LARP Long Nb_3Sn Racetrack Coil Program

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***Abstract*—Development of high-performance Nb_3Sn quadrupoles is one of the major goals of the LHC Accelerator Research Program (LARP). As part of this program, long racetrack magnets are being made in order to check that the change in coil length that takes place during reaction is correctly accounted for in the quadrupole design and to check for length effects in implementing the "shell" method of coil support. To check the racetrack magnet manufacturing plan, a short racetrack magnet is being made. This magnet will be the first to use restack-rod process Nb_3Sn, making it a "long sample" test vehicle for this new material. The paper reports the reaction and characterization of the Nb_3Sn, and construction features and test results from the short racetrack magnet. The paper also reports on the status of the construction of the first long racetrack magnet.**

***Index Terms*—LARP, Nb_3Sn, racetrack, superconducting.**

I. Introduction

THIS paper reports work on the development of accelerator magnets made as part of the LHC Accelerator Research Program (LARP). The goal of LARP is to support the commissioning, operation, and eventual upgrade of the LHC at CERN. Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley National Laboratory, and Stanford Linear Accelerator Center are collaborating on LARP activities. Approximately half of the LARP work is concentrated on the development of high-field magnets for use in a possible upgrade of the LHC. Work has started in advance of the operation of the LHC because the magnets needed for an upgrade will have to use a superconductor, such as Nb3Sn, that has a higher critical field than NbTi.

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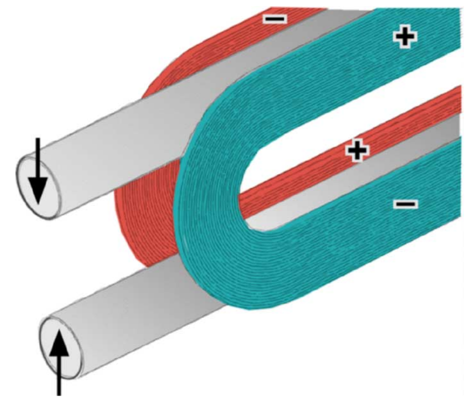

Fig. 1. Two racetrack coils connected in the common coil configuration.

This paper discusses magnets made with short and long racetrack coils supported by a shell-type support structure [1]. The short racetrack magnets, generically denoted SRS, are built to test magnet manufacturing methods before they are implemented in long magnets. The long racetrack magnets, generically denoted LRS, have the goal of checking for length-dependent effects in coils and in shell-type support structures before the construction of the long cos-theta technology quadrupoles (LQ), planned for the LARP program. The length of the LRS coils has been chosen to be $\sim$4 m so that they can be tested in vertical dewars at either BNL or Fermilab.

Each magnet consists of two racetrack windings. Coils in SRS (LRS) magnets are 300 mm (3.61 m) long. The magnets are wired in the "common coil" configuration [2] with minimal gap between them (Fig. 1). The coils are clamped by an iron yoke, which is held by a thick aluminum shell (Fig. 2). Preload perpendicular to the plane of the coils is applied by a system of bladders and keys. Additional preload is applied during cooldown due to the differential thermal contractions of the shell and other components. When powered, the predominant force is in the direction of the preload, with modest forces along the other two axes.

II. SRS01 Construction and Test

A. Superconductor

The Nb3Sn superconductor used in this magnet was made by the "restack rod process" (RRP) by Oxford Instruments, Superconductor Technology [3]. Properties of the strand are given in Table I. These properties are very similar to those of the strand planned for the LRS magnets, except for the twist pitch, which is longer than the desired 14 mm. (The strand was made as part of the conductor development program; production strands have the correct pitch.) Dimensions of the rectangular cable used in

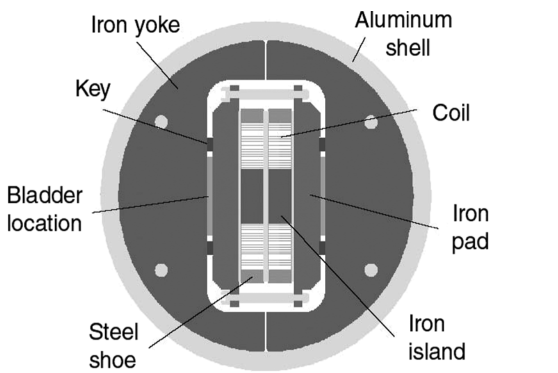

Fig. 2. Principal components of a magnet with racetrack coils supported by a shell-type structure.

TABLE I
STRAND PROPERTIES MEASURED BY OST

Billet Number	8220
Strand Diameter	0.7 mm
No. of subelements	54
Cu fraction	46.2% ±0.35%
IC (12 T, 4.2K)	629 ± 15 A
JC (12 T, 4.2K) (1)	3035 ± 94 A/MM2
RRR	235 ± 24

(1) reaction cycle $210°C$ $(48\ h)$ + $400°C$ $(48\ h)$ + $665°C$ $(48\ h)$

TABLE II
PROPERTIES OF WITNESS SAMPLE OF CABLE

Cable ID	935R
Number of Strands	20
Pre-anneal dimensions	7.826 mm x 1.297 mm
Re-roll dimensions	7.767 mm x 1.282 mm
Pitch	53.9 mm

the racetrack coils are given in Table II. The anneal noted in this table was at 200 C for 4 h. The cable was annealed to reduce the length change that occurs during reaction.

The magnet critical current was determined from tests of extracted strands at BNL and Fermilab is 9.7 kA, with an uncertainty of $\pm 1\%$ [4]. The uncertainty arises from the strand-to-strand variation in critical current and from uncertainties in the measurement procedure for these high-current strands, which is still in development.

The stability current, I_s, is an important parameter in magnet performance, as it would limit the magnet current if it is lower than the desired operating current. It is determined by setting the current in the strand or cable short-sample and ramping the background field until the sample quenches [5], [6]. For low values of the background field (0 T–4 T), an unstable conductor will exhibit flux jump quenches for current levels above I_s. Low values of the reduced resistance ratio (RRR) of the copper in the strand lower I_s in the conductor. It has been found that RRR greater than 100 results in strands which have I_s much greater than the maximum current in LARP magnets [7], [8]. All strands tested for SRS01 have I_s greater than the strand critical current in the magnet, 485 A. The cable measurement of I_s yields values consistent with the strand measurements.

B. *Cold Mass Fabrication and Assembly*

The cable was insulated with a continuous, woven S-glass sleeve. The double-layer, flat racetrack, coil was wound around an iron island with the layer-to-layer transition in the pole turn. The island is insulated from the coil by a 0.13 mm-thick coating of aluminum oxide. The winding tension was 111 N and the coil was clamped on one side while the opposite side was wound. A layer contained 21 turns of cable. A double-layer coil required 23 m of cable. When winding was complete, two stainless-steel end shoes, one covering the return end and both sides, the other covering the lead end, were placed around the coil. The faces of the coil were insulated with S-glass and the top and bottom plates of the reaction fixture bolted to the two pieces that covered the sides of the coil. The coils were reacted in a vacuum oven equipped so that a continuous flow of Ar was maintained during the heating cycle. The nominal reaction cycle was 72 h at 210°C, 52 h at 400°C and 48 h at 639°C. Witness samples were placed in the oven during the coil reaction. After reaction, NbTi leads were soldered to the coils and the coils were then transferred to other fixtures for vacuum impregnation with CTD101K [9] epoxy. For simplicity, the coils have minimal instrumentation (voltage taps on the leads, a voltage tap on the island turn near the ramp, and a spot heater with voltage taps on both sides at the high field point, turn 10).

The two coil modules were bolted together in between two iron pads and then inserted into the support structure. The support structure is composed the yoke (six 50.8 mm-thick steel plates) and a 12.7 mm-thick Al cylindrical shell with 215.1 mm inner diameter and 304.8 mm long. Stainless steel bladders were used to expand the shell, permitting keys to be inserted between the yoke and the coil pack. The bladders were removed, allowing the keys to determine the preload, which was estimated to be 31.5 MPa. Splices between coil modules were then made, external to the magnet. A full description of the magnetic design and support structure is given in a separate paper [10]. For SRS01, the peak field at the conductor critical current is 12.3 T.

C. *Test Results*

SRS01 was tested in liquid helium at a nominal temperature of 4.5 K (Fig. 3). There were two test periods. During the first period, there was a large ripple in the current (e.g., at 6 kA, 25 A ripple peak-to-peak at 180 Hz and 50 A ripple peak-to-peak at 60 Hz) due to problems with the firing circuits in the power supply. The circuits were replaced between the two test periods and the ripple decreased to negligible values.

During the first test period, the quench currents were strongly dependent on ramp rate. Both the current ripple and the larger-than-design pitch length of the strand contributed to eddy current heating during these tests. After repair of the power supply and a decrease in ramp rate to 1 A/s, the magnet quickly reached 96% of its critical current. The 1 A/s quenches originated near the interlayer ramp.

III. LRS01 STATUS

A. *Design and Fabrication Features*

It was decided to make LRS01 as much like SRS01 as possible, so that possible effects due to changes in length would not

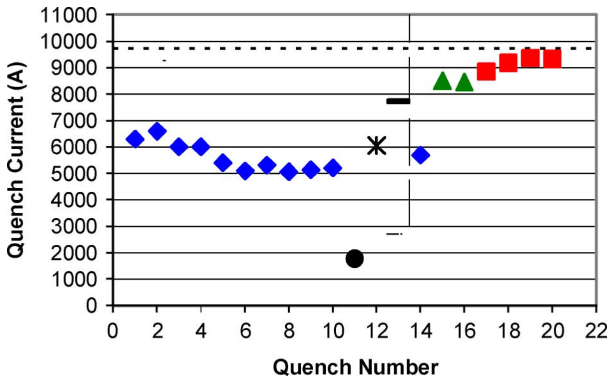

Fig. 3. Quench test history for SRS01. The symbols indicate the ramp rates: 20 A/s (diamond), 100 A/s (circle), 4 A/s (asterisk), 2 A/s (triangle), and 1 A/s (square). The vertical line indicates a thermal cycle. The horizontal line indicates the estimated critical current. The horizontal bar indicates a ramp at 2 A/s to 7718 A, the power supply maximum current at the time, without a quench.

be masked by other effects. Thus, the island will be made of iron. Because the coil shrinks due to the reaction, the island must be shorter than the length allowed for it during coil winding. The gap for the iron island in the 3.6 m LRS coils will be set based on experience in reacting 0.7 m-long TQ coils [11], [12]. The gap will be implemented by dividing the island into five equal-length segments, with a gap between each pair of segments.

Other length-related changes have been made. Because of their greater length, the LRS coils are supported by saddles at each end and full length stainless steel rails on each side. The saddle, coil, and island will be clamped together during the reaction cycle in order to assure that the good fit of these components after reaction. The electrical integrity will be increased by adding a 0.13 mm-thick layer of glass cloth between the two layers of the coil and by doubling the thickness of the aluminum oxide coating on the island to 0.25 mm. During the first phase of the reaction, when the palmitic acid is vaporized, the flow of argon will be increased significantly.

The coil instrumentation and quench protection heaters will be printed circuits on a Kapton substrate. Each of the four coil surfaces will be protected by two redundant heaters. Voltage taps will be placed at the leads, the coil ends, the layer transition, and the high field point (turn 10 on the inner part of the coil). Voltage taps will also bracket the spot heater, which will be in the high field region of the coil.

Practice winding with a copper cable insulated with an overwrap of S-glass is now underway. The copper coil will be taken through all the production steps except coil reaction. This will allow a partial test of the coil-to-island electrical integrity and full tests of the fit of the instrumentation trace to the coil, the completeness of the vacuum impregnation, and the fit and operation of most of the tooling

It was decided that the maximum strain in the reacted coil should not exceed 0.05%. This is a factor of four lower than the nominal benchmark for significant ($\sim$10%) effects of strain in this material. An additional safety factor of five has been applied to the design of the coil handling tooling; that is, the design maximum strain is 0.01%. The material to be used for the reaction fixture is 347H stainless steel. Two sets of coil handling tooling

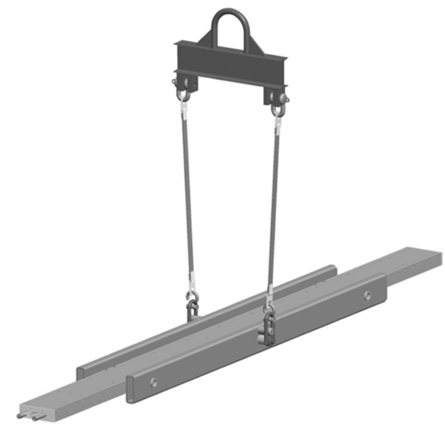

Fig. 4. Devices to manipulate reacted coil in fixture.

Fig. 5. Device to manipulate coil installed in support structure.

are needed. One set consists of beams and a spreader that handle two uses: to transport, flip, and upright the coil in the reaction and impregnation fixtures (Fig. 4), and to upright the completed cold mass for vertical testing. The beams attach to the reaction fixture and cold mass at the two quarter points. In both cases, the calculated maximum deflection of the coil is less than 0.08 mm. The other set (Fig. 5) of tooling lifts up the reacted coil using holes in the rails. The tooling is designed so that the maximum deflection of the coil is less than 0.03 mm.

B. Fabrication Status

As noted above, practice winding with the copper coil is underway. Sufficient cable is available to allow for a Nb_3Sn practice coil. The pacing element in the schedule is the reaction oven, which is to be delivered in September. The support structure is due to be sent from LBNL to BNL at the end of October. Tests of LRS01 are scheduled for Feb., 2007.

IV. Future Plans: SRS02, LRS02

To achieve the uniform coil size needed for the IR quads, the coils for the LQ quadrupoles will be coated with a ceramic binder that will be cured under pressure to a fixed size before the coils are reacted [12]. The reaction fixture will be slightly larger than the curing fixture, also in order to achieve uniform coil size. These features will be tried initially in a short racetrack coil (SRS02) and then in a long racetrack coil (LRS02) before construction of the LQ coils begins.

V. Summary

Test results from SRS01 indicate that the technology for making short racetrack magnets has been successfully transferred from LBNL to BNL. The results also indicate that the conductor is sufficiently stable for use in the LARP program. The first 3.8 m magnet, LRS01, is well underway.

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