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Applied Metrology for the Assembly of the Nb_3Sn MQXFA Quadrupole Magnets for the HL-LHC AUP

K. L. Ray, G. Ambrosio, D.W. Cheng, P. Ferracin, S. Prestemon, M.J. Solis

***Abstract*— The US HL-LHC Accelerator Upgrade Project (AUP) is building Nb_3Sn quadrupole magnets, called MQXFA, with plans to install 16 of them in the HL-LHC Interaction Regions. Variability in coil size must be dealt with at the assembly level, which requires timely and repeatable measurement of each coil. In this paper we will present the methodology used for coil measurements and the geometrical size data for the coils that have been measured thus far. We will also show the coil measurements of 8 coils before and after cold test. The Leica AT960-MR laser tracker with Spatial Analyzer software acquired to achieve these measurements has been used elsewhere in the project to great effect.**

I. Introduction

The U.S. Hi-Lumi LHC Accelerator Upgrade Project (AUP) will deliver 20 superconducting quadrupole magnets to CERN as part of the Hi-Lumi LHC upgrade [1], [2]. The project plans to build 23 magnets with 4 coils each to account for the possibility of failed magnets. This means that a minimum of 92 coils will be assembled into magnets.

Achieving the correct coil preload targets is critical in producing a successful MQXFA magnet [3]. In order to achieve this, the coils must be shimmed such that the variances of all four coils are brought to a more uniform size. This requires that each coil be measured.

The first production magnet, MQXFA03, was completed in the fall of 2019. Five additional magnets, MQXFA04, A05, A06, A10, and A11, have since passed cold testing as well. Magnets A07 and A08, however, underwent cold testing but did not pass the acceptance current [4]. Magnet A09 assembly was completed, but was discovered to have a folded insulation layer between coils that was deemed too risky to proceed to testing. Those three magnets were subsequently disassembled, and the coils were remeasured. The data from the coils of these mag-nets, as well as magnet A12, which is being assembled at the
time of this writing, are presented and discussed in this paper.

Coils for the MQXFA magnets are wound and cured [5], [6] at Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL) before being shipped to Lawrence Berkeley National Laboratory (LBNL) to be assembled into magnets. FNAL builds the 100-series coils and BNL builds the 200-series coils.

The coils used in magnets A03-A05 were measured on a Zeiss CMM, whereas the coils in MQXFA06 and later were measured with a Leica AT960-MR and T-probe.

II. Measurement Methods

A. Current Methods

The two primary goals of coil measurement at the magnet assembly stage are to 1) determine the proper amount of shim to be applied to the coil's midplanes, and 2) ensure that the bore of the assembled magnet remains clear for the eventual beam tube insertion.

A coil measurement method was established at CERN during the short model prototype stage of the project [7]. A similar measurement method is used on the production MQXFA coils, though slightly modified from CERN's method for the longer

Fig. 1. (Left) The Leica AT960-MR in the magnet assembly area (Right) Method of supporting the coils during measurement. The coil rests on four supports.

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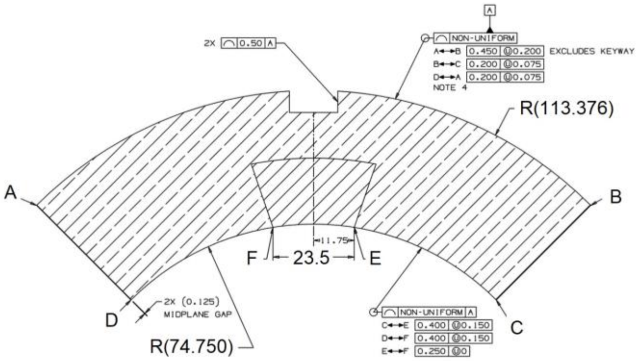

Fig. 2. Coil cross-section. A-B is the outer diameter. B-C and D-A are the midplanes, their combined deviation from nominal is the arc length excess, C-E and D-F are the inner diameter and E-F is the pole inner diameter. The notch between A and B is the keyway. (Courtesy of Miao Yu)

TABLE I
COIL TOLERANCES

Coil Section	Upper Tolerance (mm)	Lower Tolerance (mm)
Outer Diameter	+0.200	-0.250
Arc Length Excess	+0.150	-0.250
Inner Diameter	+0.150	-0.250
Pole Inner Diameter	+0.000	-0.250
Keyway	+0.250	-0.250

coils and different measurement goals, as described in the following.

Similar to the previously established method, we are measuring the coils at specifically located cross-sections along the length of the coil and comparing the coil radial size and coil azimuthal size to the nominal CAD model, with deviations from nominal reported. Each cross-section is treated independently, which means that we do not have to perfectly align the support structure (shown in Fig. 1). It also means that we do not measure any overall twist or bend in the coil.

The coil cross-section is split into different sections with different tolerances. These sections are the outer diameter, midplanes, inner diameter, pole inner diameter and keyway. See Fig. 2 for the diagram and Table 1 for the tolerances on each section.

During magnet assembly we insert five or six 1.2 mm thick Ryton R4 pads (called pions) along the inside of the coil pole at 11 different axial locations to provide support to the beam tube. We perform 11 of our cross-section measurements at these pion locations, taking additional points at the position where the pion is to be glued (see Fig. 3). This allows us to shave down the thickness of any pions where the coil protrudes further into the bore than desired. A 12th cross-section is measured at the location where we install the coil strain gauges in order to have a direct measurement of coil size at that location. Two cross-sections are measured on the lead end endshoe and one on the return end endshoe; a total of 15 cross-sections are measured per coil.

Each cross-section is fit to the CAD model using the points along the outer diameter and midplanes with equal weighting and imposing as symmetrical the two midplane offsets as shown

Fig. 3. (Left) Fixture for guiding the T-probe with a circle around the pole inner diameter to acquire more points (Right) T-probe guided by fixture

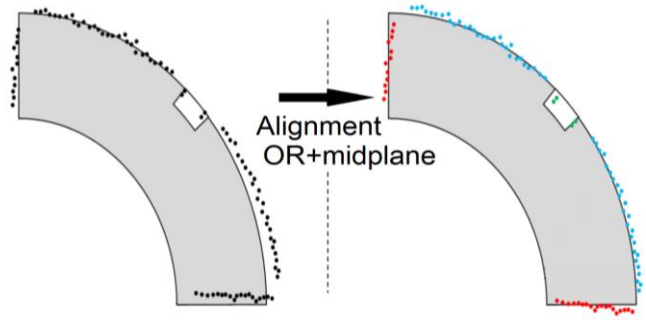

Fig. 4. The outer radius and midplane points are used to fit the points to the nominal CAD model. Each point is given equal weighting and the midplanes are imposed to be symmetrical. (Courtesy of Dariusz Pulikowski, CERN)

in Fig. 4. This is the primary difference from the method used on the short model prototypes, which used the outer diameter and keyway as the aligning features. The reason for this is that we have moved away from using the keyway to force the coils into position with respect to the support structure. Analyses suggest that contact between the collars (support structure) and pole keys (inserted in the keyway) intercept the pre-load in a way that damages coils [4].

B. *Method Changes During Production*

The coils for magnets MQXFA03, A04 and A05 were measured on a Zeiss CMM with a 2440 mm (8 ft) long envelope. This presented a few logistical issues that had to be overcome. First, this required two set ups to measure the entire 4532 mm long coil, and did not allow us access to measure the inner diameter. This also required transporting the delicate Nb_3Sn coils to a different building. Lastly, the Zeiss CMM is a shared resource whose use must be scheduled well in advance. For these reasons, AUP decided to invest in a Leica AT960-MR laser tracker with its handheld T-probe (Fig. 1 shows the laser tracker and Fig. 3 shows the T-probe). The T-probe allows us to measure points on the backside and underside of the coil, unlike a more standard corner cube.

The Leica AT960-MR allows us to perform the coil measurements in the magnet assembly area without having to transport it to another building. The laser tracker is set up halfway down the length of the coil and approximately 2 meters

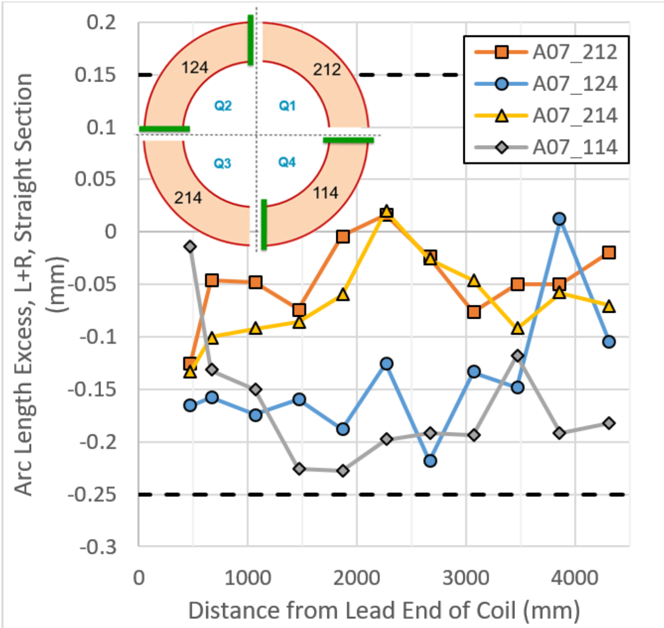

Fig. 5. Arc Length Excess at each measurement location for the four coils in MQXFA07. Most coils are smaller than nominal, and the 100-series coils are smaller than the 200-series coils. Only the straight section is shown as the coil endshoes tend to be smaller, therefore not used for shim calculations. Coil order is shown in upper left. Coil 124 and 114 in Q2 and Q4 were shimmed.

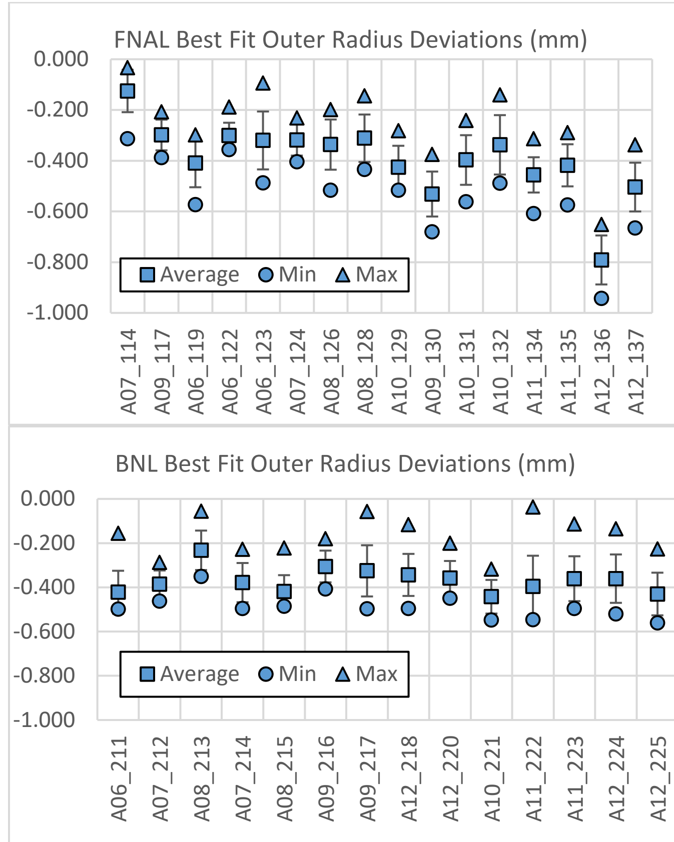

Fig. 7. Best fit outer radius deviation from nominal (in mm) for the coils in magnets A06-A12. This particular measurement does not have a tolerance limit.

away, which allows us to see the entire coil in one set-up. Our coil supports are tall enough that the T-probe can access the underside of the coil. A few drawbacks must still be noted, however: while the assembly area is climate controlled, it is not as tightly held as the metrology room with the dedicated Zeiss CMM. Some scheduling issues also remain; for example, the overhead crane cannot be used while we are performing measurements.

III. Results

A. Arc Length Excess

The critical measurement for coil shimming purposes is the coil azimuthal size, also called the arc length excess. The arc length excess is the sum of each measured midplane's deviation from the nominal CAD model. Since we fit the measurements to the CAD model using the midplanes and outer radius, the arc length excess is twice the midplane deviation. Fig. 5 shows the arc length excess at each cross-section along the straight length for each of the four coils in MQXFA07. From this data, we were able to determine that coils 124 and 114 should have 0.050 mm shims added to each midplane to match the arc length of the other two coils. We can also see that the arc length excess can vary down the length of the coil by 0.142 mm (coil 212) to 0.230 mm (coil 124). We use only one thickness of shim for the

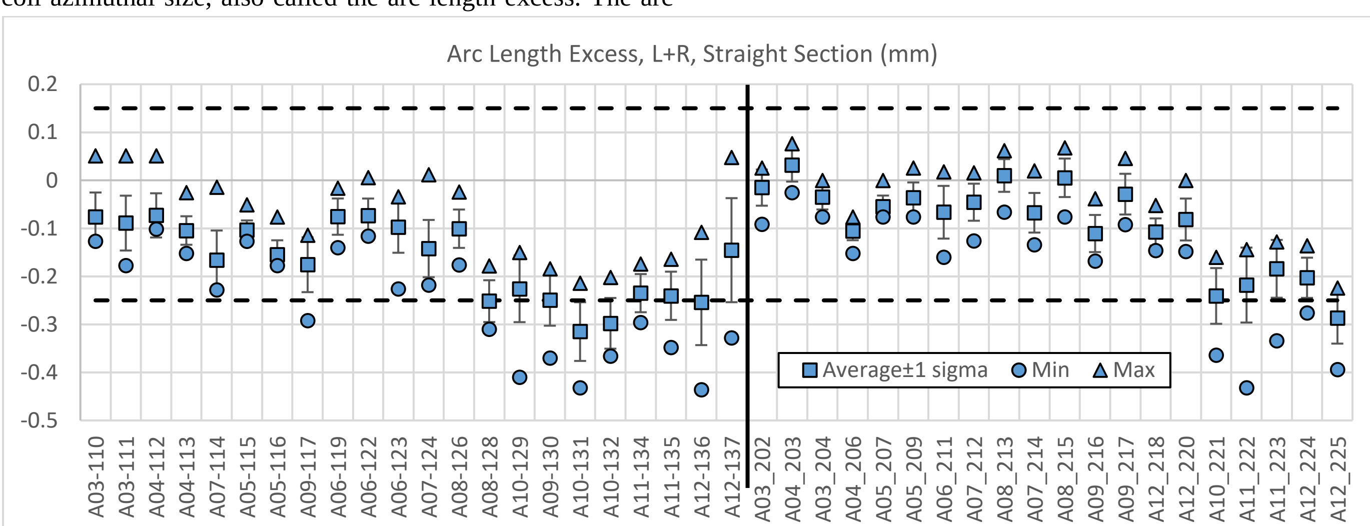

Fig. 6. Average Arc Length Excess for all coils for magnets A03-A12 in order of production. FNAL's 100-series first then BNL's 200-series. Y-axis is arc length excess (mm). Coils labeled A03, A04, A05 were measured on the Zeiss. There has lately been a drop in coil size that we are investigating.

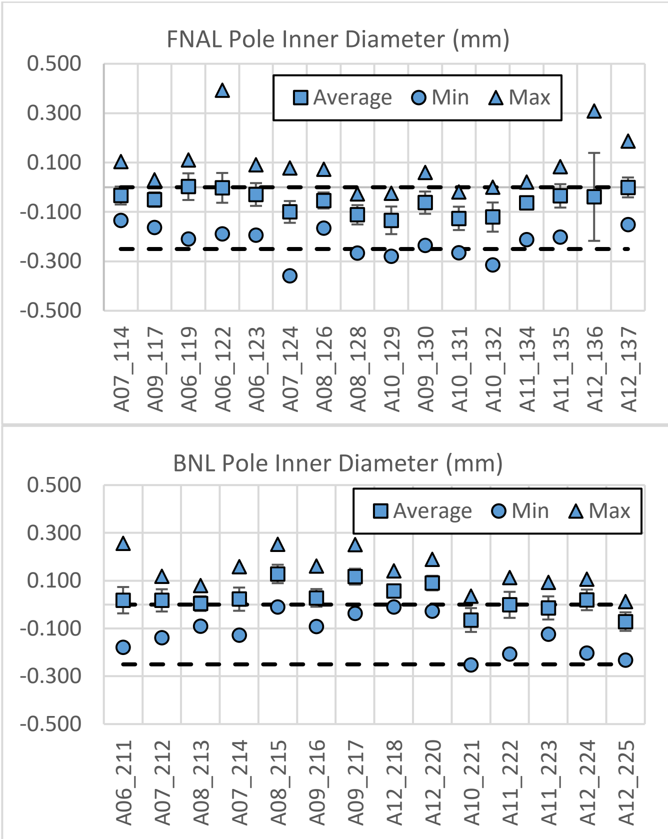

Fig. 8. Pole Inner Diameter deviation from nominal (mm) for the coils in magnets A06-A12. Positive numbers indicate a more material condition that requires removing material from pions.

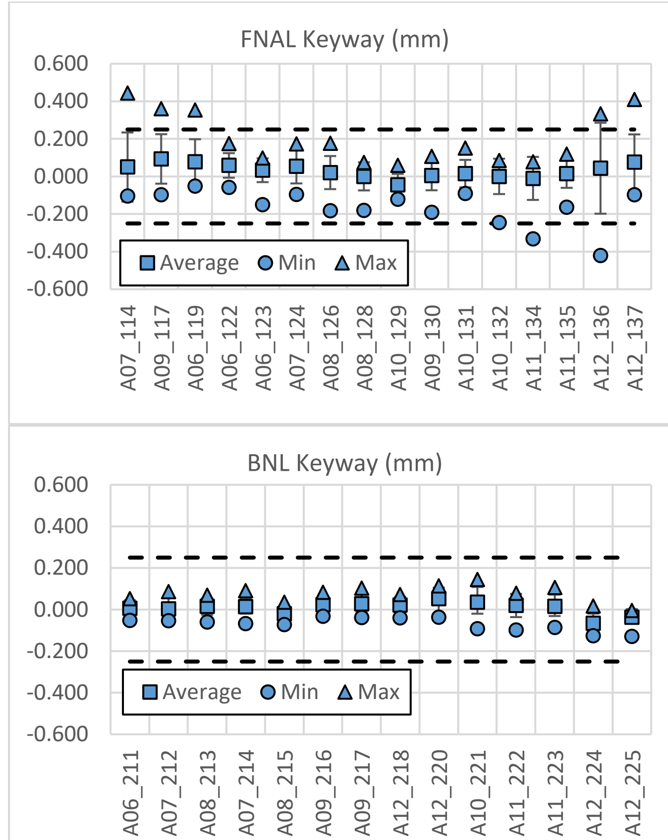

Fig. 9. Keyway offset (mm) for the coils in magnets A06-A12. Positive numbers indicate a keyway shifted to the left when viewed from the lead end with the outer radius up. Coils 114, 117 and 119 were out of spec in the first two cross-sections.

entire coil, as putting a step in the thickness could induce uneven loading and strand breakage.

To track this data over many coils, we collapse the data down into a minimum, maximum and average value over the entire length of the straight section, with error bars showing ±1σ, as shown in Fig. 6. As can be seen in Fig. 6, coil 128-136 and 221-225 exhibit a significant reduction in arc length. An investigation was initiated to identify the possible causes, focusing on both coil parts dimensions and coil fabrication process. At the time of the submission of the paper, a clear cause has not yet been found.

B. Outer Radius

The coil radial size is also monitored. We ensure that the minimum, maximum and average deviation from the nominal outer radius remains within the tolerance, and also track the radius of the best fit circle to the measured points, which does not have a fixed tolerance. Fig. 7 shows the difference between the nominal outer radius and the best fit circle radius. The coils tend to have a smaller outer radius than nominal. This means that the midplane blocks tend to be pushed towards the center of the aperture.

C. Inner Diameter and Pole Inner Diameter

The inner diameter and the pole inner diameter are measured to ensure adequate bore clearance. The pole inner diameter data are taken directly in the location where we place the pions that support the beam tube. Fig. 8 shows the pole inner diameter deviation from nominal for the coils in magnets A06-A12. Data from magnets A03-A05 are not available, as they were measured under the original set-up that did not allow for inner diameter measurement. Positive numbers indicate a more material condition. The 200-series coils from BNL tend to protrude into the bore more than the 100-series coils from FNAL. For each pion location with an out of spec pole inner diameter measurement, the pion would be shaved down to ensure bore clearance. For the most out of spec coils, 215 and 217, the coils were positioned in one of the upper quadrants, so that the bore tube does not sit on the thinner than designed pions. The pole inner diameter tolerance is the tightest of all the coil tolerances, and not reliably achievable.

D. Keyway

The position of the coil keyway is measured to determine if the pole key that is inserted into the keyway needs modification in any way. Fig. 9 shows the keyway deviation from nominal for magnets A06-A12. Positive numbers indicate the keyway is

TABLE II
DIFFERENCE BEFORE AND AFTER PRELOADED AND/OR TESTED COILS

Magnet, Quadrant, and Coil Number	Difference in Best Fit Outer Diameter (mm)	Difference in Arc Length Excess (mm)
A07, Q1, 212	0.149	0.068
A07, Q2, 124	0.283	0.074
A07, Q3, 214	0.157	0.045
A07, Q4, 114	0.309	0.102
A08, Q1, 215	0.384	0.135
A08, Q2, 126	0.493	0.132
A08, Q3, 213	0.350	0.093
A08, Q4, 128	0.470	0.096
A09, Q2, 216	0.183	0.098
A09, Q3, 130	0.059	0.051

towards the left of a viewer standing on the end of the coils with the leads, with the coil outer radius up. Coils 114, 117 and 119 were found to have a short section of keyway misaligned at the lead end of the coil. The information was communicated to the team at FNAL, who discovered the cause of the issue and fixed it. The pole keys for those three coils were modified to ensure that the pole keys remain centered even though the keyway is off.

E. After disassembly

Magnets MQXFA07, A08 and A09 were disassembled and the coils remeasured. Magnets A07 and A08 were disassembled after failing cold test and magnet A09 only after pre-loading. Only two coils' data is shown here, pending measurement processing of the two others. The difference in the arc length excess and best fit outer diameter before and after disassembly are shown in Table 2. A positive number indicates that the coil is smaller after disassembly. The coil size changes in magnet A07 resulted in an overall decrease in coil pack height and width of 0.125 mm.

IV. OTHER USES OF THE LEICA

The Leica AT960-MR was acquired to perform coil measurements as discussed in the bulk of this paper. Having this tool and operators dedicated to AUP, however, has additional benefits.

Firstly, when the coils are assembled into the first level of support structure, called the coil pack, we measure the height, width and squareness of the coil pack. Prior to the COVID-19 epidemic, we did this with a standard micrometer based measurement fixture that required 2 technicians to stand less than 2 meters apart while taking 26 measurements. We replaced this measurement fixture with the use of this laser tracker during the pandemic.

Secondly, when we determined that the coil pack squareness was more critical [4], [8], we added additional width and height measurements after each torqueing pass to allow us to dial in the coil pack squareness. The laser tracker allows quicker measurement feedback in a shorter amount of time compared with the standard measurement fixture. This is extremely beneficial, as up to nine iterations have been necessary to dial in the squareness of the coil pack to specifications.

Thirdly, fiducial measurements taken of MQXFA10 revealed a 0.500 mm bend over its ~5 m length, which is not something that can be caught by eye or conventional measurement fixtures. A step to measure the straightness of the outer support structure with this laser tracker was added prior to inserting the coil pack.

V. CONCLUSION

The assembly of Nb_3Sn accelerator magnets requires many precise interfaces over long length scales. The use of the Leica AT960-MR has shown itself to be capable of taking measurements of coils and structural elements with the required accuracy for the purpose of generating these precise fits. The HL-LHC AUP has benefited from developing metrology skills in the magnet assembly build team.

Statistical data on coil size for a full production run of Nb_3Sn coils has not previously been available. From the first 10 MQXFA magnets we can see that arc length excess can vary over the length of the coil by on average 0.150 mm and as much as 0.300 mm. The tolerance range of 0.400 mm for arc length excess is likely achievable, although further investigation into the cause of the decrease is necessary to make that a definitive statement. The tolerance range of 0.250 mm for pole inner diameter has not been achievable, requiring adjustment of other parts of the assembly to avoid blocking the bore. Systematic differences between coils coming from different labs are visible despite efforts to closely match the tooling in each lab. The project has aimed to use two 100 series and two 200 series coils per magnet, alternating series by quadrant.

For future work, it may be informative to search for correlations between a full set of consistently taken coil geometry data and the geometric field quality of the built magnets.

The authors hope this paper provides useful information to those looking to build Nb_3Sn magnets in the future.

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REFERENCES

[1] G. Ambrosio, "Nb_3Sn high field magnets for the high luminosity LHC upgrade project," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 4002107.

[2] D. W. Cheng *et al.*, "Fabrication and assembly performance of the first 4.2 m MQXFA magnet and mechanical model for the Hi-Lumi LHC

upgrade," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018, Ar. no. 4006207.

[3] P. Ferracin *et al.*, "Development of MQXF: The Nb_3Sn low-β quadrupole for the HiLumi LHC," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 4000207.

[4] G. Ambrosio *et al.*, "Challenges and lessons learned from fabrication, test and analysis of 10 MQXFA low beta quadrupoles for HL-LHC," *IEEE Trans. Appl. Supercond.*, submitted for publication.

[5] E.F. Holik *et al.*, "Fabrication and Analysis of 150-mm-Aperture Nb_3Sn MQXF Coils," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. No. 4000907

[6] E.F. Holik *et al.*, "Fabrication of First 4-m Coils for the LARP MQXFA Quadrupole and Assembly in Mirror Structure," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Ar. No. 4003605

[7] J. F. Troitino *et al.*, "Applied metrology in the production of superconducting model magnets for particle accelerators," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018, Art. no. 4002106.

[8] D. W. Cheng *et al.*, "The challenges and solutions of meeting the assembly specifications for the 4.5 m long MQXFA magnets for the Hi-Luminosity LHC," *IEEE Trans. Appl. Supercond.*, submitted for publication.