# Progress in the Long $Nb_3Sn$ Quadrupole R&D by LARP

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***Abstract*—After the successful test of the first long $Nb_3Sn$ quadrupole (LQS01) the US LHC Accelerator Research Program (LARP, a collaboration of BNL, FNAL, LBNL and SLAC) is assessing training memory, reproducibility, and other accelerator quality features of long $Nb_3Sn$ quadrupole magnets. LQS01b (a reassembly of LQS01 with more uniform and higher pre-stress) was subjected to a full thermal cycle and reached the previous plateau of 222 T/m at 4.5 K in two quenches.**

**A new set of four coils, made of the same type of conductor used in LQS01 (RRP 54/61 by Oxford Superconducting Technology), was assembled in the LQS01 structure and tested at 4.5 K and lower temperatures. The new magnet (LQS02) reached the target gradient (200 T/m) only at 2.6 K and lower temperatures, at intermediate ramp rates. The preliminary test analysis, here reported, showed a higher instability in the limiting coil than in the other coils of LQS01 and LQS02.**

***Index Terms*—LARP, Long magnet, Nb3Sn, Superconductor stability, Superconducting magnet.**

## I. INTRODUCTION

BETWEEN the end of 2009 and the middle of 2010 LQS01 [1], the first 3.7 m long $Nb_3Sn$ quadrupole, reached its target gradient of 200 T/m, and its ultimate goal of 222 T/m at 4.6 K (reproducing the performance of the best short model made with the same conductor). Both milestones demonstrated the significant progress of LARP [2] (the US LHC Accelerator Research Program, collaboration of BNL, FNAL, LBNL and SLAC) toward its goal of demonstrating that $Nb_3Sn$ is a viable option for the luminosity upgrade of the LHC at CERN. LARP is presently advancing toward this goal along two R&D lines: (i) demonstrating training memory, reproducibility, and performance at 1.9 K with the Long Quadrupole models; (ii) demonstrating larger aperture, higher forces, and accelerator quality features with the HQ models [3]. All these features will be finally combined in a long magnet: the LHQ.

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The latest steps of the Long Quadrupole R&D have demonstrated good training memory with LQS01b second thermal cycle. On the contrary, an attempt to reproduce LQS01 performance with four new coils using the same RRP 54/61 conductor (Restack-Rod-Process with 54 $Nb_3Sn$ subelements by Oxford Superconducting Technology) showed limited performance.

## II. LQS01b 2ND THERMAL CYCLE

In order to assess the training memory after warm up, LQS01b was retested after a full thermal cycle. The magnet was warmed up to 300 K and subsequently cooled down to 4.6 K while maintaining a maximum top-bottom temperature difference of 100 K. The quench history (Fig. 1) shows that after a training quench at 208 T/m the magnet reached the same plateau of the first thermal cycle at 222 T/m. All quenches at plateau started in the pole turn of the outer layer of coil 8, as did the plateau quenches at the end of the first thermal cycle.

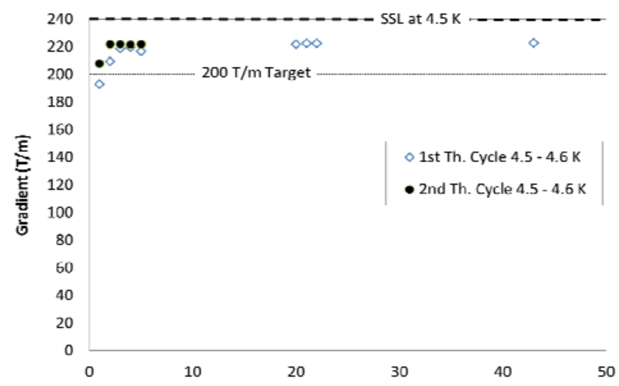


Fig. 1. Quench history of LQS01b 1st and 2nd thermal cycles. Only the quenches at 20 A/s ramp rate are presented.

## III. LQS02 COIL FABRICATION AND MAGNET ASSEMBLY

LQS02 had four new coils (10 - 13) fabricated at BNL and FNAL, and instrumented at LBNL. All coils were made with the same conductor and design of the LQS01 coils [1]. The only exception was coil 13. In this coil the insulation on the inner diameter (ID) was reinforced in order to try to prevent the partial de-bonding of the protection heaters seen in the

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LQS01 coils after test [1]. Additional material was added before impregnation to the coil ID. Three options were explored each one covering one third of the coil length: one layer of S2-glass 127 um thick; two layers of Nomex ® 51 um thick each; one layer of ceramic cloth 152 um thick.

The LQS02 Readiness Review found significantly fewer discrepancies in the LQS02 coils than in the LQS01 coils. Since coil 13 limited LQS02 performance only its discrepancies are reported: large variations of the cross-sections (+229/-99 μm peak to peak measured by a portable coordinate measuring machine) along the length; and a tin leak observed on a witness sample after the heat treatment of coil 12 (the cable of coils 12 and 13 came from the same spool).

Since the cross-sections are measured with the coil ID resting on a mandrel, the measurements on coil #13 may have been affected by the use of different materials on its ID. Further investigation of the strand and cable used for coils 12 and 13 did not find any issue.

LQS02 was assembled and preloaded at LBNL from February to April 2011. After an initial test with pressure sensitive films to verify the homogeneity of the contact pressure between coil and structure, bladder pressurization and axial piston actuation operations were executed. The aluminum shell was pre-tensioned to 56 ±8 MPa, a more conservative value compared to the 65 ±5 MPa reached in LQS01b, and the rods to 92 ±2 MPa. As a result, the pre-load measured by the strain gauges mounted on the pole was -69 ±27 MPa, compared to -115 ±25 MPa in LQS01b.

## IV. LQS02 Short Sample Limit

The short sample limit (ssl) of LQS02 was computed using the results of extracted strand tests. The samples were heat treated together with the respective coil in order to reproduce as close as possible the expected performance of each coil. Coil 13 samples showed a slightly lower average than the other coils and were used to compute the ssl. The same procedure used to compute the LQS01 ssl [4] was adopted and gave similar results: 13.8 kA at 4.6 K, generating a field gradient of 241 T/m. At this current the coil peak field is 12.3 T and is reached both in the straight sections of the pole turn of the inner layer, and in the ends of the pole turn of the outer layer.

Assuming an additional strain of -0.085% [4] the LQS02 ssl at 4.6 K is 13.35 kA.

## V. LQS02 Test Results

### *A. Quench History*

LQS02 was tested at FNAL Vertical Magnet Test Facility [5] from June 22 to August 19, 2011. The cooldown took about 7 days keeping a maximum top-bottom temperature difference of 150 K. The test was interrupted at the end of July for a week in order to allow unplanned cryo-plant maintenance. Liquid helium availability, and competing requests for other cold tests, limited the number of quenches to about a dozen per week. During cool-down, the shell and rod stress increased to 183 ±9 MPa and 235 ±10 MPa respectively. The coil's pole azimuthal compression reached -133 ±28 MPa, similar to the -130 ±30 MPa observed in LQS01b.

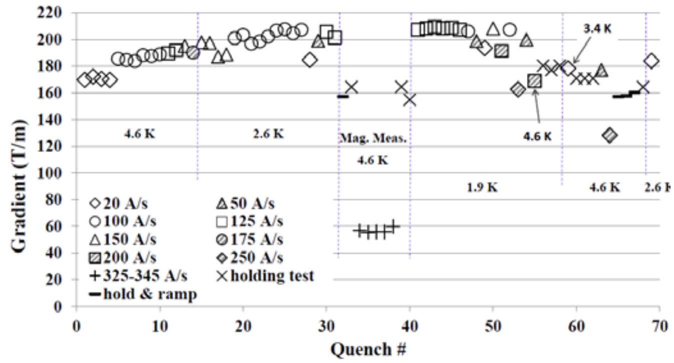


Fig. 2. Quench history of LQS02 showing bath temperature and current ramp rate.

LQS02 quench history is presented in Figs. 2 and 3.

The test started at 4.6 K bath temperature. The first four quenches, at 20 A/s, initiated in the same location (midplane block in the outer layer of coil 13) at approximately the same current (9340 - 9490 A range) without signs of training. When the ramp rate was increased to 100 A/s LQS02 started training with quenches in the pole turn of the inner layer (IL) of coil 10. Nonetheless at about 10.5 kA the quenches moved back to the outer layer (OL) of coil 13. At 125 A/s the quench current in the OL of coil 13 increased up to 10.7 kA. At 150 A/s the quench (10.9 kA) started in the IL of coil 10. At 175 A/s the quench (10.6 kA) started almost simultaneously in several coils and segments as in a typical high-ramp-rate quench.

The test continued at 2.6 K. The first four quenches, with a ramp rate of 150 A/s, occurred at current in the range 10.4 – 11.1 kA, possibly because of a combination of training, high ramp rate and small differences in the bath temperature. Six subsequent quenches at 100 A/s showed training in the pole turn of the inner layer of coils 10, 11 and 12, with quench current ($I_q$) from 11.0 to 11.7 kA. Nonetheless the following three quenches, still at 100 A/s, started in the OL of coil 13 (with $I_q$ from 11.5 to 11.7 kA). At 20 A/s the quench current decreased to 10.3 kA with the quench starting, as expected, in the OL of coil 13.

After a few quenches to complete the ramp rate dependence, and magnetic measurements at 4.6 K (reported in [6]), the test continued at 1.9 K. At this temperature the test started with 125 A/s ramp rate. In the first three quenches (all initiating in the pole turn of coil 10 IL) LQS02 trained from 11.7 to 11.8 kA, and reached the highest gradient during this test (209.3 T/m). In the following three quenches (with $I_q$ between 11.7 and 11.8 kA) at the same ramp rate the quench location moved from coil 11 to 12 and back to 11, always in IL pole turns. At 150 A/s and high ramp rates the magnet showed typical ramp rate dependence. At 20 A/s it quenched (10.8 kA) in coil 13 OL; at 50 A/s it quenched (11.2 kA) in coil 10 IL; and at 100 A/s it quenched (11.7 kA) the first time in coil 10 OL and the second time in coil 11 IL.

In the last part of the test, after magnetic measurements at 1.9 K, a series of special tests (combinations of constant ramp rates and constant currents) were performed. They are described in the following sections.

At the end of the test the residual resistivity ratio (RRR) was measured during magnet warm up. All segments had RRR larger than 200; and all segments in coil 13 OL showed RRR larger than 250.

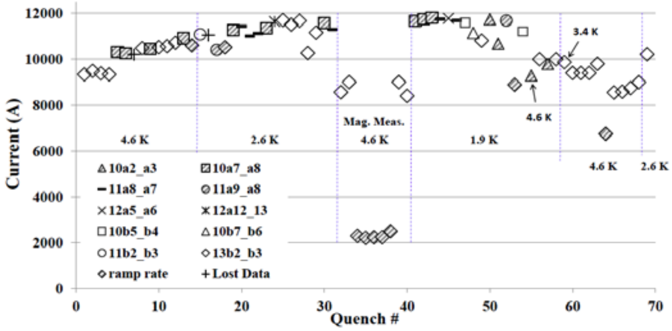


Fig. 3. Quench history of LQS02 showing the location of each quench start.

## B. *Ramp Rate and Temperature Dependence*

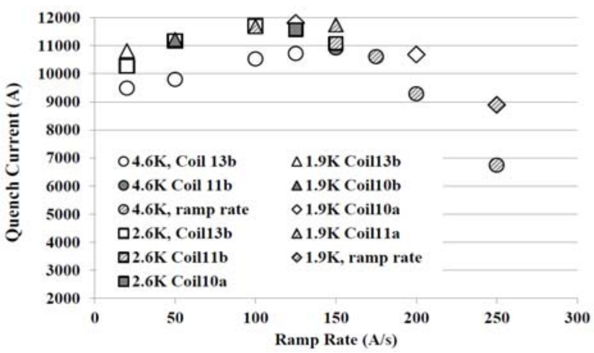


Fig. 4. Limiting coil (a = IL, b = OL) at different ramp rate and temperature.

Fig. 4 presents the ramp rate dependence of the quench current at different temperatures. The markers show the highest current reached at ramp rates where the magnet demonstrated training, or they show the average current where the magnet exhibited a plateau with some fluctuations (typically smaller than +/- 80 A).

Fig. 4 shows that coil 13 OL limited the magnet performance at low ramp rates (from 20 to 125 A/s at 4.6 K; below 100 A/s at 2.6 K; at 20 A/s at 1.9 K). The quenches starting in coil 13 showed "reverse ramp rate dependence" because the quench current increased with increasing ramp rate, contrary to the typical behavior (quench current decrease due to the temperature increase caused by eddy currents in the cable). Above 150 A/s the typical behavior was observed (i.e. quenches starting simultaneously in several coils and segments due to eddy currents). At 1.9 K the flattening of the ramp rate dependence in the 100 – 150 A/s range, with quenches in the pole turn of the inner layer of coils 10 and 11, indicated that the training was not completed. The analysis of the strain gauges showed a linear variation with $I^2$ in all but two gauges, where signs of insufficient pre-stress above 10.5 kA were recorded.

## C. *Quenches in Coil 13 Outer Layer*

All quenches in Coil 13 OL showed a similar pattern: they started simultaneously in several segments (always in B1_B2 and in B2_B3, sometimes also in B3_B4 and in B4_B5); at the beginning of the quench there was always a voltage spike, presumably triggered by a flux jump [7]. In quenches at low current the voltage spike could be seen in the voltage-tap signals (an example is in Fig. 5).

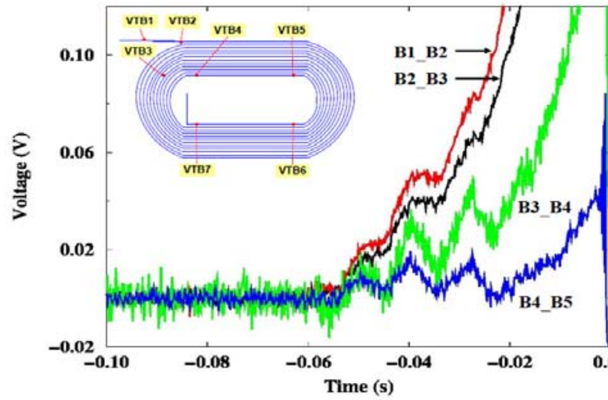


Fig. 5. Voltage growth in some segments of coil 13 OL. The inset shows the location of the voltage taps. Each segment is identified by its voltage tap pair. The voltage of segments B1_B2, B3_B4, and B4_B5 have been scaled respectively 5, 10, and 10 times. Note the three "bumps" occurring at the same time in all segments.

In quenches at higher currents the voltage spike could be seen only by the Voltage Spike Detection System (VSDS) [8]. The VSDS was used to record at high sampling rate (100 kHz) the voltage across one or two coils minus the voltage across the opposite coil(s). Fig. 6 shows a typical voltage spike at the start of a quench in coil 13 OL, and for comparison a typical voltage development when the quench started in the pole turn of an inner layer.

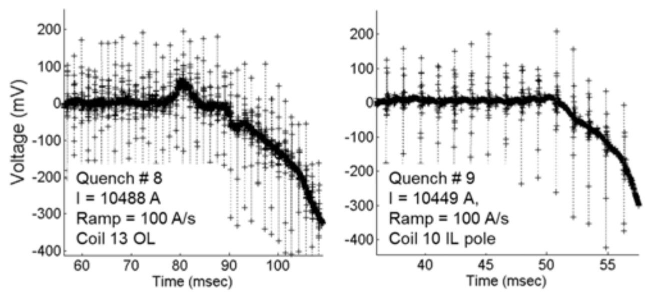


Fig. 6. VSDS signal at the start of a typical quench in coil 13 (left), and at the start of a typical training quench (right). Temperature was 4.6 K in both cases. In the plots there is a noise from the power supply with 720 Hz frequency. The actual signal is given by the thick lines.

## D. *Holding-Current Ramps and Model Comparison*

Several possible explanations of the limited performance of coil 13 have been evaluated. The two best models ("local heating", and "enhanced instability") are presented and discussed below.

According to the first model there was a source of heat above an unknown current threshold, close to the B2 voltage tap. The "reverse ramp rate dependence" is explained by the shorter time above the threshold at higher and higher ramp rates. The possibility of splice heating in the coil 13 OL was investigated by measuring the voltage across the B1 and B2 taps, at magnet currents from 0 to 8000A in 1000A steps. The same splice segment on coil 11 was simultaneously measured. The splice voltages were digitized integrating over 100 power line cycles, with 30 measurements recorded at each current setting. Although still somewhat noisy, least square fits to these data showed both splices to be reasonably good: 0.8±0.5

nΩ in coil 13, and 1.0±0.4 nΩ in coil 11.

According to the second model there was an unknown "issue" causing a decrease of the stability threshold [9] of the conductor in coil 13 OL. Possible issues are: a local damage or a non-uniform splice forcing more current in a few strands; a damage of some strands decreasing the local RRR and/or causing filaments merging. The "reverse ramp rate dependence" is explained by the larger heat generated during faster ramp rates, which decreases the critical current of the conductor and thereby increases its stability. This mechanism was demonstrated during the test of a single coil whose stability was increased by warming up the midplane of the outer layer [10]. The voltage spikes recorded at the start of each quench in coil 13 OL are caused by flux jumps and are the "signature" of this mechanism. The flux jumps can have extremely fast transverse propagation and 'coupling' of adjacent cables, as discussed in [9], which explain voltage taps data as the three "bumps" presented in Fig. 5.

A series of experiments at 4.6 K was performed in order to have a more clear understanding of the limitation in coil 13. In some of these experiments the current was increased up to 9.4 kA at 100 A/s and then held till a quench occurred (after 34, 60 and 57 s). In other experiments the current was held constant at 8 kA for up to 5 or 10 minutes and then raised to quench at 20 or 125 A/s. Fig. 7 shows these tests and the standard ramps to quench at 20 to 125 A/s. All ramps started with 200 A/s up to 3 kA.

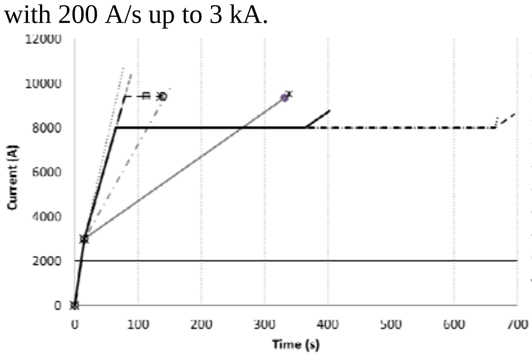


Fig. 7. Current vs. time in standard ramps to quench at constant rate, and in current holding tests. The quench occurred at the end of each line or where there is a marker (in case of tests repeated in the same conditions). All these tests were performed at 4.6 K.

The results presented in Fig. 7 do not support the "local heating" model. According to this model the time to quench should be the same under the same conditions, whereas there is a significant difference between the time spent at 9.4 kA in the first holding tests and in the second one. Using this model it is very difficult to explain why the magnet quenched at the same current despite very different final ramps (20 and 125 A/s) after holding the current at 8 kA. And it is also very difficult to correlate the results of the quenches at constant ramp rate with those of the holding quenches.

On the contrary all these results are consistent with the "enhanced instability" model assuming that the stability threshold in coil 13 OL (or part of it) is slightly above 8 kA. The results of the constant-ramp-rate quenches are explained by the warming up of the coil, which cools when the ramp is stopped and becomes unstable if the set current is above the effective stability threshold. The minimum stability threshold measured on witness samples of LQS02 coils was 800 A per strand. Therefore the issue triggering this mechanism should have raised the current of some strands by at least 2.6 times; or it decreased the stability of some strands by the same amount. The temperature dependence of the quenches at 20 A/s suggests that this issue may have similar temperature dependence (for instance it could be a local degradation). Nonetheless attempts to model it have not yet succeeded.

## VI. Plans

Five new coils using OST 108/127 RRP strand (with 108 $Nb_3Sn$ subelements) are in advanced state of fabrication and will be used in LQS03. The goal is to demonstrate that the 108/127 strand, which is more stable than the 54/61 strand (filament diameters are respectively 50 and 70 μm), allows more margin against issues similar to those that limited coil 13. The excellent performance of a 1-m model [11] fabricated with 108/127 RRP strands suggests this likely improvement in the performance of long coils.

LQS03 will also be used to test training memory after unrestricted warm-up and cool-down.

## VII. Conclusion

The first 3.7-m long $Nb_3Sn$ quadrupole has shown good training memory after a thermal cycle. An attempt to reproduce with a new set of coils the excellent performance at 4.6 K of the first model failed short of the goal. The data analysis has shown an enhanced instability of the conductor in one coil. The cause is presently unknown. A new set of coils using a more stable conductor is almost complete and will be used in the next model.

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