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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 were made in order to check the fabrication steps for long Nb_3Sn coils, that the changes in coil length that take place during reaction and cooldown are correctly accounted for in the quadrupole design, and the use of a long aluminum shell for the support structure. This paper reports the construction of the first long Nb_3Sn magnet with racetrack coils 3.6 m long. The magnet reached a nominal "plateau" at 9596 A after five quenches. This is about 90% of the estimated conductor limit. The peak field in the coils at this current was 11 T.**

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

I. INTRODUCTION

THIS paper presents 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 in 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 it would be highly advantageous if Nb_3Sn were qualified for use in the upgrade magnets, so that the LHC could take advantage of the critical field and critical temperature, which are higher than those of NbTi.

This paper reports the manufacture of 3.6 m-long racetrack Nb_3Sn coils and the test results of the magnet made with these coils. The construction and performance of a shell-type support structure used for this magnet to restrain coil motion against Lorentz forces is reported in a separate paper [1]. The magnet, denoted LRS01, has the goals of checking the fabrication steps for long Nb_3Sn coils and checking for length-dependent effects in coils and in shell-type support structures before the construction of the ~ 4 m cos-theta quadrupoles (LQ) planned for the LARP program. The performance of the quench protection system is also relevant for LQ magnets. A short (300 mm coil length) version of this magnet, denoted SRS01, was successfully tested in 2006 [2], [3]. As far as possible, LRS01 was built the same as SRS01, only longer. The length of the coils in LRS01 was been chosen to permit it to be tested in vertical cryostats at either BNL or Fermilab.

II. MAGNET DESIGN AND INSTRUMENTATION

The magnet has two 3.6 m-long racetrack coils. The coils are wired in the "common coil" configuration [4] 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 contraction of the shell and other components. When powered, the predominant force is in the direction of the preload (perpendicular to the face of the coils), with modest forces along the other two axes.

Quench propagation calculations were performed using the program QUENCHS [5],[6] in order to estimate hot spot temperatures reached during quenches, the values of $\int I^2 dt$ corresponding to these temperatures, and internal coil voltages generated during a quench. From previous work [7], it is known that Nb_3Sn cable can start degrading at temperatures above 400 K, so quench temperatures were limited to a maximum of about 300 K, corresponding to 5 MIITS. In addition, the calculations indicated that internal coil voltages could exceed 1000 V. It was decided to limit coil voltages to 500 V. Details can be found in [8].

Because of these results, it was necessary to include both an

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energy extraction circuit and quench protection heaters in order to decrease maximum quench temperatures and coil voltages. Fig. 3 shows a portion of the schematic of a flexible

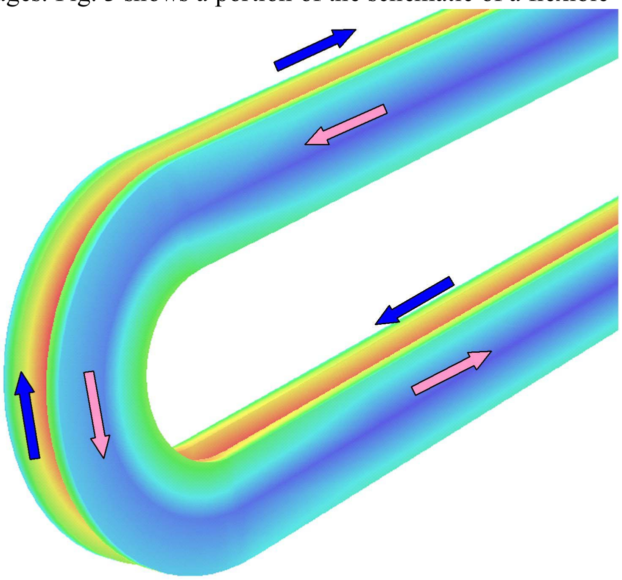

Fig. 1. Two racetrack coils powered in the common coil configuration.

circuit, or instrumentation trace that contains all coil instrumentation, including voltage taps, spot heaters, and quench protection heaters, on a 0.025 mm thick Kapton® substrate [9]. Each trace covers half of each layer. Thus, each

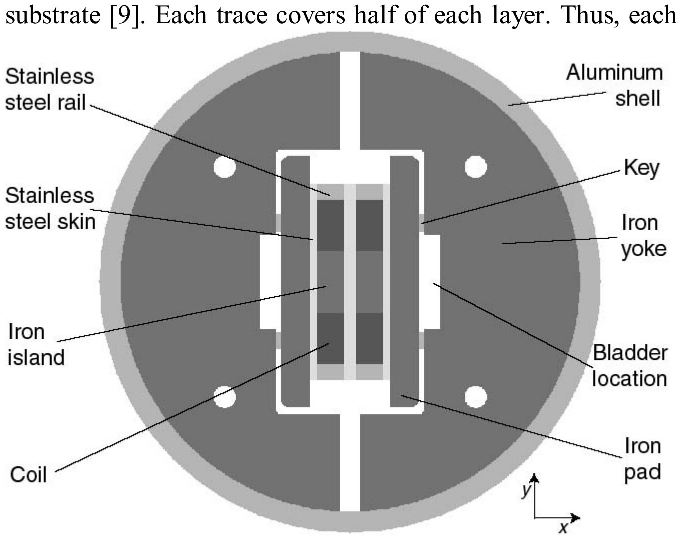

Fig. 2. Principal components of a magnet with racetrack coils supported by a shell-type structure.

of the four exposed surfaces is covered by two strips for a total of eight strips. The heater consists of 0.025 mm thick 304 stainless steel strip of nominal width 3 cm. The strips were powered by two independent power supplies and there was one strip for each surface in each circuit thus providing two redundant systems. At four locations in each strip (Fig. 3), the width is narrowed to 1 cm in order to concentrate surface power density. At 100 A, the heater delivers 283 W/cm^2, providing a large margin for initiating quenches with minimum delay. All 21 turns are covered under each narrow heater section. Each strip is about 3 Ω and, in order to lower the effective total resistances seen by each power supply and therefore the voltage required to be supplied, the strips were configured in parallel, giving a resistance of 1.3 Ω seen by each supply. Voltage taps were installed at the high field point (turn 12) and several other key points (e.g., coil ends, leads).

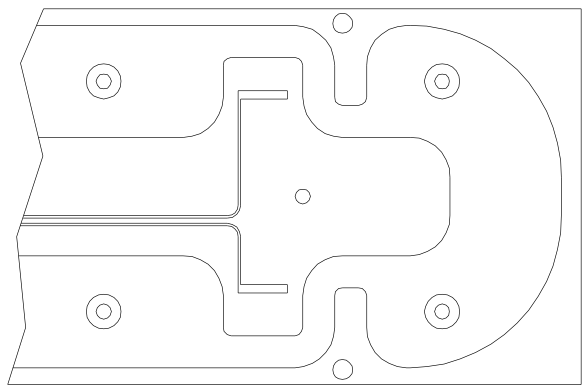

Fig. 3. End section of the trace showing two 1 cm-wide regions of the quench protection heater and connections to two voltage taps.

III. Magnet Construction

A. Superconductor

The Nb_3Sn superconductor used in this magnet was made by the "Re-stack Rod Process" (RRP) by Oxford-Instruments, Superconductor Technology (OST) [10]. Properties of the virgin strand measured by OST are given in Table I. These properties are very similar to those of the strand used for the SRS01 magnet [2]. Each pair of inner and outer coils was wound from a continuous length of cable ~ 350 m long. The nominal dimensions of the rectangular cable used in the racetrack coils are given in Table II. The cable was annealed at 200 C for 4 h prior to the final re-rolling. This annealing is done to reduce the length change that occurs during reaction.

The magnet critical current was determined from tests of extracted strands reacted along with the coils. From these measurements the short sample limit I_{ss} at 4.5 K is estimated to be 10.6 kA, with an uncertainty of ± 2%. The uncertainty reflects the strand-to-strand variation in critical current that was observed for the extracted strands, and the uncertainty in the measurements. In this calculation the self field during the strand test is taken into account. This estimate does not take into account differences between the strain state of the conductor in the magnet and the barrel-test of the strand.

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 [11,12]. 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. All round and extracted strands from the cable in LRS01 that were measured have I_s greater than the strand critical current in the magnet, 530 A. This ensures that magnet performance will not be limited by this instability. The cable measurement of I_s yields values consistent with the strand measurements.

TABLE I
STRAND PROPERTIES MEASURED BY OST

Billet Number	8647	8648
Strand Diameter, mm	0.7	0.7
No. of subelements	54	54
Cu fraction	46.1 ±0.2%	46.3 ±0.2%
I_c (12 T, 4.2K), A (1)	562 ± 10	560 ± 18
J_c (12 T, 4.2K) , A/mm^2	2752 ± 42	2711 ± 96
RRR	195 ± 10	212 ± 29

(1) reaction cycle 210º C /48h + 400º C /48h + 665º C /48h

TABLE II
PROPERTIES OF CABLE

Cable ID	942R	949R
Number of Strands	20	20
Pre-anneal sizes, mm	7.855 x 1.306	7.848 x 1.307
Re-roll sizes, mm	7.828 x 1.277	7.828 x 1.274
Cable Pitch, mm	54.5	55.0

B. Coil Manufacturing

The cable was insulated with a continuous, woven S-glass sleeve. The original sizing of the S-glass was removed by heat treatment. The S-glass was then resized with palmitic acid, which evaporates when the coil is reacted. The double-layer, flat racetrack coil was wound around a segmented iron island, with the layer-to-layer transition in the pole turn. The iron island consisted of five segments with gaps of ~ 0.5 mm between adjacent segments to prevent stretching of the cable by the island during reaction. The island was insulated from the coil by a 0.25 mm-thick coating of aluminum oxide. The winding tension was 90 N and the coil was clamped on one side while the opposite side was wound. A layer contained 21 turns of cable. When winding was complete, stainless-steel end shoes and side rails were placed around the coil. The faces of the coil were insulated with S-glass. The reaction fixture was then clamped to the coil. The construction of a separate retort was unnecessary because the fit of the mating pieces of the reaction fixture was tight enough to contain most of the Ar flow during reaction and because the furnace is gas-tight with Ar flow during the reaction. The nominal reaction cycle was 72 h at 210º C, 48 h at 400º C and 48 h at 639º C. (The reaction temperature, lower than that used by OST, increases I_s relative to OST [13].) During the reaction of the first coil (LRSC01), the ten thermometers mounted in the reaction fixture had temperatures in the range 637° C to 644° C. During the reaction of the second coil (LRSC02), temperatures were in the range 637° C – 643° C. Witness samples of extracted strand, also in an Ar flow, were placed in the oven during the coil reaction. These saw a temperature of 640° C - 641° C. After reaction, NbTi leads were soldered to each coil, the instrumentation and instrumentation trace added, and the coil installed in the vacuum impregnation fixture. The coils, in a vertical position, were impregnated with CTD101K [14] epoxy. Stainless steel skins were bolted to the side rails and end shoes. The two coils were clamped between iron pads and inserted into the support fixture, as discussed in [1]. The completed magnet was then moved to the test facility.

C. Magnet Test

The magnet was tested in a vertical dewar in liquid helium at temperatures in the range 4.51 K to 4.52 K. Most quench tests were performed by ramping the magnet current at 20A/s to 7000 A and stopping to lower the quench detector (QD) voltage threshold from 3.6 V to 0.8 V. The higher threshold below 7000 A decreased the probability of false detector trips by flux jump spikes and the lower threshold afterwards decreased the delay between quench start and detection, decreasing the value of $\int I^2 dt$. The ramp rate above 7 kA was 20 A/s except for some ramp rate study quenches done at 5, 10, 50, and 100 A/s. The delay from the QD stop trigger pulse was less than 0.2 μs.

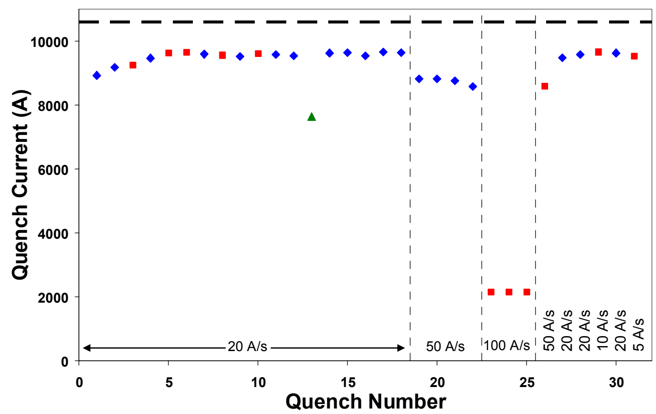

Fig. 4. LRS01 spontaneous quench history (4.5 K). Quench origins: LRSC02 inner layer (diamond), LRSC01 inner (square), LRSC02 outer (triangle). The dashed horizontal line is I_{ss}

Fig. 4 shows a plot that summarizes the 31 spontaneous quench tests. As can be seen, at the standard 20A/s ramp rate, a nominal "plateau" of average 9596 A (90% of the conductor limit estimated using self-field corrections, I_{ss}) was reached in five quenches. The maximum quench current was 9663 A. The peak field in the coil was 11 T. Quenches at 5A/s and 10A/s did not deviate in current from this plateau. The thirteenth quench (Q13) at 7650A was not included in the average. All but one of the plateau quenches at 20 A/s after this low quench were in the upper inner layer somewhere in the high field region, turns 10 to 12 and turns 12 to 15, in apparently two separate locations, and were also quickly seen in other turns. (The inner layer faces the center of the magnet; the outer layer faces the pad.) The initial dV/dt for all these quenches was very similar implying the same or magnetically similar location and very high, about 400V/s, implying high quench velocities of 100 m/s or more. The earlier quenches were in different locations from quench to quench, and in either of the inner layers. The only 20A/s plateau quench after Q13 which varied from this behavior was Q27, which had the lowest current at 9488A and was in the turn 1-2 end section. The quenches at other ramp rates, even within the plateau, were in various locations in both inner layers. This behavior contrasts with that from the short racetrack SRS01 previously tested at BNL [2]. Plateau quenches for SRS01 were at 96% I_{ss} and were located in the transition ramps between layers.

Q13 was the only quench in an outer layer. It originated in the outermost turn. Since it originated in a low-field region, its cause is thought to be a large mechanical motion of the coil, most likely in the direction parallel to the plane of the coil, where there is only modest support against the Lorentz forces. Such a quench is not expected in the quadrupoles, which are well-supported in all three dimensions.

Fig. 5 shows how the quench current varied with ramp rate. Ramp rates lower than 20A/s showed no apparent change in quench current but were at different locations: turn 1 for 10A/s and turn 21 for 5A/s, both in the lower inner layer. At higher ramp rates the current decreased sharply with quenches at 100A/s down to 2162A, and all three originated somewhere in turns 1-10, possibly at the same location since the voltage signals for these quenches were very similar. Quenches at 50 A/s were similar in development to the 20A/s quenches but were 800-1000 A lower with greater variation. The short racetrack also exhibited a sharp decrease in quench current at 100 A/s [2]. However, in the case of SRS01, the stronger dependence of quench current on ramp rate was caused by a strand twist pitch that was significantly longer than specification.

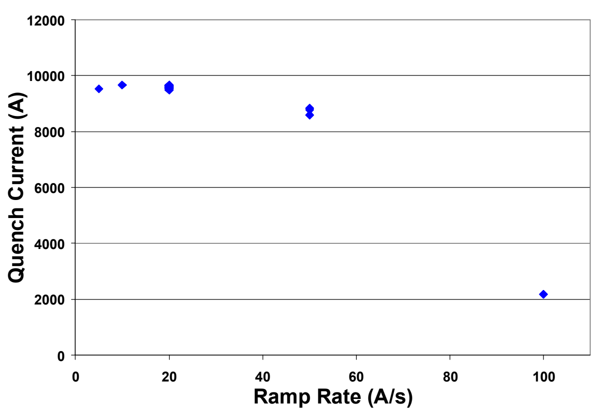

Fig. 5. Quench current as a function of ramp rate.

The value of $\int I^2 dt$ was calculated for all quenches. For all quenches except Q13 in the lower outer layer the value did not exceed 3.5 MIITS and was mostly below 3.0 MIITS. The value for Q13 was 6.0 MIITs, which corresponds to a temperature of about 400 K, below the limit where degradation starts. No apparent degradation was seen in the performance of the magnet after this event.

In order to properly test the effectiveness of the quench protection heaters, it was necessary to fire the strip heaters independently by replacing the stop trigger pulse from the quench detector with an external 5 V signal, which would fire the heater to induce a quench. In this way it would be possible to separate out the eddy current quench effect from the current decay after a shut off and better see which layers were actually experiencing a quench. A series of four tests were done with the magnet at 9000 A. For a current of 14 A, corresponding to a surface power density of 5.6 W/cm^2 into each strip, the delay for the inner layers was 15 ms, which is acceptable. At 42 A (50 W/cm^2), the delay was 6 ms, and from there it starts to approach an asymptotic value of about 5 ms, so further increases in current are not needed.

A sampling of flux jump voltage pulses was recorded using a storage scope with a time resolution of 2 µs. (The time resolution of the rest of the system is 5 ms.) Flux jumps as high as 2.2 V were recorded at ~ 5 kA.

The residual resistivity ratio RRR, defined as the resistance of the material at room temperature divided by its resistance at 18 K, was measured in strands extracted from the cable before winding and reacted along with the coil. RRR was 223±2 for coil LRSC01 and 211±2 for coil LRSC02. The surfaces of one inner layer and one outer layer were inspected after testing. No changes due to testing were found.

IV. Conclusion

The magnet performed well, reaching a plateau quench current ~ 90% of the short-sample limit in five quenches. The good performance of this magnet indicates that there are no fundamental length-related problems with the construction of Nb_3Sn-based quadrupoles of the length needed for an LHC upgrade.

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