The Challenges and Solutions of Meeting the Assembly Specifications for the 4.5 m Long MQXFA Magnets for the Hi-Luminosity LHC

D.W. Cheng, G. Ambrosio, P. Ferracin, L. Garcia Fajardo, S.O. Prestemon, K.L. Ray, G.L. Sabbi, M. Solis, G. Vallone, X.R. Wang

***Abstract*— The U.S. High-Luminosity LHC Accelerator Upgrade Project (HL-LHC AUP) has, in the recent years, developed assembly specifications for the 4.5 m long MQXFA magnets, which are 150 mm aperture high-field Nb_3Sn low-β quadrupole magnets that are being built for the CERN Hi-Luminosity LHC (HL-LHC) upgrade. While the specifications were based on lessons learned from the LHC Accelerator Research Program (LARP) effort and the MQXFS and MQXFA prototype magnets, the experience gained from having both MQXFA07 and MQXFA08 magnets not meeting performance specifications during cold testing actually catalyzed a better understanding of the impact of the target assembly specifications and a subsequent refinement of the same. This paper summarizes a body of assembly data from the Pre-Series (MQXFA03-MQXFA07) and Series magnets (MQXFA08-MQXFA11) that have been built to date, and discusses the processes employed to successfully face the challenge of ensuring that the assembly specifications are met for the duration of the project.**

***Index Terms*— High Luminosity LHC, Interaction Regions, Low-β Quadrupoles, Nb_3Sn magnets**

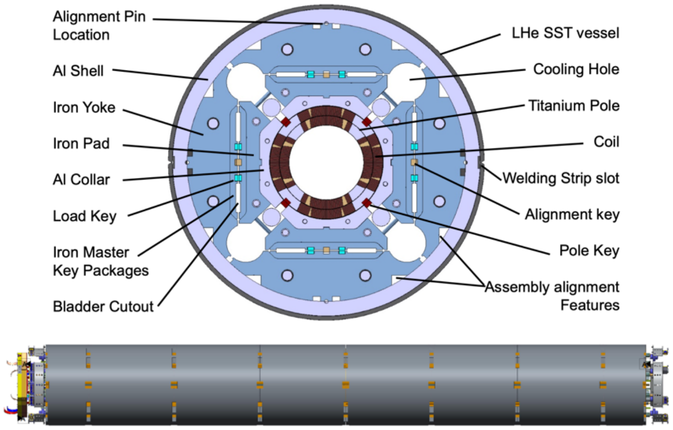

Fig. 1. Cross section of the MQXF magnets (top); the LHe SST vessel is added during the assembly of the cold mass. (Bottom) side view of the 4.56 m long MQXFA magnet. The LHe SST vessel is part of the cold mass assembly.

I. INTRODUCTION

THE US High-Luminosity LHC Accelerator Upgrade Project (HL-LHC AUP, or "AUP") [1] is in the process of fabricating ten cold masses (8 + 2 spares) to be installed in the LHC Interaction Regions as part of the High Luminosity LHC (HL-LHC) Project [2], [3]. Each cold mass contains two 4.5 m long MQXFA magnets, each with a magnetic length of 4.2 m using Nb_3Sn superconductor. CERN is also fabricating ten cold masses (8 plus 2 spares), though each will only contain a single 7.2 m long MQXFB magnet, which has an identical cross-sectional design as the AUP magnets [4], [5], as shown in Fig. 1. The MQXFA magnet effort for AUP is a collaboration between CERN, Fermi National Accelerator Laboratory, Lawrence Berkley National Laboratory, and Brookhaven National Laboratory.

These magnets are a direct descendent of the LARP program where the development of processing, limits, and the scale-up of Nb_3Sn accelerator magnets were explored [6]-[10]. As the AUP formally started in 2016 the first magnet built was the short model, MQXFS, which is a 1.5 m long model of the same cross-section as MQXFA/B. Six of these short models were built and tested [11]-[15]. Additionally, each longer MQXFA/B magnet had two prototypes that were built and tested as their respective final scale-up of the MQXF magnets before production formally started [16]-[19].

The experience gained from both the short models and the long prototypes informed a set of specifications detailed in [20], which were designed to guarantee a uniform and controlled stress in the brittle Nb_3Sn superconducting coils. To this end dimensional tolerances and targets were defined on the sub-components and sub-assemblies of the mechanical structure. Additionally, some of the assembly processes were also defined in order to meet these specifications.

To date, 11 MQXFA magnets have been built and tested, grouped in both "Pre-series" (MQXFA03-MQXFA07), and "Series" (MQXFA08-MQXFA11) magnets. Test results are reported

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D. W. Cheng, P. Ferracin (pferracin@lbl.gov), L. Garcia Fajardo (lgarciafajardo@lbl.gov), S.O. Prestemon (soprestemon@lbl.gov), K.L. Ray (klray@lbl.gov), G.L. Sabbi (glsabbi@lbl.gov), M. Solis (msolis@lbl.gov), G. Vallone (gvallone@lbl.gov), X.R. Wang (xrwang@lbl.gov) are with Lawrence Berkeley National Lab, Berkeley, CA 94720, USA (e-mail: dwcheng@lbl.gov).

G. Ambrosio (ambrosio@fnal.gov) is with Fermi National Accelerator Laboratory, Batavia, IL 80510 USA.

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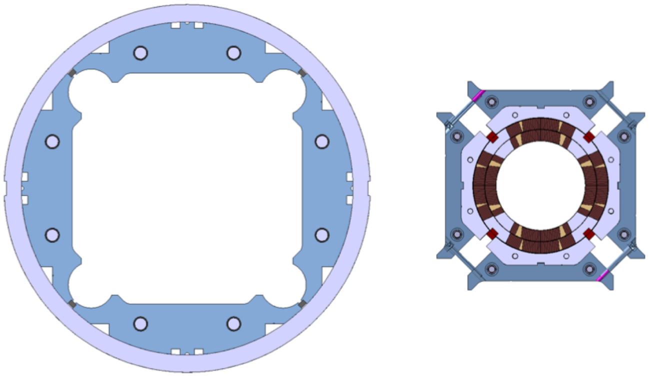

Fig. 2. (Left) Shell yoke subassembly, and (Right) Coil Pack subassembly.

in [21]-[22]. In this paper, we report on challenges encountered when trying to achieve some of these critical specifications, the lessons learned from the limitations observed in magnet testing, and finally the solutions employed in order to correct findings to prevent future occurrences.

II. CRITICAL MAGNET ASSEMBLY SPECIFICATIONS

Fig. 2 shows the two primary magnet subassemblies: the shell-yoke and coil-pack. Details of the design of the MQXFA magnets have been well described but for the purpose of discussion a simplified description is repeated here. The coil-pack sub-assembly (right) includes four coils wound around a Titanium-alloy winding pole, which includes a G11 pole key for assembly alignment. The coils are surrounded by aluminum collars and bolted iron load pads. The yoke-shell subassembly (left) is combined with the coil pack in the magnet, where two trapezoidal master keys, containing two loading (interference) keys and one central alignment key, are inserted to provide room for the water-pressurized bladders, which are used to pre-compress the coil and pre-tension the shell while the interference keys are inserted. The bladders are removed when the preload process has been completed.

The use of the bladder and key method allows for a relatively low preload at room temperature in order to protect the brittle Nb_3Sn superconductor. Specifications define that the average azimuthal coil pole preload target shall be -80 ± 8 MPa at room temperature, with additional specifications to control the effective coil average size variation to between ±100 μm, which would maintain the coil stress variation within ±13 MPa.

With the goal of maintaining a uniform preload on the Nb_3Sn coils the following specifications related to the Coil Pack sub-assembly are listed below. These will be discussed in the next section in light of the magnet performance limitations experienced during vertical testing campaigns.

A. Coil Pack Horizontal and Vertical Uniformity and Squareness

Once the coil pack has been assembled and the load pad bolts have been torqued the horizontal and vertical dimensions of the coil pack are measured at two places in each orientation at each axial location along the coil pack assembly.

- *The uniformity of the vertical and horizontal dimensions along the z axis shall be within ±0.200 mm*
- *The squareness of the vertical and horizontal dimensions along the z axis shall be within ±0.900 mm*

B. Pole Key Gap

The pole-key gap is measured on all the four coils and along the z-axis at 11 axial locations. Fig. 3 shows the detail of the pole key and collar interface; note two pole key gaps per coil are defined. The pole key gap specifications were set as the following:

- *The average pole key gap (per side) among the four coils on each longitudinal location shall be +0.200 ±0.050 mm.*

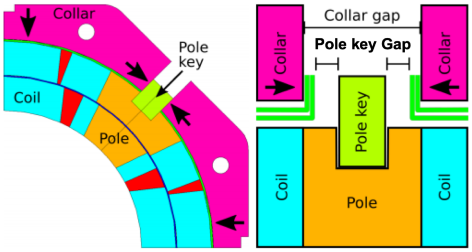

Fig. 3. (Left) Quadrant view of coil pole, and (Right) detailed view of the pole key and collar interface.

III. MQXFA07 AND MQXFA08 TEST LIMITATIONS

After the first four magnets (MQXFA03-MQXFA06) were built and tested successfully, the last Pre-Series magnet, MQXFA07, experienced a limited magnet performance and did not pass acceptance testing. Magnet training and performance details are discussed in [22], and the limiting coil was in quadrant 3. At the time these test results were being observed the assembly of the first Series magnet, MQXFA08, was underway; that magnet was completed and shipped to BNL for testing. This magnet's training performance is also discussed in [22] and, unfortunately, it also suffered from a similar limitation in the Q3 coil.

A. MQXFA07 Disassembly Observations

MQXFA07 was shipped back to LBNL and disassembled after the failing to meet acceptance criteria. A plan to measure various components and subassemblies was implemented so that the post-testing changes could be measured and compared with the untested magnet configuration. This included a warm magnetic measurement and various mechanical size measurements, including that of the coil pack once it was extracted.

In particular, the coil pack horizontal and vertical measurements were taken along with the pole key gaps. When compared to the measurements taken before the preload operations, the surprise discovery was that any asymmetries observed in the original coil pack actually persisted through the preload and testing of the magnet. For example, see Fig. 4 for the pole key

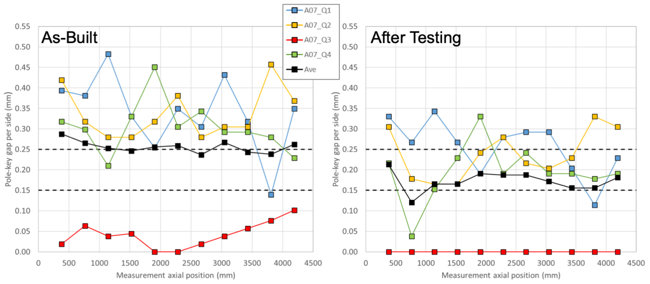

Fig. 4. MQXFA07 pole key gaps, as-built (left) and after-testing (right), measured along the axial length of the coil pack subassembly.

gap measurements, before and after. This coil pack originally had a smaller pole key gap in the Q3 coil, yet the average of the pole key gaps still met specifications. The post-test measurements showed that the Q3 pole key gap actually closed completely while the other quadrants' gaps all were uniformly reduced.

The subsequent disassembly of the MQXFA08 magnet also revealed a similar condition, and further FEA analyses of this asymmetric condition suggested that the closed pole key gap would reduce the effective azimuthal preload a coil would experience. A study of the strain gauge data from these two testing campaigns also seems to suggest this reduced preload effect since the axial behavior of the Q3 coils and axial rods appear to be less constrained as the other quadrants during testing. These observations are reported in [23]. The final confirmation, however, came from extensive micrographic analysis that was performed on the two limited coils from MQXFA07 and MQXFA08, which showed extensive broken filaments at the locations of interest predicted by the FEA [22].

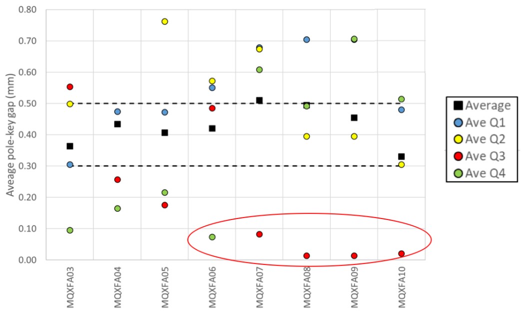

Fig. 5. Plot of pole key gaps by quadrant, per magnet. Measurements circled indicate the asymmetric pole key gap measurements that appear to be systematic, first in Q4 (MQXFA06) and later in Q3 (MQXFA07-MQXFA10).

B. *Revised Specifications and Procedures*

Ultimately, these findings from the disassembly of these magnets contradicted the assumptions that the coil pack would "square up" and that the pole key gaps would even out when the magnet was preloaded. Additionally, these findings also suggested that the final coil pack must be built as square as possible, and that the pole key gaps must be as uniform as possible prior to preload operations—these are, in fact, crucial factors to the performance of the magnet.

To this end, a new method of torqueing and measuring the coil pack subassembly was explored with the MQXFA07 coil pack before it was fully disassembled. An iterative process of torqueing combined with measurement feedback was developed from this exercise in order to achieve the squareness and uniformity of pole keys gaps. A discussion of the tools and methods used in the metrology of the coil pack measurements can be found in [24].

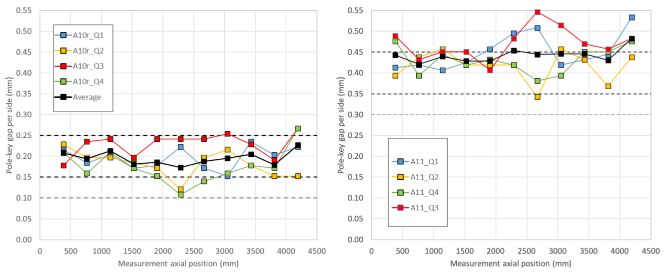

Fig. 6. Pole key gaps for MQXFA10 re-squared coil pack (Left), and MQXFA11 as built coil pack (Right).

An updated pole key gap specification was also drafted, which both increased the gap and added a minimum acceptable pole key gap, stated as follows:

- *The average pole key gap (per side) along the magnet length shall be +0.400 ±0.050 mm in each quadrant.*
- *The minimum pole key gap (per side) in any quadrant and in any longitudinal location shall be > +0.300 mm.*

It is noted that a byproduct of the improved pole key gap uniformity is that the squareness of the coil pack also improves significantly better than the ±0.900 mm called out by the specification. This was not revised in the document, however.

C. *MQXFA10 Coil Pack Re-Squaring and MQXFA11*

A stop-work had also been issued for the MQXFA10, which had already been preloaded by this time, pending the outcome of these investigations. Measurement data of the magnets built up to that point was reviewed, and it revealed a systematic pole key gaps asymmetry, starting from MQXFA06. See Fig. 5. It was later determined that this systematic change had its roots in the COVID-19 pandemic protections, and the social distancing requirements that were implemented prevented the most experienced technician in the coil pack assembly operation from participating.

Armed with the newly developed procedure of coil pack squaring from the MQXFA07 disassembly, the MQXFA10 coil pack was also re-squared to ensure more uniform pole key gaps. Fig. 6 (left) shows the resulting more uniform pole-key gaps achieved after this exercise. Not fully disassembling the coil pack avoided additional weeks of delay, while at the same time, there was confidence gained from the successful MQXFA03-06 magnets (that were built to the original specified pole key gaps) that the magnet would meet performance requirements. MQXFA10 was subsequently preloaded and it successfully passed the vertical testing campaign [22].

MQXFA11 was the first magnet that was fully built to the new pole key gap specification. This entailed machining of the G11 pole keys in order to provide the necessary additional gap clearance, and the coil pack was assembled using the newly

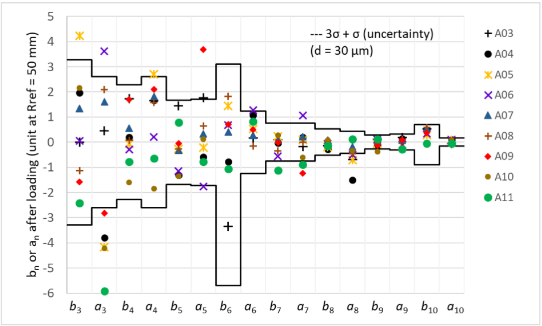

Fig. 7. Magnetic field harmonics, measured for each magnet MQXFA03-A11.

developed procedures to improve squareness. Fig. 6 (right) shows both the larger and more uniform of pole key gaps that were achieved as a result. Once again, this magnet successfully passed the vertical testing campaign [22].

IV. ADDITIONAL SPECIFICATION CHALLENGES

A. *Magnetic Field Harmonics*

At a reference radius of 50 mm the field harmonics of the MQXFA magnets shall be optimized at nominal current. Graphically represented, the envelope of allowed harmonics is shown in Fig. 7, with measured data plotted from each of the magnets built to date. Measurements are taken at the coil pack assembly stage and after the magnet has been preloaded. Minor corrections to some harmonics can then be made by using magnetic shims (ARMCO iron bars) to fill particular bladder slots in the magnet. Not all magnets require shimming, but a further discussion of this method can be found in [25]. It is yet to be seen whether the changes implemented to the coil pack assembly squareness consistently affect the harmonics in a beneficial way.

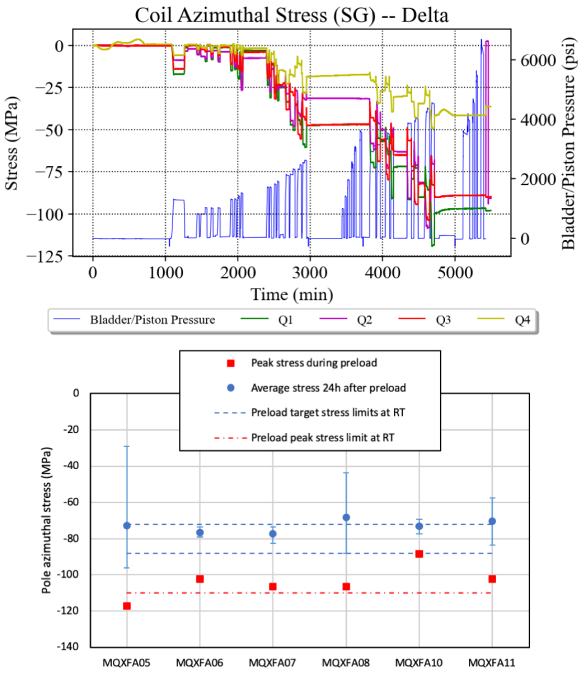

Fig. 8. (Top) Pole azimuthal stress during the preload operations of MQXFA05, showing that one coil experienced -117 MPa of stress. (Bottom) Summary plot of each magnet's average, and max/min stresses observed in coils during preload operations; max and min values are shown as the error bars.

B. *Magnet Preload processes*

During magnet preload operations every bladder pressurization cycle requires an overshoot in order to insert the interference keys. A maximum stress of -120 MPa in the coil at room temperature has been established based on experience from LARP short model magnets [7]. A more conservative specification of -110 MPa was chosen in order to account for dimensional variations of the longer MQXFA coils, which should not be exceeded at any point during the preload operations. FEA analyses show that when the bladders in one quadrant are pressurized the two coils opposite of those bladders see the higher stress. This understanding allows us to choose the order of quadrant pressurizations, thereby keeping at a minimum the stress excursion that any one coil may experience.

Of the magnets built to date, only MQXFA05 exceeded this value. See Fig. 8. It should be noted, however, that in spite of this excursion, the magnet has since successfully passed the endurance test, surviving more than 40 induced quenches and multiple thermal cycles. The SG and mechanical performance of that and the other MQXFA magnets is discussed in [23].

A method of preloading without the usual large overshoots was recently developed at CERN for their MQXFB magnets [26]. While this option is now available, the additional tooling and bladders required complicates the implementation for MQXFA assemblies—and it may not even be necessary; this is still under discussion.

V. SUMMARY AND OUTLOOK

This paper describes some of the critical specifications that each assembled MQXFA magnet must meet in order to pass acceptance criteria. Significant challenges have been encountered, namely with the limitations observed in the Q3 coils of both MQXFA07 and MQXFA08. Solutions to these challenges have included redesign, updates of specifications, and process refinements. Magnets MQXFA10 and MQXFA11, built to updated specifications, have been successfully tested. These last two test results suggest that, while building magnets that meet specifications remains a challenge, we have systems and processes in place to enable us to build these magnets that will pass all criteria successfully.

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