Analysis of Nb_3Sn Accelerator Magnet Training

S. Stoynev, K. Riemer, A. V. Zlobin, G. Ambrosio, P. Ferracin, G.L. Sabbi and P. Wanderer

***Abstract* — Nb_3Sn accelerator magnet technology has made significant progress during the past decades. For the first time, it is planned to be used in a real accelerator. A relatively small number of Nb_3Sn quadrupoles and dipoles will be installed in the LHC to increase machine luminosity. Although it will prove the possibility of using Nb_3Sn magnets in real machines, many questions of scaling this technology up remain. One of them is related to slow training of Nb_3Sn magnets compared to the traditional Nb-Ti accelerator magnets. Since the goal is to operate thousands of Nb_3Sn magnets in a future post-LHC accelerator, the slow training will affect both the practical design margin and the nominal operation field. Consequently, the cost of the project to reach the design field level is also increased. To improve our understanding of slow magnet training the existing Fermilab data from Nb_3Sn magnet tests were re-analyzed. A summary of coil training features and correlations with fabrication parameters observed is presented in this paper.**

***Index Terms*— Nb_3Sn accelerator magnets, superconducting coils, superconducting magnet training, quench performance**

I. Introduction

TRAINING of Nb_3Sn accelerator magnets requires tens of quenches, which takes typically many days and uses significant resources. This is unsustainable for thousands of magnets in a large high energy collider. Understanding of training mechanisms is the subject of various studies [1]-[3] and those are to be supported by developments in instrumentation and technology [4], [5]. Previous work on Nb-Ti magnets also suggests that statistical aspects of the analyses could yield valuable insights and information [6], [7].

Although the Nb_3Sn superconductor was discovered earlier than Nb-Ti and has higher performance potential, it is still trying to reach its maturity. There are multiple non-trivial challenges associated with Nb_3Sn magnet technology. Wire and cable properties should follow stringent requirements. Coils contain multiple turns and parts that need to be placed and kept at precise positions. Magnets should sustain huge forces and at no phase performance of the final product shall be affected. A summary of the main difficulties can be found in [8], [9] but each step in magnet fabrication has the potential to affect magnet training and performance in general.

Nb_3Sn accelerator magnets are still only short models or prototypes and test statistics are limited. Series of R&D magnets often progress by introducing multiple "improvements" in each new unit of the series. Both features present a challenge for statistical analysis of those data.

In this paper we analyzed training data from TQC[10], HQ[11], MQXFS[12] and MBHS[13] Nb_3Sn magnet series. The models are 1-1.5 m long shell-type dipoles and quadrupoles. The TQC, HQ and MQXFS are quadrupole series from the LARP program [14] and the MBHS are dipoles from the "11 Tesla" program [15]. Their cross-sections are presented in Fig. 1 and the main parameters are summarized in Table I. In this study, we present *coil training* data. The data encompass only the magnets tested at the Vertical Magnet Test Facility at Fermilab [16]. TQC models were tested in 2007-2012, HQ – in 2013-2015, MQXFS – in 2015-2017 and MBHS – in 2011–2015. The analysis aims coils trained for the first time.

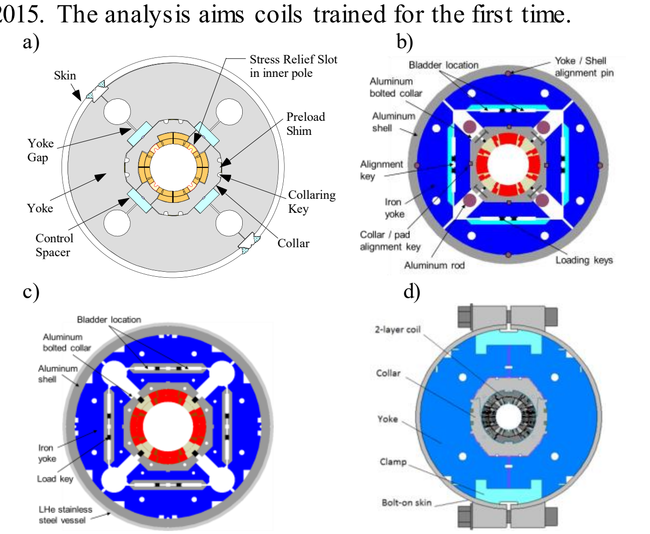

Fig. 1. The structures of the four magnet series discussed: a) TQC, b) HQ, c) MQXFS and d) MBHS.

TABLE I
MAIN MAGNET PARAMETERS

Parameter	TQC	HQ	MBHS	MQXFS
Coil ID, mm	90	120	60	150
Nb3Sn wire type	MJR/RRP	RRP	RRP	RRP
Strand diameter, mm	0.7	0.8	0.7	0.85
Number of strands	27	35	40	40
Cable width, mm	10.05	15.15	14.85	18.09
Collar material	SS	Al	SS	Al
Yoke OD, mm	400	520	400	556
Skin material	SS	Al	SS	Al/SS
Skin thickness, mm	12	25	12.5	29/8

Table I: MJR stands for Modified Jelly-Roll and RRP – for Restack Rod Process, those are two of the main methods to fabricate multi-filamentary Nb_3Sn superconductor. SS denotes stainless steel and Al – Aluminum, OD/ID are outer/inner diameters.

Manuscript receipt and acceptance dates will be inserted here. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, through the US LHC Accelerator Research Program (LARP) and the US LHC Accelerator Up-grade Project (AUP), and by the High Luminosity LHC project at CERN and in part by the Fermi Research Alliance, LLC, under contract no. DEAC02-07CH11359 with the U.S. Department of Energy (Corresponding author: Stoyan Stoynev, e-mail: stoyan@fnal.gov).

S. Stoynev, K. Riemer, A. V. Zlobin and G. Ambrosio are with the Fermi National Accelerator Laboratory /FNAL/, Batavia, IL 60510 USA.

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

G.L. Sabbi is with Lawrence Berkeley National Laboratory /LBNL/, Berkeley, CA 94720 USA.

P. Wanderer is with the Brookhaven National Laboratory, Upton, NY 11973 USA.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

II. Training Studies

A. *Magnet vs Coil Training*

Most of the papers, which discuss magnet training, focus on training of the whole magnet. However, the smallest unit to associate training with is the coil. Each coil is fabricated individually and characterized by its own short sample limit (SSL). In a magnet, coils are exposed to the same conditions. Therefore, training analysis of individual coils is beneficial for understanding of this phenomenon. There are also magnets with a single coil, a.k.a. "mirror magnets" (the "missing" coils are "replaced" with iron blocks) [17], which are easier to fabricate and still very useful to analyze. Performance of coils in the same series could be compared directly whereas coils in different series require a more cautious approach rendering direct statistical analysis less reliable. The same can be said about magnets but each magnet contains multiple coils making the coil a better suited unit for statistical analysis as well. It is understood that model magnets in the same series were fabricated with different parameters. Since listing all details is beyond the scope of the current paper we emphasize coil or magnet parameters that were likely to have contributed to performance variances.

As will be seen, and is known, initial training is hardly dependent on the temperature of liquid helium – the quench current is typically well below the SSL. Thus, plotting the current normalized to the temperature dependent SSL would be misleading. Further training however is very much dependent on temperature – reaching the 4.5 K conductor limit still gives margin for current increase at 1.9 K. On one hand this means that training curves will depend on temperature conditions and there is, overall, little benefit at training at 4.5 K. On the other hand, this also means that at some point plotting the normalized (to SSL) current becomes preferable – the discontinuity between 1.9 K and 4.5 K training disappears as long as the current is close to the conductor limit. Given that the inflection point between the two types of behavior is a-priori unknown, independent training information is contained in both curves.

The SSL based on extracted strand data for the coils in respective series for 1.9 K and 4.3-4.6 K are shown in Table II. Later SSL are linearly interpolated/extrapolated according to temperatures measured at a given quench.

B. *TQC series*

The coil training in TQC01, TQM03, TQM04 and TQM05 (models with "M" in the name denote "mirror" magnets) [10], [18], [19] is shown in Fig. 2. The coil training quenches are numbered for each coil independently on temperature. TQC01 coils are the only ones in this analysis that used MJR type strands (Table I). They experienced uncommon training behavior where both absolute and normalized current plateaus differed between 1.9 K and 4.5 K. This behavior was associated with conductor instabilities [20]. However, TQC01 training already shows that similar coils in a magnet could train in very distinctive ways. Two of the coils, 9 and 10, reached 80% of their SSL at 1.9 K with virtually no training, while the other two followed a different curve. Based on these results, new coils of this series were fabricated using more stable RRP wire having smaller Nb_3Sn sub-elements size and higher RRR of the copper matrix. These coils were also used in three "mirror" magnets in the series.

TABLE II
Magnets and Coils Tested (in Order of Testing Inside Series)

Magnet series	Magnet number	Coil number	SSL at 1.9K, [kA]	SSL at 4.3-4.6 K, [kA]
TQC	TQC01	9	14.306	12.934
		10	14.306	12.934
		12	14.442	13.054
		13	14.442	13.054
	TQM03	34	14.000	12.690
	TQM04	35	13,880	12.290
	TQM05	36	15.100	13.400
HQ	HQ02	15	18.530	16.738
		16	18.468	16.683
		17	18.199	16.433
		20	18.271	16.499
	HQ03	22	17.911	16.258
		23	17.976	16.319
		24	17.886	16.236
		26	17.907	16.254
MQXF	MQXFSM1	2	21.065	18.734
	MQXFS1	3	22.279	20.118
		5	21.846	19.725
		103	21.500	19.550
		104	21.775	19.775
MBHS	MBHSP02	5	15.811	14.105
		7	15.830	14.105
	MBHSM01	8	15.765	14.126
	MBHSP03	9	15.075	13.235
		10	15.075	13.235

Table II: SSL at 4.3-4.6 K refers to: 4.5 K for TQC, 4.5 K for HQ, 4.3 K for MQXFS, 4.6 K for MBHS.

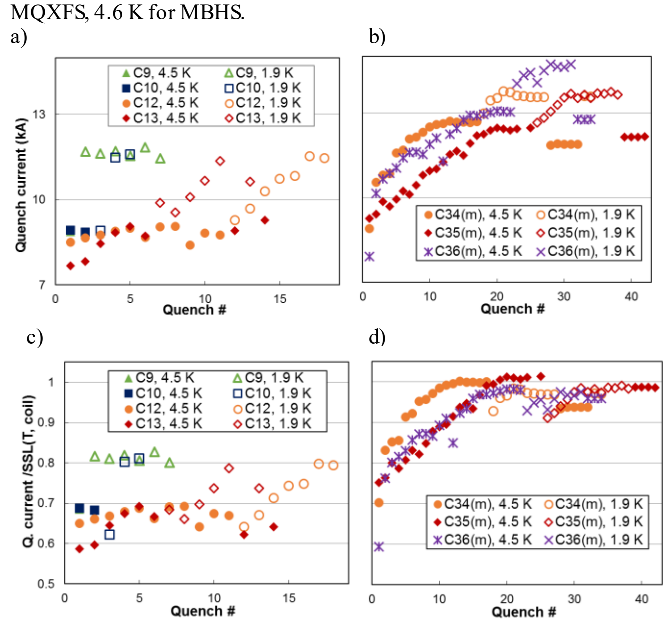

Fig. 2. Quench training vs current (top) and vs normalized current (bottom): a) and c) – TQC coils, b) and d) - TQM coils.

Training of all "mirror" magnets started at 4.5 K, then continued at 1.9 K and finished at 4.5 K. All coils reached their conductor limit as can be seen in the continuity of training curves in normalized currents after reaching a 1.9 K plateau. All coils reached nearly 100% of SSL proving that cable degradation could be limited in "mirror" structures. Still, coil 34 trained twice as fast as the other two though detraining was observed with further tests and more quenches. Apart from lower pre-stress levels, coil 34 differed from the other mirror coils by using a cable without a stainless-steel core and E-glass tape instead of S2-glass sleeve for cable insulation [21].

C. *HQ series*

HQ02 training which started at 4.5 K and then continued at 1.9 K, is reported in [22] and presented in Fig. 3 with coil quench locations. The HQ02 coil training is shown in Fig. 4 a) and c). Coil 15 was trained previously in another test and is not relevant for this study. Coils 16 and 20 had very similar behavior reaching 16 kA (~90% of SSL at 1.9 K) although the first quench currents were different. Instead, coil 17 started to train only at 1.9 K and reached 90% of SSL in only 4 quenches.

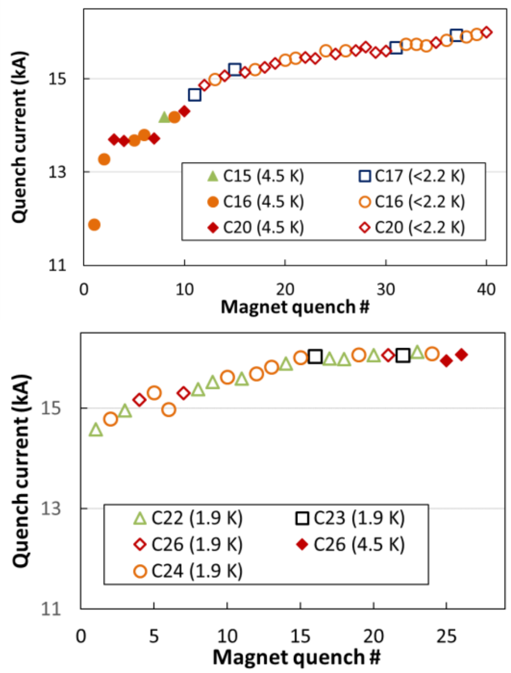

Fig. 3. HQ02 (top) and HQ03 (bottom) magnet training indicating quench locations in coils.

HQ03 training started at 1.9 K [23] and is shown in Fig. 3. The magnet had two similarly slow training coils, 22 and 24 (see Fig. 4 b) and d)). Coil 26 trained faster at 1.9 K, and the only two 4.5 K quenches in the whole magnet developed in this coil. It indicates that the coil is far from its conductor limit and the observed current limitation is likely of mechanical nature. Coil 23 did not train at all, going straight to 90% of SSL.

The fastest training coils in this series, coils 17 and 23, had a common fabrication feature – a pole gap increase after reaction linked to larger pole gap contraction after coil winding [24]. There is no other known difference associated with those coils that may have contributed to their better performance.

D. *MQXFS series*

MQXFS tests at Fermilab were conducted on one "mirror" (MQXFSM1) [25] and one quadrupole (MQXFS1) [26] magnet. Both magnets were trained at 1.9 K and then quenched at 4.5 K as a part of temperature dependence studies. The quadrupole training is unique among the investigated models as its azimuthal pre-stress was increased by ~25%, while the coils were still training. This step shifted the beginning of the observed coil-pole separation from occurring at ~ 15 kA to occurring at ~17 kA. Figure 5 presents the magnet training with coil quench locations. Figure 6 presents training curves of the coils with the initial and the increased azimuthal pre-stress together with the coil from the "mirror" magnet. The latter was fabricated and tested first. It had a long training reaching the conductor limit at ~90% of SSL.

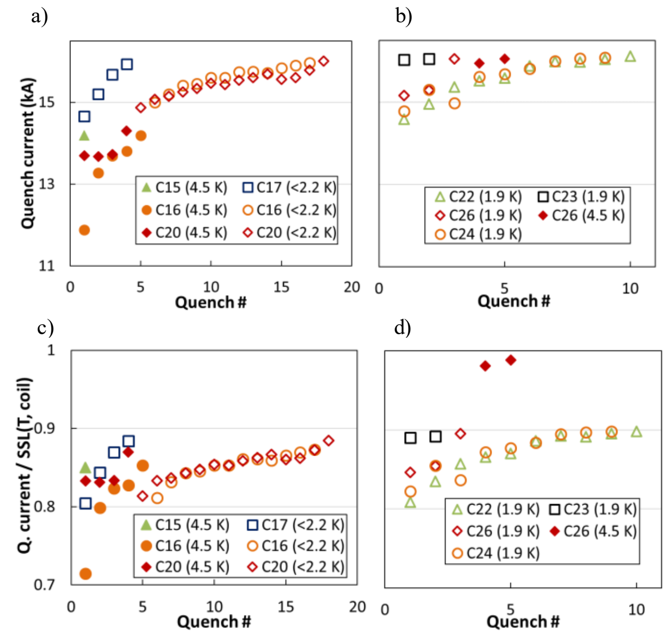

Fig. 4. Quench training vs current (top) and vs normalized current (bottom): a) and c) - HQ02 coils, b) and d) - HQ03 coils.

Coil 103 and 104 in the quadrupole showed training behavior similar to the "mirror" coil, and coil 104 in particular is tracing the "mirror" training in the normalized plot. Those two coils in the magnet also showed no change in the training curve after the significant increase of the magnet azimuthal pre-stress (test "b" in Fig. 6). Note that the training curve of coil 104 was continuous in terms of current ("absolute" training plot), despite changes in both temperature and pre-stress. Coil 3 and 5 in the quadrupole trained very fast before reaching an unstable plateau though away from its conductor limit (as observed in coil 5 where the coil reached ~95% of SSL at 4.5 K but was unstable above ~83% of SSL at 1.9 K). They both developed a mechanically driven "weak point" around one of the wedges near the lead-end [27]. Plateau quenches in the "mirror" magnet (coil 2) were also around the same wedge area, although no single weak spot of the type that occurred in the quadrupole was identified. Coils 103 and 104 had most of the high-current quenches in the pole area with no clear plateau reached during magnet training. Coils 3, 5 and 2 were fabricated in similar manner in the USA, "LARP" coils, whereas coils 103 and 104 were fabricated at CERN. Although LARP and CERN coils had similar design they had notable differences [28]. The ones most likely to had affected training were the use of more flexible end-parts in the CERN coils and some differences in coil lengths.

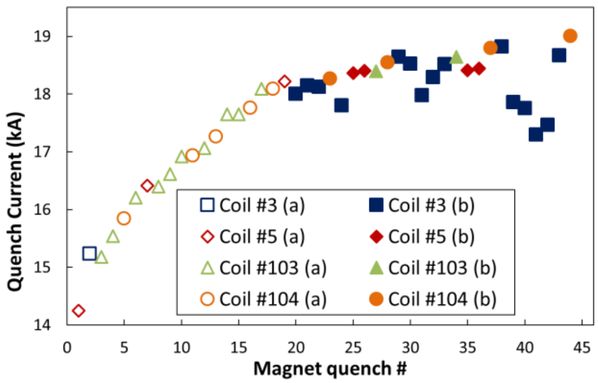

Fig. 5. MQXFS1 magnet training indicating quench locations in coils. Two tests are marked as "a" and "b", with "b" corresponding to a higher azimuthal pre-stress with respect to "a".

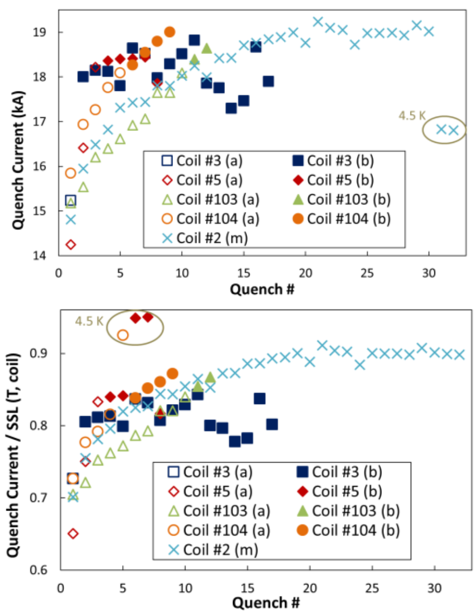

Fig. 6. Quench training vs current (top) and vs normalized current (bottom) in MQXFS magnets. Two tests for the quadrupole are marked as "a" and "b", with "b" corresponding to a higher azimuthal pre-stress with respect to "a", and "m" denotes the "mirror" magnet test. Only two/three quenches were at 4.5 K in the mirror/quadrupole test as seen on the figures, the rest – at 1.9 K.

E. *"11 Tesla" series*

Training curves of two dipole models, MBHSP02 [29] and MBHSP03 [30] are presented in Fig. 7. Their coil training together with the training of a "mirror" magnet, MBHSM01 [31], is presented in Fig. 8. The magnets started training at 4.5 K before shifting to 1.9 K and eventually back to 4.5 K. The SSL for the "mirror" coil 8 was increased by ~10% to reflect the fact that only two strands had usable data with SSL results differing by those 10%. The higher value was consistent with SSL of coils 5 and 7.

Training of the MBHSP02 magnet with coils 5 and 7 was limited by coil 7, which reached current close to its conductor limit. Unlike coil 7, coil 5 did not slow its training up to 80% of SSL and was the better performing coil. The "mirror" magnet was tested after MBHSP02, and training of its coil 8 tracked coil 5 training remarkably close. This suggests that coil training in "mirrors" and full prototypes could be similar despite some differences in their mechanical structures and force distributions. Coil 8, being the only coil in the "mirror" model, continued training to ~90% of SSL, close to its conductor limit as seen in Fig. 8.

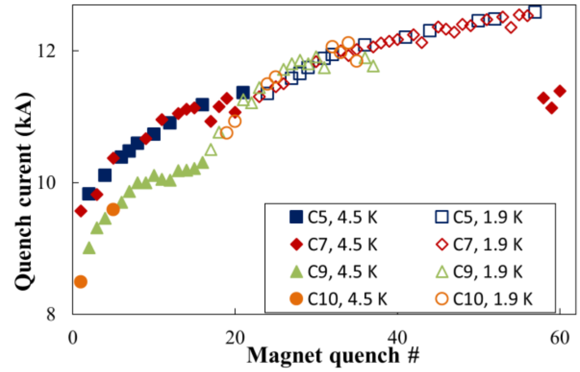

Fig. 7. MBHSP02 (coils 5 and 7) and MBHSP03 (coils 9 and 10) magnets training indicating quench locations in coils.

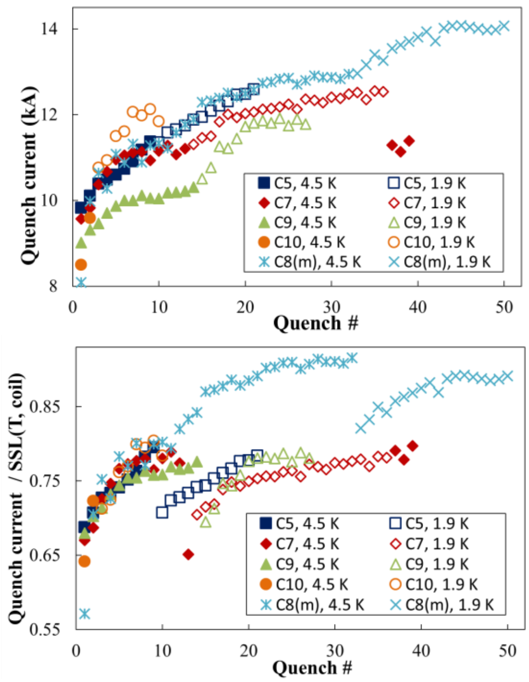

Fig. 8. Quench training vs current (top) and vs normalized current (bottom) in MBHS magnets. "m" denotes the "mirror" magnet test.

The second dipole model MBHSP03 with coils 9 and 10, and lower pre-stress with respect to MBHSP02, also had a limiting coil – coil 9. Coil 9 had 14 quenches at 4.5 K while the similar coil 10, with similar SSL, in the same magnet, had only two quenches at 4.5 K. A significant part of the coil 9 training at 4.5 K consisted of quenches close to its conductor limit. The bottom plot in Fig. 8 shows that coil 9 reached its conductor limit just below 80% of SSL, which is manifested by the same level of normalized current at 4.5 K and 1.9 K.

Figure 8 also shows that coil training in all models, including the "mirror", is similar in the beginning of training. The training plateaus of the three magnets were shaped by one of their ingredient coils. In all cases those quenches developed around one of the wedges of the coils. The most likely cause of this observed limitation is conductor damage and based on quench locations it is not a single spot that got damaged.

Those are the areas with the highest stress concentration after magnet cooling down, and which are relaxed during powering. The revised SSL of the "mirror" and its quench locations together with similarities in training behavior with dipole coils, including locations, suggest that cable degradation had the same origins in all coils in both structures, but the magnitude of the effect was different. In dipoles, degradation was confirmed only in one coil for each of the two magnets, coil 7 and coil 9. Both reached approximately the same normalized current at 1.9 K and 4.5 K, as seen in Fig. 8.

III. DISCUSSION AND CONCLUSIONS

Post-LHC accelerators will utilize Nb_3Sn magnets and fast training is important to reduce budget and schedule constraints. An advanced analysis on training of Nb_3Sn dipole and quadrupole short models tested previously at Fermilab was presented with an emphasis on coil training. Coil training is shown to be superior for understanding of magnet performance. Both absolute and normalized training plots were needed to describe training. One case demonstrated how uncertain SSL estimations could be, thus suggesting uncertainties on SSL are given in future as well. While the magnet prestress is important for its mechanical stability the level of the azimuthal pre-stress, within the limits applied in the reviewed tests, is not directly linked to the coil training characteristics.

We showed that coils in "mirror" magnets and their well performing equivalents in dipoles/quadrupoles train similarly. Thus "mirror" magnets are excellent candidates for training studies in magnets. Similar training in "mirror" and magnet coils suggests that training in coils is driven by "local" effects with little influence from the global state contributed to by other (quenching) coils.

Training of "good" coils at 1.9 K is overall beneficial as the conductor limit is first reached at 4.5 K and training would naturally slow in that case. Still, 4.5 K quenches toward the end of training are of importance to establish the training state of a coil.

Other aspects of training, in particular related to RRR/"heat treatment", were previously also shown to be of interest [3].

An extension to this study involving all available Nb_3Sn accelerator magnet data worldwide will be of great interest to the community. Efforts in that direction will be made.

ACKNOWLEDGMENT

The authors thank the technical staff at BNL, CERN, FNAL and LBNL for contributions to magnets fabrication and tests.

REFERENCES

[1] P. Ferracin et al., "Mechanical Analysis of the Nb_3Sn Dipole Magnet HD1", *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1119-1122, 2005.

[2] P.P. Granieri et. al., "Slip–Stick Mechanism in Training the Superconducting Magnets in the Large Hadron Collider", *IEEE Trans. Appl. Supercond.*, vol. 21, no. 5, pp. 3555-3560, 2011.

[3] S. Stoynev et al., Quench Training Analysis of Nb_3Sn Accelerator Magnets, Conf. Proc. NAPAC-2016-MOPOB40 (2016).

[4] M. Marchevsky and S. A. Gourlay, "Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks", Appl. Phys. Lett. 110, 012601 (2017).

[5] M. Marchevsky et al., "Magnetic Quench Antenna for MQXF Quadrupoles", *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017, Art. no. 9000505.

[6] M. Calvi et. al., "Statistical Analysis of Conductor Motion in LHC Superconducting Dipole Magnets", *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 223-226, 2004.

[7] E. Todesco et. al., "Training Behaviour of the Main Dipoles in the Large Hadron Collider", *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017, Art. no. 4702807.

[8] Giorgio Ambrosio, "Nb_3Sn High Field Magnets for the High Luminosity LHC Upgrade Project", *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, 2015, Art. no. 4002107.

[9] L. Bottura et al., "Advanced Accelerator Magnets for Upgrading the LHC", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, Art. no. 4002008.

[10] R. H. Bossert et. al., "Development and Test of LARP Technological Quadrupole Models of TQC Series", *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 175-178, 2008.

[11] H. Felice et. al., "Design of HQ-A high field large bore Nb_3Sn quadrupole magnet for LARP", *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1235-1239, 2009.

[12] P. Feracin et. al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC", *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016, Art. no. 4000207.

[13] A. V. Zlobin et. al., "Design and Fabrication of a Single-Aperture 11T Nb_3Sn Dipole Model for LHC Upgrades", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, Art. no. 4001705.

[14] S. A. Gourlay et. al., "Magnet R&D for the US LHC Accelerator Research Program (LARP)", *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 324-327, 2006.

[15] A. V. Zlobin, et. al., "Development of Nb_3Sn 11 T single aperture demonstrator dipole for LHC upgrades", Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA.

[16] M. Lamm et al., "A new facility to test superconducting accelerator magnets," in Proc. 1997 Particle Accel. Conf., Vancouver, BC, Canada, 1997, pp. 3395–3397.

[17] A. V. Zlobin et al., "Testing of quadrupole coils using magnetic mirror structure", AIP Conference Proceedings 1218, 1031 (2010); doi: 10.1063/1.3422262.

[18] G. Chlachidze et al., "The Study of Single Nb_3Sn Quadrupole Coils Using a Magnetic Mirror Structure", *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1692-1695, 2011.

[19] A. V. Zlobin et al., "Test results of a Nb_3Sn quadrupole coil impregnated with radiation-resistant Matrimid 5292", Proceedings of IPAC2013, Shanghai, China (2013)

[20] A. V. Zlobin, "Status of Nb_3Sn accelerator magnet R&D at Fermilab", FERMILAB-PUB-11-001-TD; CERN Yellow Report CERN-2011-003, pp. 50-58.

[21] R. Bossert et al., "Tests of insulation systems for Nb_3Sn wind and react coils", AIP Conference Proceedings Vol. 986, Issue 1, 161 (2008)

[22] G. Chlachidze et al., "Performance of HQ02, an Optimized Version of the 120 mm Nb_3Sn LARP Quadrupole", *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1-5, 2014.

[23] J. DiMarco et al., "Test results of the LARP Nb_3Sn quadrupole HQ03a", *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016, Art. no. 4005105.

[24] F. Borgnolutti et al., "Fabrication of a Third Generation of Nb_3Sn Coils for the LARP HQ03 Quadrupole Magnet", *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, 2015, Art. no. 4002505.

[25] G. Chlaachidze et al., "LARP MQXFSM1 (Mirror) Magnet Test Summary", Fermilab technical note, TD-15-018 (2015).

[26] S. Stoynev et al., "Summary of Test Results of MQXFS1 —The First Short Model 150 mm Aperture Nb_3Sn Quadrupole for the High-Luminosity LHC Upgrade", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, 2018, Art. no. 4001705.

[27] T. Strauss et al., "Quench Location in the LARP MQXFS1 Prototype", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, 2018, Art. no. 4001604.

[28] G. Ambrosio et al., "MQXFS1 Quadrupole Fabrication Report", Fermilab technical report, FERMILAB-TM-2660-TD (2016).

[29] A. V. Zlobin et al., "Quench performance of a 1 m long single-aperture

11 T Nb_3Sn dipole model for LHC upgrades", *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, 2014, Art. no. 4000305.

[30] A. V. Zlobin et al., "Status of 11 T 2-in-1 Nb_3Sn dipole development for LHC," presented at the International Particle Accelerator Conference, Dresden, Germany, 2014, Paper WEPRI097.

[31] A. V. Zlobin et al., "Testing of a single 11 T Nb_3Sn dipole coil using a dipole mirror structure," presented at the International Particle Accelerator Conference, Dresden, Germany, 2014, Paper WEPRI099.