FERMILAB-PUB-12-921-TD
Accepted

Test of Optimized 120-mm LARP Nb_3Sn Quadrupole Coil Using Magnetic Mirror Structure

G. Chlachidze, G. Ambrosio, N. Andreev, M. Anerella, E. Barzi, R. Bossert, S. Caspi, D. Cheng, D. Dietderich, H. Felice, P. Ferracin, A. Ghosh, A. Godeke, A. R. Hafalia, V. V. Kashikhin, M. Lamm, M. Marchevsky, A. Nobrega, I. Novitski, D. Orris, G. L. Sabbi, J. Schmalzle, P. Wanderer, and A. V. Zlobin

***Abstract*—The U.S. Large Hadron Collider accelerator research program is developing a new generation of large-aperture high-field quadrupoles based on Nb_3Sn conductor for the high-luminosity upgrade of the Large Hadron Collider. Tests of the first series of 120-mm-aperture high-gradient quadrupole (HQ) coils revealed the necessity for further optimization of the coil design and fabrication process. Modifications in coil design were gradually implemented in two HQ coils previously tested at Fermi National Accelerator Laboratory using a magnetic mirror structure (HQM01 and HQM02). This paper describes the construction and test of an HQ mirror model with a coil of optimized design and with an interlayer resistive core in the conductor. The cable for this coil was made of a smaller diameter strand, providing more room for coil expansion during reaction. The 0.8-mm strand, used in all previous HQ coils, was replaced with a 0.778-mm Nb_3Sn strand of RRP 108/127 subelement design. The coil was instrumented with voltage taps, heaters, and strain gauges to monitor mechanical and thermal properties and quench performance of the coil.**

***Index Terms*—High-luminosity upgrade of Large Hadron Collider (HiLumi-LHC), LHC accelerator research program (LARP), magnetic mirror, Nb_3Sn quadrupole magnet, quench performance.**

I. Introduction

As PART of the LHC luminosity upgrade, the U.S. LHC accelerator research program (LARP) [1] is developing a new generation of accelerator magnets based on Nb_3Sn superconductor. High gradient quadrupole (HQ) coils with a 120 mm diameter bore and 15 mm wide cable [2] are currently being produced and studied as a step toward the eventual aperture of 150 mm. Tests of the first series of HQ coils revealed the necessity for further optimization of the coil design and fabrication process [3], [4].

An efficient way to optimize coil parameters is to test them in a magnetic mirror structure [5], [6]. This allows individual coils to be tested under conditions similar to those of an actual magnet. Only one coil needs to be made instead of four, minimizing cost and turnaround time. Several short (1 m long) and one long (4 m long) coils have been successfully tested at Fermi National Accelerator Laboratory (Fermilab) using quadrupole mirror structures [5]–[8].

Modifications in coil design were gradually implemented in two HQ coils HQ12 and HQ13, previously tested at Fermilab using a magnetic mirror structure (HQM01 and HQM02 respectively) [9]. Both coils had the space increased for coil expansion during reaction, HQ12 by directly increasing the azimuthal space in the reaction mold, and HQ13 by eliminating one mid-plane turn in each layer. This was done to reduce the azimuthal pressure on the coil during reaction.

This paper describes the construction and testing of HQM04, the third quadrupole mirror with an HQ coil. Coil HQ15 is made of smaller diameter strand (0.778 mm instead of 0.8 mm) than in previous coils, and represents the latest optimized version of HQ cable. The new cable allows for increased room for azimuthal expansion during reaction without making special adjustments to the reaction cavity as was done with coils HQ12 and HQ13. HQ15 coil also includes an increased axial gap and additional improvements to the end parts and the overall insulation system [4].

II. HQ Mirror Structure and Construction

The HQM mirror assembly includes the coil, an iron "mirror" which replaces the three missing quadrupole coils, an iron yoke and a stainless steel shell. The assembly is bolted together as shown in Fig. 1. Details of the HQM mirror design and assembly procedure were previously reported in [9]. The magnetic flux distribution is similar to that of real quadrupoles and is shown in Fig. 2.

HQM04 contained coil HQ15, made using 35 strand Rutherford cable with 0.778 mm diameter RRP strand of 108/127 sub-element design produced by Oxford Superconductor Technologies, Inc. [10]. The strand has a sub-element size of $\sim$47 μm, a non-copper fraction of 47%, a twist pitch of 14 mm and J_c (4.2 K, 12 T) of 2900 A/mm^2. The cable included a 25 μm thick by 8 mm wide stainless steel (SS) core and was produced at Lawrence Berkeley National Laboratory (LBNL). Short sample currents for each coil are based on extracted strand measurements fitted with the scaling law described in [11] including a self-field correction and assuming -0.2% axial compressive strain both in the strand and coils.

Manuscript received October 9, 2012; accepted January 16, 2013. Date of publication January 24, 2013; date of current version February 25, 2013. This work supported in part by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the U.S. Department of Energy and the U.S. Department of Energy through the U.S. LHC Accelerator Research Program (LARP).

G. Chlachidze, G. Ambrosio, N. Andreev, E. Barzi, R. Bossert, V. V. Kashikhin, M. Lamm, A. Nobrega, I. Novitski, D. Orris, and A. V. Zlobin are with Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (e-mail: guram@fnal.gov).

M. Anerella, A. Ghosh, J. Schmalzle, and P. Wanderer are with Brookhaven National Laboratory, Upton, NY 11973 USA.

S. Caspi, D. Cheng, D. Dietderich, H. Felice, A. Godeke, A. R. Hafalia, M. Marchevsky, and G. L. Sabbi are with Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA.

P. Ferracin is with the European Organization for Nuclear Research, CERN CH-1211, Geneve 23, Switzerland.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2013.2242955

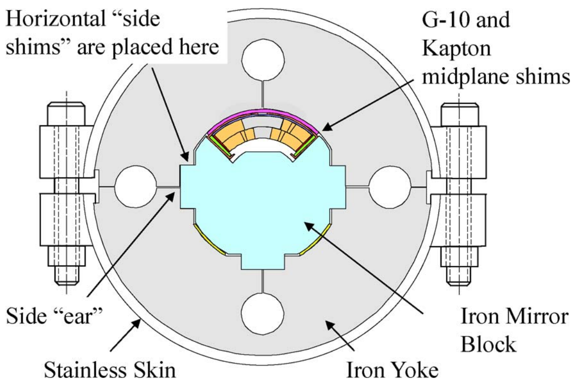

Fig. 1. HQ mirror structure.

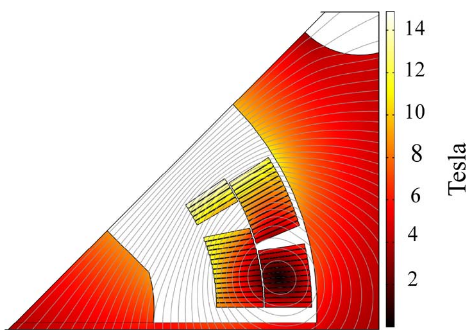

Fig. 2. HQ mirror cross-section with magnetic flux distribution at 20 kA. Peak field at inner pole is 14.9 T.

TABLE I
COIL SPECIFIC FEATURES

Coil #	Cable	Strand type	Azimuthal space for expansion (L 1/L 2)	Target axial gap for contraction (mm/m)
HQ 1-11	w/o core	varied	1.9%/1.9%	1
HQ12	SS core	54/61	5.4%/4.6%	1
HQ13	w/o core	54/61	7.6%/6.3%	2.75
HQ15	SS core	108/127	6.8%/6.8%	4.0

With respect to previous HQ coils, the cable was made smaller in thickness to allow more expansion in the mold cavity [4]. Table I describes some specific properties of HQ15 with respect to the original HQ design as well as two previous mirror coils (HQ12 and HQ13) that were made from the original cable, but were adjusted during fabrication to allow for increased expansion [4], [9]. Cable insulation for all coils in the series consisted of a 125 μm thick S2 glass sleeve.

Coil end parts were made of 304 Stainless Steel to match coil azimuthal thermal contraction while poles were made from a titanium alloy to minimize coil thermal contraction in the axial direction.

All coils were instrumented with strain gauges on the inner surface of the coil pole. Coil inner surface gauges were configured in two full bridges, one each in the azimuthal and longitudinal direction. The structure included gauges on the exterior surface of the shell and on the end preload bolts.

Coil preload in the mirror structure is provided by a 12 mm thick stainless steel skin and controlled by a series of shims placed radially and azimuthally on the coil, and to the upper surface of the side "ears" on the mirror block.

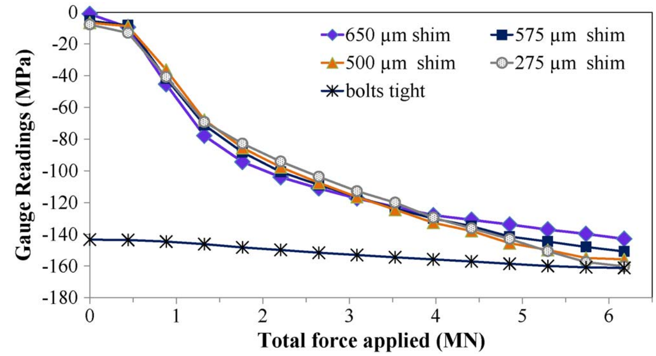

Fig. 3. HQM04 azimuthal preloads during pressing. Horizontal axis denotes total force applied over a coil of approximately one meter in length.

The coil is insulated from ground by Kapton sheets. The thickness of Kapton is adjusted to achieve the desired preload at room temperature. Before magnet assembly, the cross section size is measured in its free state on a coordinate measuring machine [12]. The measured size is used to determine the amount of mid-plane shim, based on previous experience and finite element analysis. Shims are also placed onto the horizontal surface of the side ears as shown in Fig. 1. The side shims are used to adjust the preload during pressing and control the preload during cool-down.

The structure is placed into a hydraulic press and the pressure is increased until the desired preload is achieved (verified by the strain gauges). Then the press is released, a specified amount of shim is removed, and the pressure is reapplied until the strain gauges reach the same value as they had before the shims were removed. The bolts are then tightened, leaving an open area into which the structure can contract during cool-down, increasing the preload.

The coil preload was applied using five separate pressings. After an initial pressing with a "side shim" of 650 μm, shims were removed between pressings in increments of 75 μm, until the final desired preload was achieved with a side shim of 500 μm. The "cool-down" gap of 225 μm was then added by reducing the amount of side shims to 275 μm. The final pressing was then completed and the bolts were tightened to close the structure. Strain gauge readings during this process are shown in Fig. 3.

The final azimuthal coil pre-stress of HQM04 at room temperature was 143 MPa, similar to the warm preloads of HQM01 and HQM02, which were 132 and 130 MPa respectively. The same space was left for contraction during cool-down in all cases. As in all HQ mirrors, a load of 10 kN was applied to each end through the 50 mm thick end plates.

III. TEST RESULTS

HQM04 was tested at Fermilab's Vertical Magnet Test Facility (VMTF) [13] in May 2012. The test was performed in boiling liquid helium at 4.6 K and at lower temperatures for the temperature dependence study. Quench positions were determined by voltage taps and a quench antenna.

A. Quench History

The HQM04 cold test began with training at 4.6 K. The coil exhibited slow training but gradually approached the estimated

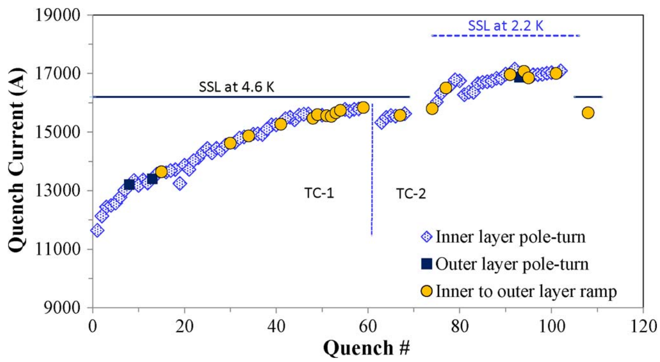

Fig. 4. HQM04 quench history with bath temperature and quench locations.

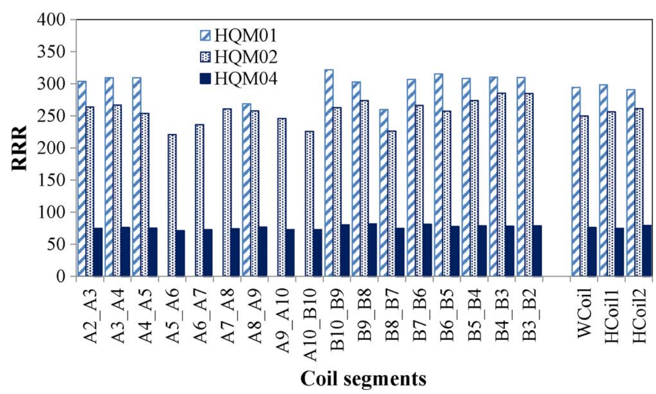

Fig. 5. RRR for all HQ mirror magnets.

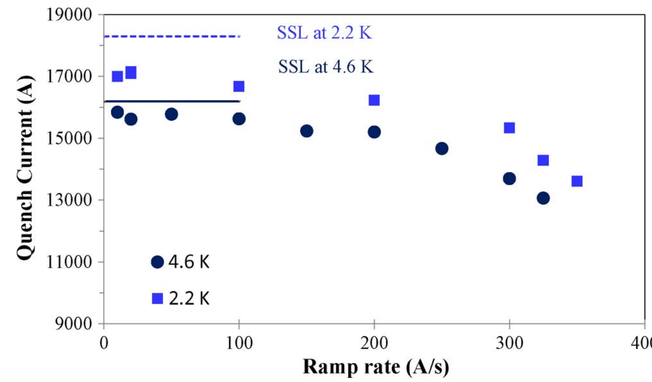

Fig. 6. HQM04 ramp rate dependence.

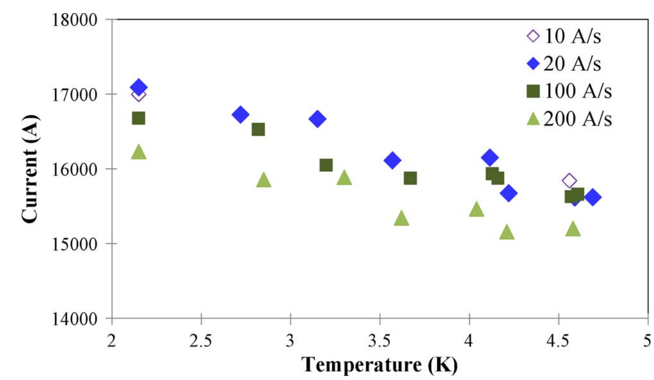

Fig. 7. Temperature dependence for HQM04.

short sample limit (SSL) of 16.2 kA. Eventually, 98% of the SSL was reached at 4.6 K. Most quenches developed in the pole-turn segments of the inner coil layer.

The magnet quench history with quench locations is summarized in Fig. 4. Only a few of the quenches originated from the pole turn segment of the outer coil layer. All training quenches were performed at a ramp rate of 20 A/s, although the highest quench current was reached at 10 A/s.

After the initial 4.6 K testing was completed, a previously unplanned thermal cycle to room temperature took place, so ice could be cleaned from the VMTF heat exchanger transfer lines. After cleaning was completed, a few additional quenches were performed at 4.6 K to verify the magnet quench memory. The plateau was reached within two quenches, although the location was still changing from quench to quench.

Slow training continued at 2.2 K. Most quenches at 2.2 K were initiated in the pole turn segments of the inner coil layer.

After testing at 2.2 K was completed, the quench plateau at 4.6 K was verified. The Residual Resistivity Ratio (RRR) of HQ15 coil was measured during magnet warm up, with values varying from 70 to 80. Much larger RRR had been measured in the previously tested HQ12 and HQ13 coils (see Fig. 5). However, the relatively low RRR values did not negatively affect the performance in HQM04. In particular, no signs of conductor instabilities were observed during the test.

B. Ramp Rate and Temperature Dependences

The ramp rate dependence of the quench current of HQM04 at 4.6 K and 2.2 K is presented in Fig. 6. The expected temperature dependence is observed for the ramp rate quenches. All quenches at ramp rates of 200 A/s and below occurred in the high field area. Only quenches at very high ramp rates (250–350 A/s) were initiated in the mid-plane block of the inner and outer coil layers.

The temperature dependence of the magnet quench current is presented in Fig. 7. Quenches were performed at different ramp rates, and expected reduction of magnet quench current with temperature increase was observed at all ramp rates.

C. Strain Gauges

Strain gauge data in HQM04 are nearly identical to HQM01/02 for the magnet cool-down, training and warm-up. Strain gauges mounted azimuthally to the outside shell (skin) showed the expected strain increase during cool-down and were flat as expected during excitation. End load increased as expected during cool-down and during excitation. Azimuthal gauges placed on the interior pole surface showed inconsistencies during cool-down, possibly due to slight coil bending within the structure.

IV. Discussion of Test Results

HQM04 reached the highest percent of the SSL among all HQ coils tested in both the mirror and quadrupole structure. Quench performance of all HQM mirror magnets are compared in Fig. 8.

HQM01 quenches developed in a low field area—in the mid-plane turns, while HQM02 and HQM04 training quenches originated from the high field area. A stainless steel core was placed inside the cable in HQM01 and HQM04.

The ramp rate dependence in different HQ mirrors at 4.6 K is compared in Fig. 9. The poor performance of HQM01 could be related to conductor damage resulting in reduced strand stability. HQM04, which contained a similar SS core in the

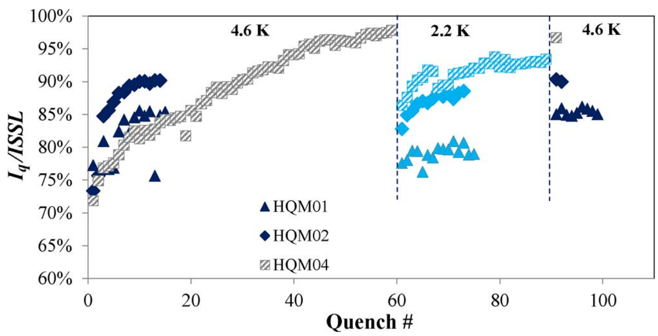

Fig. 8. Quench training of all HQ mirror magnets. I_q/I_{SSL} on vertical axis is a ratio of quench current to the short sample limit.

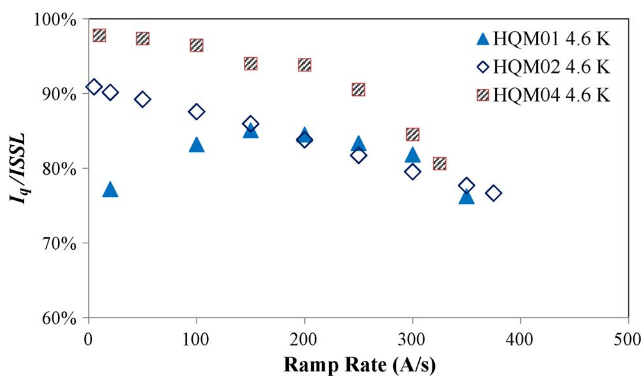

Fig. 9. Ramp rate dependence of all HQ mirror magnets at 4.6 K.

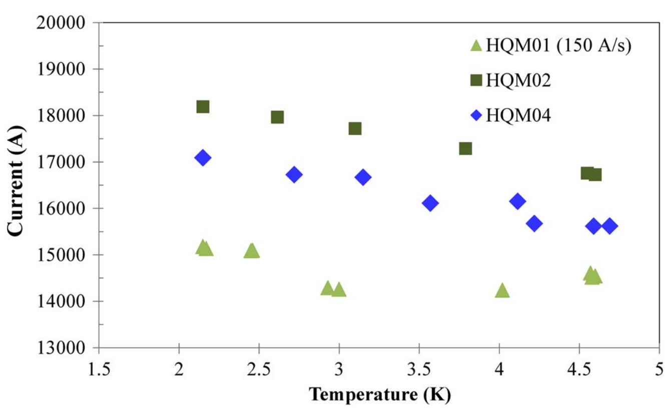

Fig. 10. Temperature dependence of all HQ mirror magnets.

conductor as HQM01, reached a higher percent of SSL than either HQM01 or HQM02.

Temperature dependences of all three HQ coils are presented in Fig. 10. HQM01 data is shown at a ramp rate of 150 A/s for which the coil reached the highest current.

V. Conclusion

Three LARP quadrupole coils of the HQ design (HQ12, HQ13 and HQ15) have been tested in a quadrupole mirror structure. All coils were made with additional space for azimuthal expansion during reaction than the baseline HQ coils. In addition, coils HQ12 and HQ15 were made of cable with a stainless steel core. The goal of this experiment was to assess the effect of reduced coil compaction during reaction as well as the effects of the internal cable core on the quench performance.

Coil HQ15, with an optimized cable design, reached the highest percent of SSL of 98% at 4.6 K and 94% at 2.2 K. Coil HQ13 reached 91% of its SSL, while coil HQ12 reached only 82%, with almost all quenches in the low field area near the inner layer mid-plane. Insufficient space for the coil expansion during reaction may have caused conductor damage during fabrication and increased instability in coil HQ12. Based on the results of this experiment, future HQ coils will be fabricated with increased room for expansion during reaction.

The excellent results obtained in HQM04 also demonstrate that a stainless steel core can be introduced in the HQ coils without causing performance degradation. On the other hand, the mirror structure is not suitable to investigate the advantages of the core from the viewpoint of field quality and ramp rate dependence. Further tests of coils with an optimized design and cored cables in full quadrupole configuration will be necessary to verify the overall impact on the magnet quench performance.

Acknowledgment

The authors would like to thank S. King, J. Swanson, D. Horler, and C. Kozy for assistance during coil construction; J. Alvarez, S. Gould, S. Johnson, R. Jones, S. Krave, L. Ruiz, and M. Whitson during mirror magnet assembly; and W. Mumper and F. Lewis during testing.

References

[1] S. A. Gourlay, G. Ambrosio, N. Andreev, M. Anerella, E. Barzi, R. Bossert, S. Caspi, D. R. Dietderich, P. Ferracin, R. Gupta, A. Ghosh, A. R. Hafalia, C. R. Hannaford, M. Harrison, V. S. Kashikhin, V. V. Kashikhin, A. F. Lietzke, S. Mattafirri, A. D. McInturff, F. Nobrega, I. Novitsky, G. L. Sabbi, J. Schmazle, R. Stanek, D. Turrioni, P. Wanderer, R. Yamada, and A. V. Zlobin, "Magnet R&D for the US LHC accelerator research program (LARP)," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 324–327, Jun. 2006.

[2] H. Felice, G. Ambrosio, M. Anerella, R. Bossert, S. Caspi, D. W. Cheng, D. R. Dietderich, P. Ferracin, A. K. Ghosh, R. Hafalia, C. R. Hannaford, V. Kashikhin, J. Schmalze, S. Prestemon, G. L. Sabbi, P. Wanderer, and A. V. Zlobin, "Design of HQ—A high field large bore Nb_3Sn quadrupole magnet for LARP," *IEEE Trans. Appl. Supercond.*, vol. 19, pt. 2, no. 3, pp. 1235–1239, Jun. 2009.

[3] S. Caspi, G. Ambrosio, M. Anerella, E. Barzi, B. Bingham, R. Bossert, D. W. Cheng, G. Chlachidze, D. R. Dietderich, H. Felice, P. Ferracin, A. Ghosh, A. R. Hafalia, C. R. Hannaford, J. Joseph, V. V. Kashikhin, G. L. Sabbi, J. Schmalzle, P. Wanderer, W. Xiaorong, and A. V. Zlobin, "Test results of 15 T Nb_3Sn quadrupole magnet HQ01 with a 120 mm bore for the LHC luminosity upgrade," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1854–1857, Jun. 2011.

[4] H. Felice, G. Ambrosio, M. D. Anerella, D. Bocian, R. Bossert, S. Caspi, B. Collins, D. Cheng, G. Chlachidze, D. R. Dietderich, P. Ferracin, A. Godeke, A. Ghosh, A. R. Hafalia, J. M. Joseph, J. Krishnan, M. Marchevsky, G. Sabbi, J. Schmalzle, P. Wanderer, X. R. Wang, and A. Zlobin, "Impact of coil compaction on Nb_3Sn LARP HQ magnet," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4001904, Jun. 2012.

[5] A. V. Zlobin, N. Andreev, E. Barzi, R. Bossert, G. Chlachidze, V. S. Kashikhin, V. V. Kashikhin, M. J. Lamm, I. Novitski, M. Tartaglia, J. C. Tompkins, D. Turrioni, and R. Yamada, "Testing of Nb_3Sn quadrupole coils using magnetic mirror structure," in *Proc. Adv. Cryog. Eng.*, 2010, vol. 55B, pp. 1031–1038.

[6] N. Andreev, E. Barzi, R. Bossert, G. Chlachidze, V. S. Kashikhin, V. V. Kashikhin, M. J. Lamm, F. Nobrega, I. Novitski, M. Tartaglia, D. Turrioni, R. Yamada, and A. V. Zlobin, "Magnetic mirror structure for testing shell-type quadrupole coils," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 288–291, Jun. 2010.

[7] G. Chlachidze, N. Andreev, E. Barzi, R. Bossert, V. S. Kashikhin, V. V. Kashikhin, M. J. Lamm, F. Nobrega, I. Novitski, D. Orris, M. Tartaglia, J. C. Tompkins, D. Turrioni, R. Yamada, and A. V. Zlobin, "The study of single Nb_3Sn quadrupole coils using a magnetic mirror structure," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1692–1695, Jun. 2011.

[8] R. Bossert, G. Ambrosio, N. Andreev, E. Barzi, G. Chlachidze, V. Kashikhin, M. Lamm, A. Nobrega, I. Novitski, D. Orris, M. Tartaglia,

D. Turrioni, R. Yamada, and A. Zlobin, "Fabrication and test of 4 m long Nb_3Sn quadrupole coil made of 114/127 RRP strand," in *Proc. CEC/CEC*, Jun. 2011, vol. 57, pp. 869–876.

[9] R. Bossert, G. Ambrosio, N. Andreev, M. Anerella, E. Barzi, S. Caspi, D. Cheng, G. Chlachidze, D. Dietderich, H. Felice, P. Ferracin, A. Ghosh, A. R. Hafalia, V. V. Kashikhin, M. Lamm, A. Nobrega, I. Novitski, G. L. Sabbi, J. Schmalzle, P. Wanderer, and A. V. Zlobin, "Optimization and test of 120 mm LARP Nb_3Sn quadrupole coils using magnetic mirror structure," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4003404, Jun. 2012.

[10] J. A. Parrell, Y. Zhang, M. B. Field, P. Cisek, and S. Hong, "High field Nb_3Sn conductor development at oxford superconducting technology," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 3470–3473, Jun. 2003.

[11] A. Godeke, B. ten Haken, H. H. J. ten Kate, and D. C. Larbalestier, "A general scaling relation for the critical current density in Nb_3Sn," *Supercond. Sci. Technol.*, vol. 19, no. 10, p. R100, Oct. 2006.

[12] TD-12-016 R. Bossert and R. Riley, "Coil HQ15 CMM measurements," Fermilab Technical Division Note 2012, TD-12-016.

[13] M. J. Lamm, J. DiMarco, E. Desavouret, S. Feher, J. D. Garvey, C. Hess, P. J. Limon, J. M. Nogiec, D. F. Orris, J. Pachnik, T. Peterson, S. Sharonov, J. B. Strait, C. Sylvester, J. W. Sim, M. Tartaglia, J. C. Tompkins, and A. V. Zlobin, "A new facility to test superconducting accelerator magnets," in *Proc. Particle Accel. Conf.*, 1997, pp. 3395–3397.