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Test Results of the First 3.7 m Long Nb_3Sn Quadrupole by LARP and Future Plans

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***Abstract*—In December 2009 during its first cold test, LQS01, the first Long Nb_3Sn Quadrupole made by LARP (LHC Accelerator Research Program, a collaboration of BNL, FNAL, LBNL and SLAC), reached its target field gradient of 200 T/m. This target was set in 2005 by the US Department of Energy, CERN and LARP, as a significant milestone toward the development of Nb_3Sn quadrupoles for possible use in LHC luminosity upgrades.**

LQS01 is a 90 mm aperture, 3.7 m long quadrupole using Nb_3Sn coils. The coil layout is equal to the layout used in the LARP Technological Quadrupoles (TQC and TQS models). Pre-stress and support are provided by a segmented aluminum shell pre-loaded using bladders and keys, similarly to the TQS models. After the first test the magnet was disassembled, reassembled with an optimized pre-stress, and reached 222 T/m at 4.5 K.

In this paper we present the results of both tests and the next steps of the Long Quadrupole R&D.

***Index Terms*—LARP, long magnet, Nb3Sn, superconducting magnet.**

I. INTRODUCTION

THE US LHC Accelerator Research Program (LARP), a collaboration among BNL, FNAL, LBNL, and SLAC, aims at demonstrating that Nb_3Sn quadrupole magnets [1] are a viable option for LHC luminosity upgrades. A significant milestone toward this goal was set in April 2005, when the US Department of Energy, CERN, and LARP agreed to reach 200 T/m in a 4 m long, 90 mm aperture quadrupole made with Nb_3Sn coils, by the end of 2009. In order to meet this milestone LARP developed the Long Quadrupole (LQ) [2],[3]. The LQ is 3.7 m long because this is the maximum length that can be tested at FNAL Vertical Magnet Test Facility (VMTF) [4] (the longest vertical test facility allowing 4.5 and 1.9 k testing, among the LARP laboratories). The LQ, with 90 mm aperture, and two-layer shell-type coils, is based on the 1 m LARP Technological Quadrupoles (TQ) [5], [6]. Similarly to the TQ models it uses a 10 mm wide cable made of 27 strands with 0.7 mm diameter. The strands of the first model (with 54 Nb_3Sn subelements) have been manufactured by Oxford Superconducting Technology, using the Restack-Rod-Process (RRP).

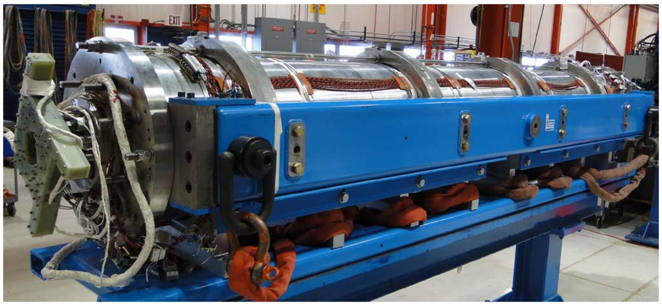

Fig. 1. LQS01, fully assembled and instrumented, during preparation for lifting. Bottom raft and side beams are used for handling and are removed before test.

Some modifications were introduced to the coil design and fabrication technology in order to improve the fabrication of long Nb_3Sn coils [7]. The structure [8], using a segmented aluminum shell, is based on the TQS [6] and the Long Racetrack [9] development.

The first model (LQS01) was assembled at LBNL with the first production coils (#6–#9) fabricated at BNL and FNAL. It should be noted that three coils (#6, #7 and #9) had one severe discrepancy (i.e. a discrepancy that could limit magnet performance) during fabrication. All discrepancies were fixed [2] and a review assessed the readiness of the coils for testing (Fig. 1).

The main features of LQS01 are presented in Table I. The short sample limit (s.s.l.) was computed based on extracted strands reacted with the coils (witness samples). Two LQ cables reacted with a coil and tested at FRESCA (CERN cable test facility) [10] showed a critical current lower than the strand critical current, likely because of different strain [2]. If the LQS01 s.s.l. is computed based on the cable samples it is ~3% lower than in Table I.

The first test of LQS01 (LQS01a) started in November 2009 and at the beginning of December LQS01a reached its target field gradient of 200 T/m. Despite this significant achievement the training was stopped at 202 T/m in order to avoid possible

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TABLE I
LQS01 AT 4.5 K S.S.L

Field Gradient	240 T/m
Current	13.75 kA
Peak Field	12.25 T
Stored Energy	460 kJ/m

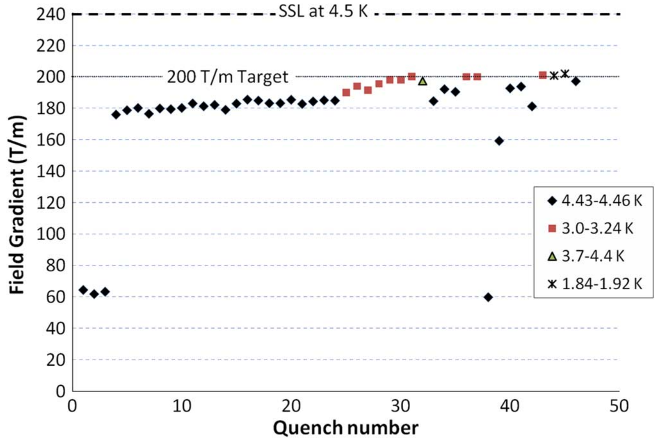

Fig. 2. LQS01a quench history. Different markers are used to show quenches at different ranges of bath temperature. The short sample limit at 4.5 K and the field gradient target are also shown.

coil damages. The magnet was subsequently disassembled, inspected, and reassembled with higher and more uniform preload [11] using all four original coils. The test of the reassembled magnet (LQS01b) started in July 2010.

II. LQS01a Test Results

At the start of magnet training, large voltage spikes caused by flux jumps [12] triggered the quench protection system several times. The detection thresholds of both the analogical and digital (FPGA based) systems were increased at low current, up to 5–6 volts, in order to be higher than these spikes. In addition it was necessary to increase the ramp rate at low current in order to improve the stability of the conductor by eddy-current heating. The first three quenches (Fig. 2) occurred at 200 A/s during the fine tuning of this procedure. Finally the following variable ramp rate was adopted for the whole training: ramp at 200 A/s to 3 kA; ramp at 50 A/s to 5 kA; ramp at 20 A/s to 9 kA; ramp at 10 A/s to quench.

The training with this variable ramp rate started at 176 T/m $(\mathrm{I} = 9.7\ \mathrm{kA})$ and was very slow as shown by a gain of only 10 T/m after 20 quenches. After lowering the temperature to 3 K, the training was faster and LQS01a reached 200 T/m (its target gradient at 11.2 kA) in 7 quenches. In a few subsequent quenches at 4.4 K LQS01a reached 192 T/m. After ramp rate studies at 4.4 K (quenches 38 to 42) LQS01a reached 202 T/m in two quenches at 1.9 K, and 197 T/m in the last quench at 4.4 K. At this point the training was stopped because almost all strain gauges located on coil poles showed insufficient pre-load on the inner layer above 170–180 T/m. FEM analysis [11] showed that this low pre-stress on the inner layer could be caused by a mismatch between the outer diameter of the coils and the inner diameter of the pads. The mismatch was caused by an oversize of the coils on midplanes of 100 $\mu\mathrm{m}$ $(\pm 50\ \mu\mathrm{m})$ due to spring-back after impregnation. The FEM analysis also showed that the bending, caused by the mismatch, was increasing the pre-load on the midplanes so that it could reach excessive values above 200 T/m. The increase of the quench current at 4.5 K, after training at low temperatures, showed that the previous plateau was caused by insufficient preload on the inner pole and not by conductor limitation. Analysis of the voltage rise after quench and of the quench start locations confirmed that all coils had margin for improvement under more uniform and higher pre-stress.

All coils participated in the training although most quenches started in coil #7. All training quenches started in the straight section of the inner layer. Voltage taps and a quench antenna covering about half of the central straight section (longest segment) showed that the quench start location was continuously changing. The recovery time between quenches was at minimum two hours and the test lasted about four weeks.

The ramp rate dependence and magnetic measurements are presented in the following with LQS01b test results.

Voltage spikes as high as 4.5 volts were recorded at 50 A/s ramp rate, at the end of the test, during a study of the spike dependence from the ramp rate. A detail report of LQS01a test results is presented in [13].

III. LQS01a Disassembly, Coil Inspection and LQS01b Assembly

A. *LQS01a Disassembly and LQS01b Assembly*

The LQS01 pre-stress target values were chosen in order to avoid separation between coil and pole at field gradient of 230–240 T/m, according to FEM computation. In LQS01a, the aluminum shell and stainless steel rods reached after cool-down a pre-tension consistent with calculations. On the contrary a large discrepancy was observed between measured and expected azimuthal coil pre-load [11]. In addition, most of the pole gauges showed a “stress plateau” during current ramps indicating coil-pole separation.

After the LQS01a test, the magnet was unloaded and disassembled at LBNL. Tests with pressure sensitive paper confirmed the mismatch between the coil outer surface and the pad inner surface. Based on the results of these tests and additional measurements, it was decided to apply two modifications to LQS01b structure and loading. The thickness of the G10 shim providing electrical insulation between coils and pads was reduced from 0.765 mm to 0.380 mm. In addition the pre-load was increased, based on the successful experience with the TQS03 series [14], to further mitigate the risk of low coil pre-stress. After the modifications were implemented the pole compression at cold increased to -130 ± 31 MPa (corresponding to 165 MPa in the coil), and no separation was observed between coil and pole during excitation.

B. *Coil Inspection After LQS01a Test*

The LQ coils are instrumented using a flexible circuit called the trace [15] which is made of a Kapton/stainless steel laminate.

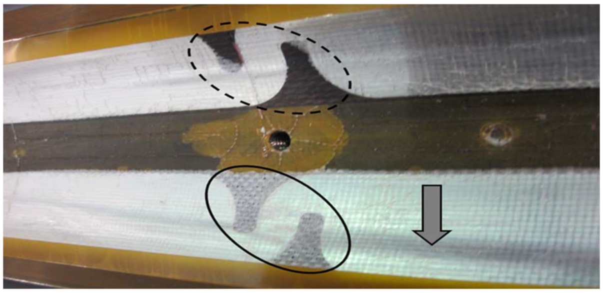

Fig. 3. An LQ inner layer trace shows signs of de-lamination (white areas inside the continuous oval, and shadow indicated by arrow).

It includes the voltage taps circuits as well as the protection heaters. The trace is positioned on the inner and outer diameter of each reacted coil, and is covered by a layer of glass, before coil impregnation. The Kapton layer has holes along the length to allow a better bounding of the epoxy.

After the disassembly of LQS01a all coils were inspected and some signs of de-lamination (Fig. 3) were found on the inner layer protection heaters. In addition some “bubbles” were observed on the inner diameter of all coils, mostly located over the large sections of the heaters. From the visual inspection, it was difficult to see if the bubbles were underneath the stainless steel or between the stainless steel and the glass sheet. Bubbles have been observed in some TQ magnets [16] and were attributed to the superfluid helium properties at 1.9 K. LQS01a experienced only 2 quenches at 1.9 K which may not justify the large number of bubbles observed on the LQ coils after disassembly. The bubbles could be a consequence of (or be enhanced by) the heaters on the inner layer. It should be noted that LQ is the first LARP magnet to have protection heaters on the inner layer. Finally, unlike the TQ bubbles, the bubbles observed in the LQ coils did not expose any conductor.

C. *Repair and Plans for Future Coils*

High-pot tests (up to 1 kV) were performed between the coils and the protection heaters in order to evaluate the impact of these bubbles on the magnet protection. The tests gave unreliable results with 1 μA leakage current threshold (successfully used before magnet test); whereas all heaters passed the hi-pot test after the threshold was increased to 10 μA. It is not clear if this behavior is a direct consequence of the bubbles and will require additional investigation.

A protection heater failed at the end of LQS01a test. A close inspection showed a small burnt area at the edge of a bubble. The carbon and the Kapton below the stainless steel heater were removed exposing a small area of conductor. Some Stycast was deposited on top of the exposed conductor and covered with Kapton. An insulated wire was used to link the two heating stations. The repaired protection heater was subjected to a high-pot test and passed.

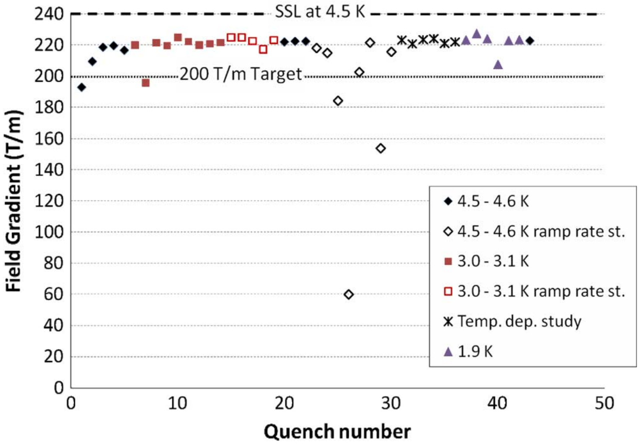

Fig. 4. LQS01b quench history. Different markers are used to show quenches at different ranges of bath temperature, and ramp rate studies. The short sample limit at 4.5 K and the field gradient target are also shown.

Some work is ongoing to try to avoid or minimize these bubbles. A possible solution is to reinforce the insulation by adding material on the inner surface of the coils. This solution has been implemented in LQ coil #13 where three materials (Nomex, ceramic cloth, and S2 glass) have been used to reinforce different sections.

Another possible solution is to install some protection heaters between the inner and the outer coil layer. However this solution requires a change of technology since the protection heaters should survive the reaction process at 650 degrees Celsius.

IV. LQS01b TEST RESULTS

A. *Modification of Ground Fault Detection*

The existing coil grounding and associated ground fault detection systems at VMTF were modified in order to improve magnet protection. The ground fault detection system was changed into an “active” system by implementing a 5V circuit connected in series with the ground current limiting resistor. It allows fault detection at any ramp rate, magnet inductance or current, and it makes the ground fault detection independent on the fault location.

In addition, symmetric grounding was implemented for the protection heaters. An active coil grounding system coupled with grounding of the protection heaters allows faults between the coil and heater to be detected even at zero current. These two modifications lower the risk of testing the long quadrupole with protection heaters on both the inner and outer coil layers.

B. *Test Results*

LQS01b quench history is shown in Fig. 4. The magnet training started at 4.5 K with a quench at 193 T/m (10.7 kA), and already in the second quench it reached 209 T/m exceeding the target field gradient of 200 T/m. In four quenches the magnet reached 220 T/m (12.45 kA). In order to reduce liquid helium consumption, training was continued at 3 K. The magnet performance at 3 K was slightly erratic with quench currents varying from 12.5 kA to 12.8 kA (220–225 T/m), and with a set back at 196 T/m.

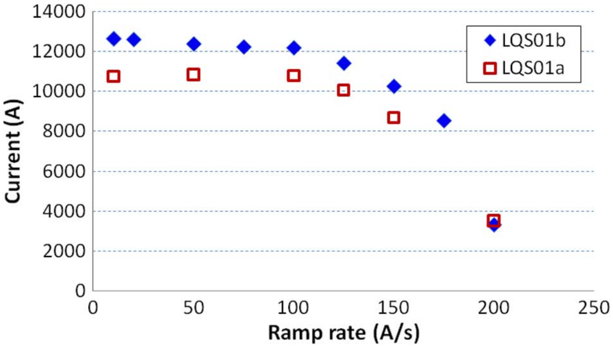

Fig. 5. LQS01a and LQS01b ramp rate dependence at 4.5 K.

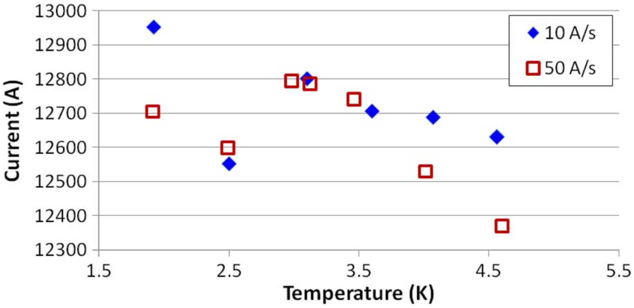

Fig. 6. Highest quench current in LQS01b at different temperatures and ramp rates.

Coils #6, #7 and #8 participated in the training at 4.5 K. All training quenches at 4.5 K started in the pole turn of the inner layer with the only exception being the third quench that started in a multi-turn segment of the outer layer of coil #8. At 3 K the first quenches occurred in the pole turn of the inner layer of coil #6, #8 (set back quench) and #9; and the last 5 quenches occurred in the same segment of coil #6 (inner layer, pole turn, central segment).

After ramp-rate studies at 3 K, LQS01b showed a plateau of 222 T/m (12.63 kA) at 4.5 K with all quenches starting in the straight section of coil #8 outer layer pole turn.

Toward the end of the test LQS01b reached 227.5 T/m (12.95 kA) in the second quench at 1.9 K. However it also showed another set-back at 208 T/m. All quenches at 1.9 K started in coil #9 from different segments (pole turn of inner or outer layer, or inner layer multi-turn midplane block).

LQS01a and LQS01b ramp rate dependence at 4.5 K is shown in Fig. 5. In LQS01b quenches at high ramp rates developed in the mid-plane blocks of coils #6 and #9. Low ramp rate quenches were located in the pole-turn segments of coil #8.

The temperature dependence at 10 and 50 A/s (maximum current at each temperature and ramp rate) is shown in Fig. 6. The shallow slope of the temperature dependence, the large variations of the quench current below 4.5 K, and the temperature-dependent location of the quenches below 4.5 K show that the limited stability of the conductor affected LQS01b performance below 4.5 K.

Magnetic measurements performed on LQS01a and LQS01b [17] showed differences of a few units, at 22.5 mm reference radius, between measured and calculated harmonics. These values are consistent with the TQ harmonics, with the exception of a 6-unit octupole that is under investigation. It could be caused by some differences between the fixtures used for LQ coil impregnation at BNL and FNAL. The differences between measured and computed harmonics are higher than in NbTi magnets. However it should be noted that neither the TQ models nor the LQS01 had alignment features during coil fabrication and magnet assembly. LARP has introduced these features in the HQ [18] that aims, among other goals, at assessing the field quality of $\mathrm{Nb_3Sn}$ magnets.

V. LONG QUADRUPOLE R&D PLANS

The next steps of the LQ plans include: (i) the demonstration of reproducibility by using four new coils made of 54/61 RRP conductor; (ii) the demonstration of better performance below 4.5 K by using coils made of 108/127 RRP conductor; (iii) the demonstration of short training and good memory; (iv) the demonstration of assembly procedures for 8 m long shell-based magnets by using 4 m long bladders and keys instead of the present 2 m long ones; (v) and the demonstration of a cable insulation suited for long $\mathrm{Nb_3Sn}$ coil production (instead of the present sleeve manually applied on the cable). Some R&D is needed to address the damage to heaters and insulation caused by the "bubbles" on the coil inner layer.

VI. CONCLUSION

LQS01 is the first long $\mathrm{Nb_3Sn}$ quadrupole ever built. It performed exceptionally well by reaching its target field gradient of 200 T/m during the first test, and by reproducing the performance of the best short model (TQS02c) made with the same conductor (RRP 54/61) during the second test. After the first test LQS01 was disassembled and reassembled with higher and more uniform pre-stress using the four original coils. Since three coils were repaired during fabrication LQS01 performance demonstrated that $\mathrm{Nb_3Sn}$ coil fabrication technology has reached the level where long coils can be successfully fabricated and repaired. It also showed that a segmented shell-based structure can be successfully used for long $\mathrm{Nb_3Sn}$ magnets, and that the quench protection tools used are adequate for protecting long $\mathrm{Nb_3Sn}$ magnets. The next steps of the Long Quadrupole R&D aim at completing the demonstration that there are no scale-up issues for the adoption of long $\mathrm{Nb_3Sn}$ magnets in particle accelerators.

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