Field Quality Study of the LARP Nb_3Sn 3.7m-long Quadrupole Models of LQ series

G.V. Velev, G. Ambrosio, N. Andreev, M. Anerella, R. Bossert, S. Caspi, G. Chlachidze, J. DiMarco, J. Escallier, H. Felice, P. Ferracin, V.V. Kashikhin, M.J. Lamm, F. Nobrega, E. Prebys , G.L. Sabbi, J. Schmalzle, C. Sylvester, M. Tartaglia, P. Wanderer, A.V. Zlobin

***Abstract*—After the successful test of the first long Nb_3Sn quadrupole magnet (LQS01), the US LHC Accelerator Research Program (LARP) has assembled and tested a new 3.7 m-long Nb_3Sn quadrupole (LQS02). This magnet has four new coils made of the same conductor as LQS01 coils, and it is using the same support structure. LQS02 was tested at the Fermilab Vertical Magnet Test Facility with the main goal to confirm that the long models can achieve field gradient above 200 T/m, LARP target for 90-mm aperture, as well as to measure the field quality. These long models lack some alignment features and it is important to study the field harmonics. Previous field quality measurements of LQS01 showed higher than expected differences between measured and calculated harmonics compared to the short models (TQS) assembled in a similar structure. These differences could be explained by the use of two different impregnation fixtures during coil fabrication. In this paper, we present a comparison of the field quality measurements between LQS01 and LQS02 as well as a comparison with the short TQS models. If the result supports the coil fabrication hypothesis, another LQS assembly with all coils fabricated in the same fixture will be produced for understanding the cause of the discrepancy between short and long models.**

***Index Terms*— Magnetic Field Measurement, Superconducting accelerator magnets.**

I. INTRODUCTION

For the past several years, a collaboration of four US National Laboratories, BNL, FNAL, LBNL and SLAC, has been performing a research program on developing Nb_3Sn superconducting quadrupoles for LHC [1]. This effort is a part of the US-LHC Accelerator Upgrade Program, LARP. The main goal of this collaboration is to prove that Nb_3Sn magnets are a feasible alternative for substitution of the interaction region (IR) quadrupoles in a future LHC high luminosity upgrade.

The research program on developing Nb_3Sn quadrupoles was executed in several steps. In an earlier step, two 1-m long Nb_3Sn quadrupole models (so-called technology quadrupoles, TQC and TQS with 90 mm aperture) assembled with the same type of coils in different supporting structures were built and tested. Elsewhere [2]-[5], one can find detailed information about the designs, production, quench performance and field quality measurements of the TQ magnets.

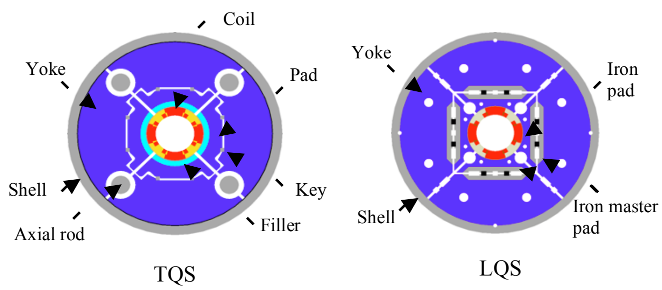

Fig. 1. Cross section view of the TQS (left) and LQS (right) quadrupoles.

As a following step, for the first time, a 3.7 m-long Nb_3Sn quadrupole (LQS01) with a shell-based segmented mechanical structure was built and tested. The comparison between TQS and LQS cross-sections is shown in Fig.1. LQS01 quadrupole performed extremely well during the quench tests, and magnetic field quality measurements were taken with two different coil pre-stresses. More information about the LQS01 production and testing is presented elsewhere [6]-[8].

For LQS01, the field analysis [8] showed somehow higher than expected discrepancy between modeled and measured field harmonics. The next logical step was to build a second long quadrupole, LQS02. In this paper, we present the results of LQS02 magnetic measurements. Room temperature measurements were performed at yoked assembly prior to cooling down. They were followed by sets of magnetic measurements during cold testing of the magnet. The results are compared with the LQS01 and TQS measurements and prediction from the magnetic field calculations.

II. Magnetic Field Measurements

All results in this paper are expressed in terms of harmonic coefficients defined in a series expansion given by

$$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0} \right)^{n-1} \quad (1)$$

where B_x and B_y in (1) are the field components in Cartesian coordinates, b_n and a_n are the 2n-pole normal and skew

Manuscript received 12 September 2011. This work was supported by the U.S. Department of Energy.

G. Ambrosio, N. Andreev, R. Bossert, G. Chlachidze, J. DiMarco, V.V. Kashikhin, M.J. Lamm, F. Nobrega, E. Prebys, C. Sylvester, M. Tartaglia, G.V. Velev, A.V. Zlobin are with Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA, (e-mail: velev@fnal.gov).

S. Caspi, H. Felice, P. Ferracin, G.I. Sabbi are with the Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.

M. Anerella, J. Escallier, J. Schmalzle, P. Wanderer are with the Brookhaven National Laboratory, P.O. Box 5000, Upton, NY 11973, USA.

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

coefficients at the reference radius r_0 =22.5 mm. For additional details on the measurement, one should look at Ref. [9].

A. *Room temperature Measurements*

Full-length warm measurements were made on LQS quadrupoles with the magnets positioned horizontally. A 0.485 m-long, 59 mm diameter rotating coil was used for these tests. The probe, known as the "Ferret", is a self-contained coil and encoder system, positioned manually using tethers connected to the probe. The Ferret measurement coil consists of wire traces on a printed circuit board (PCB), and incorporates bucked radial coils to suppress dipole and quadrupole components. Amplifiers are available on-board the PCB for both bucked and un-bucked channels, with gain of 1000 for the dipole-quadrupole-bucked signal. The probe rotation is driven externally via a non-magnetic flexible shaft. Measurements were performed at ±10A, and the data combined at each position to remove the effects of remnant fields.

The analysis of the warm z-scan data pointed to a relatively large variation of the geometric harmonics in the body of the magnets. This effect was confirmed by the cold z-scans, at different currents, and points into the direction of the need for alignment features in these magnets.

B. *Cold Measurements*

Similarly to LQS01 and TQS quadrupoles, the LQS02 magnetic measurements were completed at the Fermilab Vertical Magnet Test Facility. LQS02 tests were performed at 1.9 K and 4.5 K. Most of the measurements presented in the paper are taken at 4.5 K. For the cold tests, we utilized two tangential-type rotating coil probes with a similar geometry and different lengths of approximately 0.1 m and 0.8 m. TQ model magnets were measured with 0.1 m-length probe, while LQS measurements were performed with both probes. Due to the restriction in the length of the measurement shaft, we could perform z-scan tests only on the half body of the LQS magnets.

The transfer function (TF) for LQS and TQS magnets versus the excitation current is shown in Fig. 2. The plotted results are obtained from the current loops executed with an acceleration of 20 A/s. As expected, LQS02 shows a similar pattern compared to LQS01 and TQS magnets, which is determined in part by the common design and in part by the iron characteristics. Like LQS01, LQS02 coils are manufactured with the same RRP 54/61 conductor (Restack-Rod-Process with 54 Nb_3Sn subelements). Therefore, we observed similar to LQS01 low ramp rate and low current conductor instability [9], which prevented us from executing current excitation loops bellow 3.5 kA.

Table I summarizes the average geometric harmonics in the TQS and LQS magnets at 45 T/m. At this gradient the magnetic field fully penetrates the superconductor cable and it is still below the iron saturation. Therefore, the measurements are not affected by these phenomena and it makes possible to compare them with a simplified field modeling. For these magnets, even though achieving an accelerator quality field was not a primary program goal, one can see that harmonics are in a good agreement with calculated ones [10] except for the LQS02 sextupole and LQS01 octopole which deviates by 14 and 6.2 units respectively.

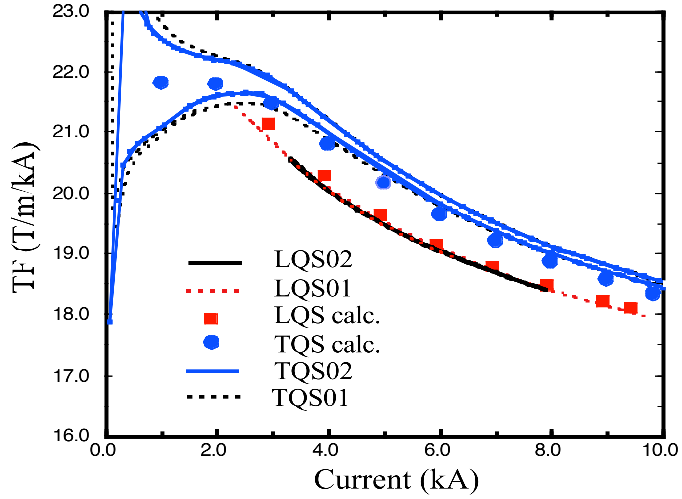

Fig. 2. Transfer functions for the magnets versus the excitation current. The filled dots represent the calculations for TQS and LQS respectively. For comparison, the TQC02 TF is plotted too (dashed line).

TABLE 1 CALCULATED AND MEASURED TQS AND LQS HARMONICS

b_n a_n	TQS			LQS		
	calc.	measured		calc.	Measured	
		01	02		01	02
b_3	-	-1.46	2.98	-	3.43	-14.0
b_4	-	-0.52	1.31	-	6.20	2.64
b_5	-	3.06	-1.45	-	-0.16	-3.16
b_6	5.00	5.40	6.23	8.45	10.43	8.44
b_7	-	0.07	0.05	-	-0.10	0.54
b_8	-	-0.11	-0.13	-	-0.58	-1.28
b_9	-	0.02	0.10	-	-0.14	-0.13
b_{10}	0.04	0.02	-0.05	-0.03	-0.32	-1.13
a_3	-	4.41	0.66	-	2.11	-0.74
a_4	-	-1.99	0.82	-	1.34	0.68
a_5	-	0.71	-1.50	-	0.48	0.48
a_6	-	-0.37	0.12	-	-0.37	0.06
a_7	-	-0.11	-0.01	-	-0.30	0.61
a_8	-	-0.18	-0.10	-	-0.09	0.35
a_9	-	-0.02	0.02	-	-0.55	-1.68
a_{10}	-	0.00	-0.08	-	0.24	0.31

The average harmonics measured at a current ramp up for LQS and TQS models are compared in Table II. These measurements are taken in the magnet bodies at 12.3 T/m (LHC injection field), 100 T/m (nominal comparison point, established in the NbTi LHC program) and at highest possible stable currents for the particular magnet, close to the LHC IR quadrupole collision field. The averaging uncertainties for the low order harmonics (up to b_6 and a_6) are in the order of 0.1 units while for the higher order harmonics they are in the order of 0.15 units. It should be noted that neither the LQS nor the TQS models have alignment features for the coil fabrication and assembly. Therefore deviations of the field harmonics in the order of several units from the nominal values should be expected.

TABLE 2 TQ AND LQS HARMONICS AT 12.3 T/M, 100 T/M AND 200 T/M

b_n / a_n	TQS01-02 average			LQS01-02 average		
	12.3 T/m	100 T/m	200 T/m	12.3 T/m	100 T/m	200* T/m
b_3	0.73	0.01	0.06	-0.56	-5.55	-5.42
b_4	-1.76	0.27	0.21	5.95	4.65	4.71
b_5	-0.88	1.57	0.39	-0.53	-1.52	-1.75
b_6	-11.83	3.83	1.58	-29.64	10.07	8.34
b_7	0.06	0.06	0.02	0.92	0.16	0.12
b_8	0.04	0.00	0.01	-0.22	-0.82	-0.55
b_9	0.03	0.02	0.00	0.04	0.10	0.09
b_{10}	0.12	0.03	0.00	0.22	0.23	-0.46
a_3	0.97	1.94	0.66	-1.80	2.80	2.81
a_4	-3.70	-0.39	0.82	2.05	0.58	0.53
a_5	-0.24	0.30	-1.50	-2.11	-0.21	-0.36
a_6	0.13	-0.18	0.12	-0.59	0.08	-0.04
a_7	-0.06	-0.09	-0.01	0.60	0.26	0.32
a_8	0.03	-0.10	-0.10	-0.07	0.14	0.11
a_9	-0.01	-0.01	0.02	-0.26	-0.95	-0.33
a_{10}	0.00	-0.00	-0.08	0.10	0.37	0.15

*Measurements are performed at the maximum stable current for the corresponding magnets.

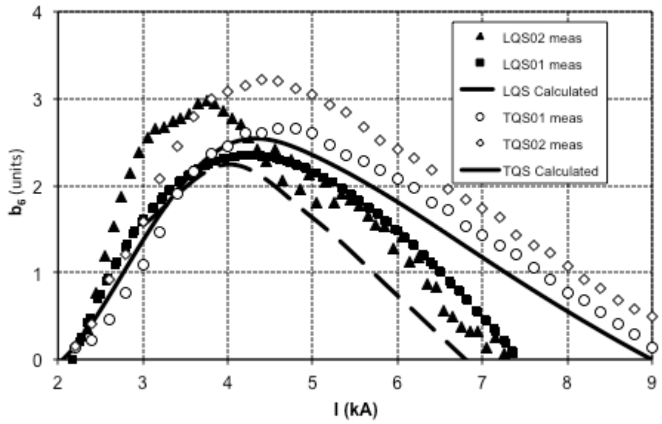

Fig. 3 Iron saturation effect in TQS and LQS magnets.

C. Iron saturation effect

We estimated the iron saturation effect as an average value between up and down ramps of the measured hysteresis dodecapole loops at 20 A/s. Fig.3 shows the calculated and measured iron saturation effect in b_6 for TQS and LQS magnets. As expected, LQS02 has a similar iron saturation behavior comparing to LQS01. For both series, the maximum observed dodecapole deviations from the simulated values are in the order of 1.5 units in LQS magnets and 1 unit in TQS in current range from 2 kA to 9 kA. As was discussed in Refs. [6]-[8] and [11], the larger saturation effect in these magnets is due to the iron pads placed next to the coils. If necessary, several methods to correct this saturation effect can be applied, for example: introducing holes into appropriate places in iron pads and/or yoke, or by substituting the iron pads with stainless ones.

D. Eddy current effect

The next standard test is to look for the Eddy current effect in the magnets. LQS02 was tested in the same way executing excitation loops with ramp rates of 20, 40 and 80A/s. Due to low ramp rate and low current conductor instability we were forced to start the current loops from 3.5 kA. The result from the measurements is shown in Fig. 4. The dots represent the "stair step", low ramp current profile measurement where the duration at every current step was set at 120 s. For comparison, the inset shows the same current loops measurements for LQS01. As expected, both magnets showed practically the same dodecapole geometric value and hysteresis widths. Based on the presented results, one can conclude that LQS magnets have relatively large Eddy current effect due to the large interstrand coupling currents.

The LQS01, LQS02 and TQS02 magnets have been built with the same type of coils and have been produced from the

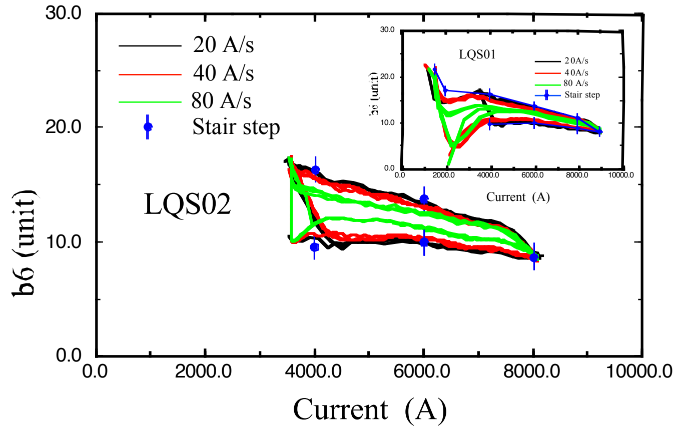

Fig. 4 LQS02 current loops executed at ramp rate of 20 A/s, 40 A/s and 80 A/s. The points represent the "stair step" measurement described in the text. For comparison, the inset shows the same measurements for LQS01.

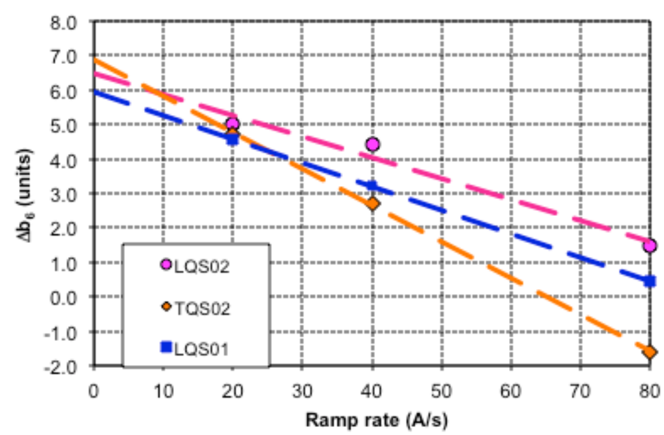

Fig. 5 Dodecapole loop width as function of the ramp rate.

same RRP conductor. Thus, for these magnets we expect similar coil magnetization effects and as consequence similar dodecapole loop widths. The b_6 width dependence on the current ramp rate is shown in Fig. 5. As expected, LQS and TQS02 show the same behavior and the extrapolation of Δb_6 to zero ramp rate confirms the large coil magnetization effect.

A. Long-term Dynamic Effects: decay and snap-back

Long-term dynamic effects, like the field decay in the superconducting magnets at a constant current, play an important role in the operation of the modern accelerators. For example, the LHC superconducting magnets, including the IR quadrupoles, need to have a constant magnetic field during the

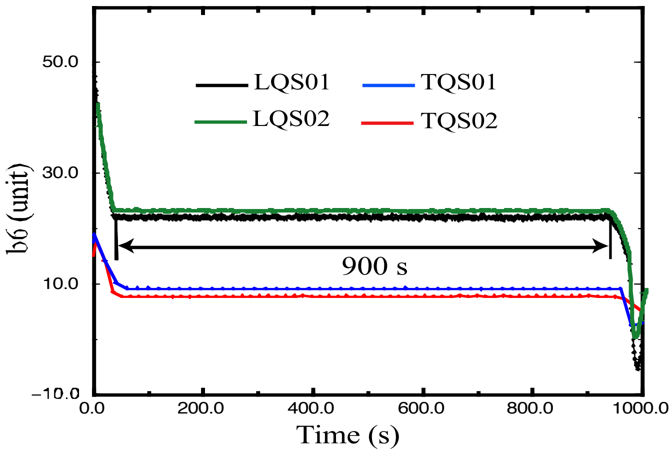

Fig. 6 Measurement of the decay and snapback of the dodecapole component for a duration of the injection of ~900 s in LQS and TQS magnets. No decay and subsequent snapback are observed.

injection phase. In this phase, the allowed field multipoles tend to decay causing significant changes in the machine tune and the beam chromaticity. Moreover, during the proton acceleration in the first few seconds of the current ramp, the allowed field multipoles snap-back for approximately 1.5 s to the original hysteresis curve.

Similarly to LQS01, we investigated dynamic effects executing measurements with an accelerator current profile used for the LHC IR quadrupole production tests. The important characteristic of this profile is summarized in [12]; the most important parameter is the duration of the injection plateau, which was set to 900 s. Our analysis was performed on the normal b_6 and b_{10} components, the first two allowed multipoles.

Fig. 6 shows the dodecapole measurements at 12.3 T/m. As we expected for LQS02, the decay and snap-back was not observed (Fig. 6, upper line). The magnet behavior fully reproduced the results from LQS01 [8] and was similar to the TQ model quadrupoles [5]. Moreover, this effect of the long-term decay and snap-back was not observed in Nb_3Sn dipole model magnets made of similar conductors [13].

Furthermore, the long-term dynamic effects were not found in next allowed harmonics, b_{10}.

In comparison, average amplitude in the NbTi LHC IR quadrupoles was found to be 0.39±0.11 [12]. This difference could be attributed to the larger filament size and production process between the Nb_3Sn and NbTi cables.

III. Summary

We performed magnetic field measurements on the second 3.7-m long Nb_3Sn quadrupole model of LQ series. The results are in very good agreement with the LQS01 measurements except for an increment of the normal sextupole to 14 units in the magnet body. The b_3 value was confirmed in the warm LQS02 body z-scan performed with the newest Fermilab magnetic measurement system (Ferret) Furthermore, a comparison with the 1-m long TQS models was presented. It should be noted that neither the LQ nor the TQ models has been designed to have coil alignment features, which explains the somewhat larger multipoles. These features have been introduced in the next LARP magnet series (HQ) [14] and therefore these quadrupoles should be more representative of the field quality in Nb_3Sn magnets.

The LQS02 eddy current effects were comparable with those observed in LQS01 and TQS02 magnets with coils made from the same type conductor. They are relatively large which is likely due to low interstrand contact resistances.

The long-term decay and snap-back effects were not observed in either of the Nb_3Sn TQ models or LQS magnets. This differs from the well-established results for NbTi magnets, which demonstrated consistent decay and snap-back effect. As we pointed in [8] this phenomenon needs future investigation and it is most probably due to the properties of the Nb_3Sn cable.

References

[1] S. A. Gourlay *et al.*, “Magnet R&D for the US LHC accelerator research program (LARP)”, IEEE Trans. Appl. Supercond., Vol. 16, Issue 2, pp. 324-327, June 2006.

[2] S. Caspi *et al.*, “Fabrication and Test of TQS01-A 90 mm Nb_3Sn Quadrupole Magnet for LARP”, IEEE Trans. Appl. Supercond., Vol. 17, 2007, pp. 1122-1125.

[3] S. Caspi *et al.*, “Test Results of TQS02, a Second Nb_3Sn Quadrupole Magnet Model for LARP”, IEEE Trans. Appl. Supercond.,Vol. 18, 2008, pp. 179-183.

[4] R.C. Bossert *et al.*, ”Development and Test of LARP Technological Quadrupole Models of TQC Series”, IEEE Trans. Appl. Supercond.,Vol. 18, 2008, pp. 175-178.

[5] G.V. Velev *et al.*, “Field Quality Measurements and Analysis of the LARP Technology Quadrupole Models”, IEEE Trans. Appl. Supercond., Vol. 18, 2008, pp. 184-187.

[6] P. Ferracin *et al.*, “Mechanical performance of the LARP Nb_3Sn quadrupole magnet LQS01”, IEEE Trans. Appl. Supercond.,Vol. 21, 2011, pp. 1683-1687.

[7] G. Ambrosio *et al.*, “Test results of the first 3.7 m long Nb_3Sn quadrupole by LARP and future plans”, IEEE Trans. Appl. Supercond.,Vol. 21, 2011, pp. 1858-1862.

[8] G.V. Velev *et al.*, “Field Quality of the first LARP Nb_3Sn 3.7m-long Quadrupole Model of LQ series”, IEEE Trans. Appl. Supercond., Vol. 21, 2011, pp. 1858-1862.

[9] A.V. Zlobin, *et al.*,“R&D of Nb_3Sn accelerator magnets at Fermilab”, IEEE Trans. Appl. Supercond. Vol 15, 2005, p. 1113.

[10] S. Russenschuck, “*Field Computation for Accelerator Magnets*”, Wiley-VCH, 2010.

[11] G. Ambrosio *et al.*, “LARP Long Nb_3Sn Quadrupole Design”, IEEE Trans. Appl. Supercond.,Vol. 21, 2011, pp. 1858-1862.

[12] G.V. Velev *et al.*, “Magnetic Field Measurements of LHC Inner Triplet Quadrupoles Fabricated at Fermilab”, IEEE Trans. Appl. Supercond., Vol. 17, 2007, pp. 1109-1112.

[13] V.V. Kashikhin *et al.*, “Field Quality Study in High-field Nb_3Sn Accelerator Magnets”, Proc. of 2005 Particle Accelerator Conference, Knoxville, TN, May 2005, pp. 366-338.

[14] H. Felice *et al.*, “Design of HQ-A High Field Large Bore Quadrupole Magnet for LARP”, IEEE Trans. Appl. Supercond.,Vol. 19, 2009, pp. 1235-1239.