racetrack surfaces. At 4 locations along each strip, cutouts are introduced, where the strip width narrows down to 1 cm and the power density increases by a factor of 9. All turns will be covered. It is shown in [10] that this scheme will provide adequate protection under all quench conditions.

The LQ quench protection is performed by using the analytical code QuenchPro [18] developed by P. Bauer. This code, based on an adiabatic approximation, computes the temperature

TABLE III
LQ QUENCH PROTECTION

	T_{max} (K)	T_{bulk} (K)	V_{ground} (V)	V_{turn} (V)
50% - No - 1 - 5ms	480	148	202	192
50% - 60 - 1 - 5ms	348	109	445	122
50% - 60 - 0.89 - 5ms	372	110	450	134
50% - 60 - 0.89 - 10ms	442	109	448	174
Low C_p of insulation	564	120	463	222

as function of MIITs in three regions: hot spot (in high field region), and the inner and outer coils, under the heaters. Voltages (turn-turn, turn-ground) are calculated based on the current, current decay, resistance, and the inductance matrix (computed from the position of each turn). Based on [19], the cable insulation is also included in the MIITs computation, resulting in 9.9 MIITs at 300 K for the 'hot spot'. The material properties used for MIITs computation have been compared with the MATPRO library used by the code QLASA [20]. The most relevant difference was the specific heat of G10 (used to model the cable insulation), which differs by a factor two at 300 K. This difference reflects the range of data available in literature. The results presented in the following have been computed using the largest value. The last line in Table III shows the effect of using the lowest value (to be compared with the previous line).

Table III shows preliminary results of simulations at 4.2 K computed under different conditions. In this analysis, values of 5 and 10 ms have been used as the quench detection time. The heater delay time was always 25 ms consistent with measurements performed at Fermilab on a Nb_3Sn dipole [21]. Each case is identified by a series of four numbers: heater coverage, dump resistance in $m\Omega$ (if used), copper to non-copper ratio, quench detection time. For each case, the hot-spot temperature (T_{max}), the temperature under the heaters (T_{bulk}) at the end of the discharge, the voltage to ground, and the turn-turn voltage computed at maximum current decay (dI/dt max) are given. With a 60 $m\Omega$ dump resistor, the voltage across the leads at full current is 810 V.

The hot-spot temperatures are overestimated due to the use of the adiabatic approximation, and because the fast current discharge ($\sim 2\times10^5$ A/s) will quench the entire magnet. Nonetheless, these results show the need of large heater coverage, energy extraction and fast detection. The proposed scenario is to employ full heater coverage with two separate systems in order to have redundancy, so that the cases in Table III represent a failure analysis. The data collected during recent tests of TQS01 and TQC01 will be used to fine tune the MIITs computation and complete the quench analysis for the first LQ.

V. CONCLUSION

LARP has started the development of long Nb_3Sn accelerator magnets. The assembly of the first 4 m long quadrupole will start in the last quarter of 2007. Several issues describe in this paper are being addressed in order to assure success to this effort.

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