Test Results and Analysis of LQS03 Third Long Nb3Sn Quadrupole by LARP

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***Abstract*— With the first test of LQS03 the Long Quadrupole (LQ) R&D by LARP (the US LHC Accelerator Research Program, a collaboration of BNL, FNAL, LBNL, and SLAC) is approaching conclusion. LQS03 is the third 3.7 m long quadrupole, with 90 mm aperture, using a full new set of Nb_3Sn coils. The LQS03 coils were made using 108/127 RRP strand (with 108 Nb_3Sn sub-elements) produced by Oxford Superconducting Technology, whereas both previous models used 54/61 RRP strand (with 54 larger Nb_3Sn sub-elements).**

In this paper LQS03 test results are presented and discussed. The test results are also compared with the performances of the previous models. Observations are made for the future use of Nb_3Sn in accelerator magnets.

***Index Terms*—Accelerator magnet, long magnet, LHC upgrade, Nb3Sn, Quadrupole.**

I. Introduction

THE EXCELLENT performance of the Large Hadron Collider at CERN and the recent discovery of a new particle [1] warrant a luminosity upgrade in order to further increase the pioneering efforts. This upgrade is currently planned around 2022-23, when the present low-β quadrupoles [2] approach the end of their lifetime due to radiation exposure. The design for the luminosity upgrade is performed by the High Luminosity LHC design project [3] with contributions from all over the world. The US LARP program [4] (collaboration among BNL, FNAL, LBNL and SLAC) was started in 2003 aiming, among other goals, at developing the Nb_3Sn technology for upgrading the LHC low-β quadrupoles. Nb_3Sn, with its critical field and temperature higher than NbTi, allows fabricating quadrupoles with larger aperture and higher temperature margin than the present LHC low-β quadrupoles. The larger apertures will be used for optics allowing higher luminosity and for absorbers reducing the radiation damage on the coils [5].

A significant challenge for utilizing Nb_3Sn in accelerator magnets is posed by the typical length of these magnets. The present LHC low-β quadrupoles are 5-6 m long, whereas all development of Nb_3Sn magnets previous to 2003 was limited to one meter models. Long lengths and the strain sensitivity of Nb_3Sn pose significant challenges during coil fabrication (for example during heat treatment because of the different thermal expansions of the coil and the reaction fixture), and also during magnet assembly and operation. A few R&D programs started addressing the fabrication and test of single Nb_3Sn coils up to ~4 m: the LARP Long Racetrack [6] using flat racetrack coils, and the FNAL Long mirror [7] using shell-type coils.

TABLE I
MAIN PARAMETERS OF LQS03, LQS01 AND TQS03

Parameter	Unit	LQS03	LQS01	TQS03
Extr. strand Jc at 4.2K 12T†	A/mm^2	2660	2670	2790
Strand Cu %		55%	46%	54%
Witness samples RRR		70-150	>150	150-190
Gradient at ssl 4.6K/1.9K*	T/m	227/250	239/263	231/254
Current at sst 4.6K/1.9K*	kA	12.9/14.4	13.7/15.2	13/14.5
Stored energy at ssl 1.9K	kJ/m	506	562	522

†Critical current density in the non-copper computed taking self-field correction (0.54 T/kA) into account.

*Parameterizations and extrapolations to 4.6 and 1.9 K are based on [8].

The LARP Long Quadrupole (LQ) R&D is the first attempt to make long Nb_3Sn accelerator-type magnets by fabricating 3.7 m long quadrupoles with 90 mm aperture and with the target gradient of 200 T/m. The shell-type coils have two layers without interlayer splice and are assembled in a shell-type structure. The main features of the LQ design are presented in [9]. Three LQ tests have been performed so far. In its first test, LQS01a, reached 200 T/m. But the test was halted to improve the prestress. In the second assembly with the same coils at a higher prestress, LQS01b, reached 222 T/m at 4.6 K and 227 T/m at 1.9 K [10]. LQS01b reached the same performance as TQS02c [11] - the best performing 1 m model with the same cross-section design and conductor (RRP 54/61 by Oxford Superconducting Technology). A new set of coils with RRP 54/61 was used in LQS02 [12] – a magnet that

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exceeded 200 T/m at 1.9 K only at intermediate ramp rates (50-150 A/s). Test data analysis showed that one coil was limiting LQS02 performance by a mechanism understood as "enhanced instability" [12]. The latest assembly, LQS03, has 4 new coils with RRP 108/127. The main features and test results of LQS03 are presented in this paper.

II. LQS03 Design and Fabrication

The main difference between LQS03 and previous LQs was the conductor used: RRP 108/127 by OST with 108 Nb_3Sn sub-elements out of 127. Conductor and magnet parameters are presented in Table 1, together with the parameters of LQS01b and TQS03 [13] (1 m model with same cross section and conductor) for comparison. The table shows that LQS03 had current and gradient at short sample limit (ssl) lower than in LQS01 because of the higher copper content of the conductor with respect to LQS01 conductor. Table 1 also shows that the LQS03 conductor had RRR significantly lower than the conductor used in TQS03 although they had the same architecture.

Five new coils (#15-19) were manufactured for LQS03 using the same design parameters and following the same manufacturing procedures as previous LQs [9]. The LQS03 readiness review decided not to use coil #19 because it had been epoxy impregnated two times since the first attempt left a dry volume at the lead end (close to the epoxy exit). The cause of this issue was found to be high viscosity due to "old" epoxy and can be easily prevented in future coils by avoiding long term storage of epoxy. CMM (coordinate-measuring machine) measurements of coil #18 showed deviations from the nominal size up to 0.16 mm whereas typical values are lower than 0.1 mm. All other LQS03 coils did not show any significant discrepancies.

LQ coils were reacted and potted at BNL and FNAL. Therefore, coils #15 and #19 were potted with one mold and coils #16 and #18 were potted with a different mold. In LQS01 and LQS02 assemblies, coils potted in the same mold were facing each other. In LQS03, they are side by side. Comparison of magnetic measurements is in progress to determine if using coils made from different molds can affect field quality.

LQS03 had the same target preload as LQS02 and used slightly smaller shims between the coils and the pads. Further details about the mechanical behavior are presented in Section IV.

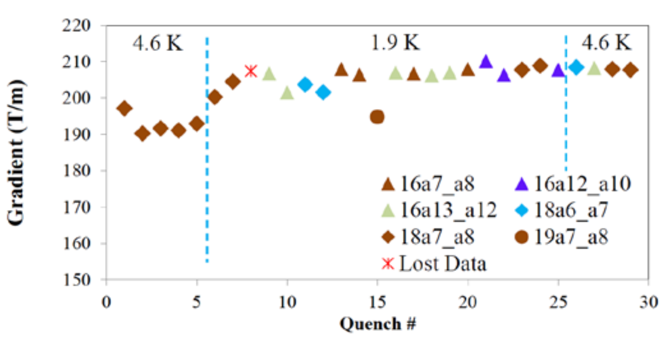

Fig. 1. LQS03 training history. All training quenches were performed ramping the current at 50 A/s up to 9 kA and 20 A/s up to quench. Markers show the segment where each quench initiated. The first number shows the coil, the following letters and numbers show the voltage tap pair. All segments in this list were on the straight section of the pole turn of an inner layer. Segments a7_a8 and a12_a10 were significantly longer than the others.

III. Test Results

LQS03 was tested at FNAL's Vertical Magnet Test Facility [14] at temperatures ranging from 1.9 to 4.7 K. During the cooldown the temperature gradient from top to bottom was kept below 100 K in order to avoid possible excessive stresses. A thermal cycle without these constrains on the temperature gradient is in the plans.

Magnet training (Fig. 1) was performed with current ramp rate to quench of 20 A/s. In order to save time the first part of the current ramp, up to 9 kA, was done at 50 A/s. In the first quench at 4.6 K, LQS03 reached 197 T/m (I = 11.05 kA; 86% of ssl). The gradient decreased to 190 T/m in the second quench and by the fifth quench it had recovered only up to 193 T/m. All these quenches initiated from the same pole turn segment in the straight section of the inner layer of coil #18. This is a long segment and a quench antenna showed that the quench start location changed from quench to quench in a random manner.

Because of the large amount of energy released into the helium bath, the recovery time was close to two hours after each quench. The number of quenches per day was also limited by the liquid helium availability. It was, therefore, decided to continue the training at 1.9 K – after a minimum number of training quenches at 4.6 K. At the lower temperature, LQS03 slightly exceeded 200 T/m at the first quench (I = 11.25 kA; 78% of ssl) and reached 207 T/m by the third quench. In the following quenches the gradient decreased a few times to 201 T/m and once to 195 T/m. Subsequently it reached 210 T/m and then remained in the range of 207 - 209 T/m.

The first two quenches at 1.9 K started from the same coil (#18) and segment were all 4.6 K quenches initiated. The following 14 quenches started in other coils (#16 and #19) and in other segments always at the pole turn of the inner layer. In the last few ramps at 20 A/s the quench onset returned to the segment in coil #18, which started the training at 4.6 K. When the temperature was increased back to 4.6 K, LQS03 showed a plateau at about 208 T/m with quenches starting mostly in coil #18 and once in coil #16.

The ramp-rate dependence, measured at 1.9 K and subsequently at 4.6 K, is shown in Fig 2. The temperature dependence of current ramps at 20 and 150 A/s is shown in Fig. 3. It can be readily seen that the magnet was current-limited in the range 11.5 – 11.8 kA (205-209 T/m). All quenches in this current range started in the inner-layer pole turn of coils #18 or #16. All quenches at high ramp rate with quench current under this plateau started in the mid-plane block of coil #19 - the coil with the highest eddy current losses. It should be noted that the superconducting cables used in LQS03 did not have a stainless steel core. Therefore, the inter-strand contact resistance could be very low and with large variations from coil to coil.

The ramp-rate and temperature dependence studies show that LQS03 was not conductor limited. Therefore, although current limited, LQS03 had a significant temperature margin at the nominal current of 11.2 kA (corresponding to 200 T/m field gradient) and at the temperature of 1.9 K. The temperature margin was demonstrated by holding the nominal current at 4.6 K for more than 40 minutes with no quench. Also the current ramp at 100 A/s at 4.6 K, with quench current above the operating current, demonstrated a temperature margin of about 3 K at the pole turn (where the peak field was located).

Analysis of quench onset through voltage tap signals (each segment) and fast acquisition system (two coils bucked against two other coils) did not show any sign of quench precursors.

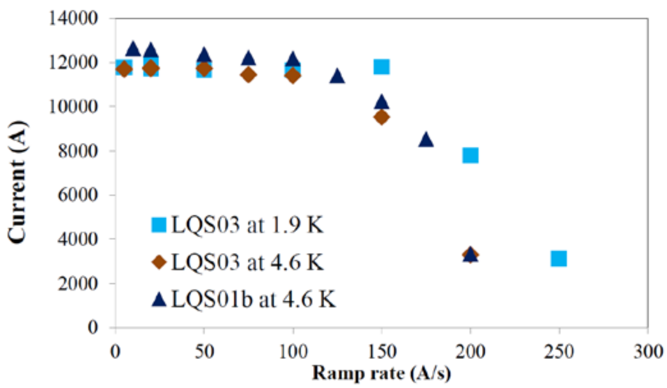

Fig. 2. LQS03 ramp rate dependence at 1.9 and 4.6 K compared with LQS01 ramp rate dependence at 4.6 K. LQS03 data show that the magnet was current limited slightly below 12 kA.

IV. Mechanical Behavior

LQS03 was assembled at LBNL from March to May 2012. Based on FEM analysis and the experience gained with the assemblies and cool-down of LQS01a, LQS01b and LQS02 [12, 15-16], the assembly targets were conservatively chosen to avoid pole piece to coil separation up to a gradient of 230-240 T/m. As described in [16], particular attention was paid to the coil to structure interface. A test with pressure sensitive paper between coils and pads was performed during coil-pack assembly. Based on the results, the radial G10 shim was reduced from 380 to 250 μm to improve the matching between the two surfaces. Like the previous LQ magnets, aluminum shell, stainless steel rods and titanium-alloy pole pieces were instrumented with strain gauges [15-16], which were monitored from assembly to excitation. Each coil pole piece was instrumented with four stations distributed longitudinally. Each station measured the strain in the azimuthal and axial directions.

After the coil-pack insertion in the yoke-shell sub-assembly, the azimuthal preload was applied by mean of bladders and keys. The shell stress reached 57 +/- 8 MPa azimuthally and the coil pole pieces strain gauges showed an azimuthal compressive stress of 78 +/- 21 MPa. Lastly, the axial preload was applied but final electrical qualification tests exposed a short between two voltage taps in coil #19, close to the extremity of the magnet. This short was found to be axial load dependent. It led to the axial unloading of the magnet and inspection of the area. After removal of the end-plate, a misplaced wire was found crushed against the coil end-shoe. It was repaired and the magnet reloaded axially.

After cool-down, the stress in the shell reached 157 +/- 8 MPa and 235 +/- 8 MPa in the rods which is in agreement with previous assemblies [16] and FEM analysis. However, some of the coil pole strain gauges showed unexpected behavior. 13 strain gauges (8 azimuthal and 5 axial) out of 32 went suddenly from compression (in the case of the azimuthal strain gauges) or from slight tension (in the case of the axial gauges) to strong tensile strain (ranging from 500 to 3000 με). This change of strain does not seem to be correlated with temperature. In addition, this sudden increase of strain seems to affect the strain gauges randomly with no consistency between axial and azimuthal strain gauges of a given station. This lack of correlation points toward a potential issue with the temperature compensator or wiring in the magnet or in the test facility. More analysis and investigation are required to completely rule out the possibility of a real mechanical issue. Warm-up measurements should provide additional information.

Finally, despite what looks like wrongful strain gauges readings, all the coil strain gauges reacted to the magnet excitation showing linear decrease of compression as a function of the square of the current. The rate of unloading was consistent with model prediction. Signs of coil pole separation starting around 10.6 kA were seen in one of the stations of coil 16 only.

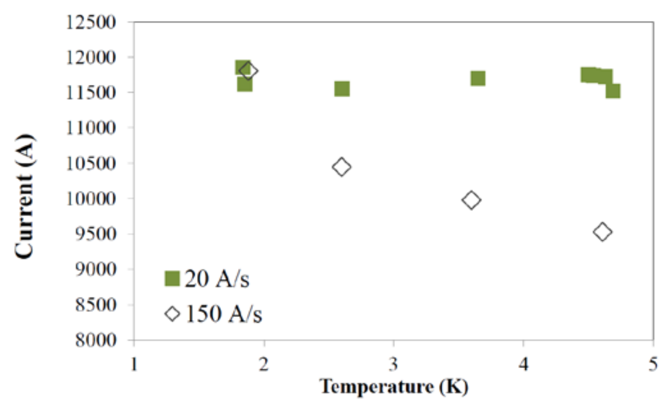

Fig. 3. LQS03 temperature dependence of current ramps to quench at 20 and 150 A/s. The two points at 1.9 K and the cluster of points at 4.6-4.7 K show the range of variation of the quench current after training. Data show that at low ramp rate the magnet was quenching independently of the temperature at current in the range 11.5-11.8 kA.

V. Magnetic Measurements

Magnetic measurements were performed with two probes of different length: an 82-cm-long tangential coil probe, and a 10-cm-long tangential coil probe, both 39 mm in diameter.

A z-scan was performed at room temperature with the 10-cm probe at 5 A, whereas both probes were used at 4.6 K for z-scan at 12.3, 100 and 185 T/m.

Additional measurements were performed at 4.6 K:

accelerator profile cycles to study multipole reproducibility, current loop measurements to study eddy current effects, and stair-step measurements to verify static behavior.

A preliminary analysis of some measurements has shown that the effects of interstrand coupling currents are consistent with crossover contact resistance in the range 0.5-1.0 $\mu\Omega$.

Most other data are still being studied and analyzed. Simulation studies to compare harmonics between LQS03 and previous LQ magnets are in progress.

VI. Analysis

After a short training with some fallbacks at 1.9K LQS03 was current limited in the range 11.5 – 11.8 kA independently of the temperature. This behavior suggests a mechanical issue, although the quench start location (in different segments of two coils) indicates that this was not a localized issue. A strain gauge on a coil pole showed signs of unloading at the current (10.6 kA) at which most 4.6 K training occurred (quenches #2-5). Coil strain gauges were located only in four sections along the coils and it is likely that the coils were experiencing unloading in other sections at similar and higher currents. Therefore the mechanism triggering the limiting quenches may be epoxy cracks and/or conductor displacements caused by the beginning of pole unloading. FEM analysis has shown that the unloading at the coil-pole interface starts from the coil inner surface, which may be the quench onset location. However this explanation is not complete: in fact TQS03 [13], which had a design and conductor similar to those used in LQS03, showed signs of significantly more unloading and was nonetheless trained above 235 T/m at 1.9 K. The comparison between TQS03 and LQS03 (Table 1) suggests a possible explanation: LQS03 witness samples showed significantly lower RRR and larger variations that TQS03 samples. Measurement of the RRR around the kinks of an extracted strand has shown further reduction down to 50. The reduction of the Minimum Quench Energy caused by the low RRR in some LQS03 spots and the possible further reduction caused by the self-field instability [17] may have made LQS03 more sensitive to smaller disturbances than TQS03.

In order to better understand the limitation cause(s) and possibly improve quench performances, a preload adjustment and magnet retest are considered in the near future.

VII. Conclusions

LQS03, the third LARP Long Quadrupole, reached its target gradient (200 T/m) in the first ramp to quench at 1.9 K. Although it was limited at a few percent above the target operating current, it demonstrated a significant temperature margin by exceeding 200 T/m at 4.6 K in ramps to quench up to 100 A/s.

The cause of the current limitation is under investigation and a preload adjustment and retest are in the plans.

LQS03 was assembled with four new coils made with RRP 108/127 Nb_3Sn conductor, whereas the previous LQs used RRP 54/61. In retrospect, LQS01 exceed the target gradient at 1.9 K by 13% and LQS02 exceeded 200 T/m only in ramps to quench at intermediate rates because of a limitation in one coil. All-in-all, the Long Quadrupole magnet series has shown that three out of three magnets were able to reach the target gradient, and that only one limiting coil out of twelve was encountered.

Although this record is not perfect it is a promising step toward the design and fabrication of long Nb_3Sn quadrupoles for the luminosity upgrade of the LHC at CERN.

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References

[1] The ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC” Phys.Lett. B716 (2012) 1-29.
The CMS Collaboration “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC” .Lett. B716 (2012) 30-61.

[2] S. Feher, et al., “Production and Installation of the LHC Low-β Triplets” *IEEE Trans. on Applied Supercond*., vol.16, no.2, pp. 437-440, 2006.

[3] L. Rossi, “LHC Upgrade Plans: Options and Strategy,” *Proceedings of IPAC2011*, San Sebastin, Spain.

[4] G.L. Sabbi “Development of Long Nb3Sn Quadrupoles by the US LHC Accelerator Research Program” *Proceedings of 2011 Particle Accelerator Conference*, New York, NY, USA, pp. 1455-1459.

[5] E. Todesco, et al., “Design Studies for the Low-Beta Quedrupoles for the LHC Luminosity Upgrade”, this conference.

[6] J.F. Muratore, et al., “Test Results of LARP 3.6 m Nb3Sn Racetrack Coils Supported by Full-Length and Segmented Shell Structures” vol.19, no.3, pp. 1212-1216, June 2009.

[7] G. Chlachidze, et al., “Quench Performance of a 4-m Long Nb3Sn Shell-type Dipole Coil”, *IEEE Trans. on Applied Supercond*., vol.19, no.3, pp. 1217-1220, June 2009.

[8] A. Godeke, B. ten Haken, H.H.J. ten Kate, and D.C. Larbalestier, Supercond. Sci. Techn. 19, R100-R116 (2006).

[9] G. Ambrosio, et al., “Long Quadrupole Design Report”, LARP report available at: https://dms.uslarp.org/MagnetRD/longquad/LQ_DR.pdf

[10] G. Ambrosio et al. “Test Results of the First 3.7 m Long Nb3Sn Quadrupole by LARP and Future Plans” *IEEE Trans. on Applied Supercond.*, Vol. 21, no. 3, pp. 1058-1062, June 2011.

[11] S. Caspi, *et al.*, “Test results of LARP Nb_3Sn quadrupole magnets using a shell-based support structure (TQS)” *IEEE Trans. Appl. Supercond.* vol.19, no.3, pp. 1221-1225, June 2009.

[12] G. Ambrosio et al., “Progress in the Long Quadrupole R&D by LARP”, *IEEE Trans. Appl. Supercond.*, vol. 22, No. 3, June 2012.

[13] H. Felice, et al., “Test Results of TQS03: a LARP Shell-Based Nb3Sn Quadrupole using 108/127 Conductor” 2010 *J. Phys.: Conf. Ser.* **234** 032010.

[14] M.J. Lamm, et al., “A New Facility to Test Superconducting Accelerator Magnets” *Proceedings of PAC97*, pp 3395-3397.

[15] P. Ferracin *et al.*, “Assembly and Loading of LQS01, a Shell-Based 3.7 m Long Nb_3Sn Quadrupole Magnet for LARP”, ,” *IEEE Trans. Appl. Supercond.*, vol. 20, No. 3, June 2010.

[16] P. Ferracin *et al*., “Mechanical Performance of the LARP Nb3Sn Quadrupole Magnet LQS01”, *IEEE Trans. Appl. Supercond.*, vol. 21, No. 3, June 2011.

[17] E. Takala, B. Bordini, L. Rossi, “Perturbation Sensitivity of the Magneto-Thermal Instability” *IEEE Trans. Appl. Supercond.*, accepted (2012), DOI: 10.1109/TASC. 2012.2217492.

[18] Caspi S *et al* 2009 Test results of LARP Nb_3Sn quadrupole magnets using a shell-based support structure (TQS) *IEEE Trans. Appl. Supercond.* **19** (3) 1221