US HL-LHC Accelerator Upgrade Project

Report of the Review of QXFA Series Coils Fabrication Specifications

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TABLE OF CONTENTS

1. GOAL AND SCOPE 3
2. TECHNICAL DETAILS 3
3. COMMENTS 4
4. RECOMMENDATION 4

1. Goal and scope

The HL-LHC AUP project is starting the fabrication of QXFA Series Coils to be used in MQXFA Series Magnets (MQXFA08-23). MQXFA magnets [1] are the low-beta quadrupoles to be used in Q1 and Q3 for the High Luminosity LHC. If QXFA Series Coils are fabricated according to the QXFA Series Coil Production Specification [2] they will be used in MQXFA Series Magnets. If these magnets meet MQXFA requirements [3] they will be used in Q1/Q3 cryo-assemblies to be installed in the HL-LHC.

Several QXFA Pre-Series coils were fabricated at BNL and FNAL, and four of them were successfully tested in MQXFA03 [4, 5]. Specifications for Pre-Series coils were included in the MQXFA Final Design Report [1].

The specifications for QXFA Series Coils are based on the specifications used for Pre-Series coils, the feedback from Pre-series coils fabrication and test, feedback from CERN and from the review of the epoxy impregnation process performed by AUP consultant Dave Evans.

The goal of this review is to assure that the specifications for QXFA Series Coils [2] are complete and that coils fabricated according to these specifications are going to allow MQXFA magnets to meet MQXFA Functional Requirement Specifications [3].

2. Technical details

Committee

Steve Gourlay (LBNL), chairperson
Paolo Ferracin (LBNL)
Susana Izquierdo Bermudez (CERN)
Arup Ghosh (BNL - retired)

Date and Time

April 23, 2020; starting at 7/9/10/16 (LBNL/FNAL/BNL/CERN)

Location/Connection

Video-link by Zoom, info by email.

Link to agenda with talks and other documents

https://indico.fnal.gov/event/24081/

3. Review Charges response

The committee was requested to answer the following questions:

1. Are the specifications for QXFA Series Coils [2] complete? Do they (including referenced documents) cover all steps of coil fabrication and QC?
2. Are coils fabricated according to these specifications going to allow MQXFA magnets to meet MQXFA Functional Requirement Specifications [3]?
3. Are these specifications sufficiently tight to allow monitoring trends before they may cause MQXFA magnets to fail Functional Requirement Specifications [3]?
4. Are these specifications not excessively tight in order to avoid excessive burden on project cost and schedule?

4. Comments

The Committee agrees that the QXFA coil specifications and supporting documents that were provided support a "yes" response to each of the charge questions with some minor qualifications discussed below.

Coil Winding

The winding procedures have quite wide parameter ranges intended to accommodate the different winding machines at BNL and FNAL. There was no target winding tension given. The committee suggests it would be better to consider narrowing the parameter range and making them specific for each system. This may minimize the coil to coil variation.

In the coil design diagram the wedges are referred to as Cu which they are not. In order to avoid confusion we suggest just calling them wedges.

Coil Curing

For coil curing the soak temperature is give as 150 ^{0}C +40/-0 ^{0}C. It was subsequently explained to the committee that the + 40 ^{0}C is to allow for the initial overshoot of the curing system. We suggest that this be clarified in the specification.

Reaction

In general, the Committee suggest comparing the different steps with those followed at CERN. There may be some small, inconsequential differences but it would be important to at least be aware of the differences and in some cases converge at some points.

The text in the Notes section of **4 QXFA Coil Fabrication Specification: Heat Treatment** reads:

"The temperature of all thermocouples set on the reaction fixture shall be within +/- 7 °C of target temperature during step 2 (soak at 210 °C) and step 4 (soak at 400 °C). Scope for this specification starts 4 hours after the start of the soak (per the definition below) and ends at the start of the subsequent ramp."

At CERN, the maximum allowed temperature is set to a value that is 10 °C lower than the lowest melting temperature of the material phases present during the concerned dwell. This would mean that the dwell at 200 ^{0}C should have a maximum of 217 ^{0}C; that at 400 ^{0}Cshould have a max of 405 ^{0}C. Since the spread of temperatures as seen by the thermocouples can be +/- 7 ^{0}C, the Step 4 dwell target temperature should be reduced to 395 ^{0}C.

To validate the coil reaction, our understanding is that the witness samples consisting of extracted and round strands (that are included with the coils) must meet the minimum requirements of the strand and the cable specification. There is reference to the requirements in the final design report. However, the Committee suggests adding a table (e.g. see below) with supporting text to the Series Coil Production Specification.

1. Witness samples shall be tested shortly after each coil heat treatment and shall demonstrate critical current and RRR above requirement values [1].

Extracted Strand critical current at 4.2 K and 12 T	> 600	A
Extracted strand critical current at 4.2 K and 15 T	> 314	A
Extracted strand *RRR* after reaction	> 100	

Impregnation

Tolerances in temperature for the epoxy curing cycle seem large, 110° C ± 10 °C and 125 °C ± 10 °C We note that if tolerances are included, the curing and post-curing temperatures can overlap. The committee suggests assessing the temperature spread and determine if it is a source of concern or not.

Magnet Length and Integrated Gradient

The specification states "The MQXFA magnetic length requirement is 4.2 m with a tolerance of ± 5 mm at 1.9 K. The precision of the measurement of the integrated gradient shall be within ±0.02%."

The elements required to assess if this tolerance can be reached were not given during the review. If the +/- 5 mm coil length variation is mainly coming from the coil ends and not from the straight section, it should be ok, but in the current version of the documents provided this is not captured.

Aperture Requirement

Table 1.1 "Coil Dimensions Specification" and the associated text created some initial confusion and as it was understood, seemed to generate an inconsistency. The subsequent explanation is the following: The tolerances on the inner and outer radius are given as profile tolerances, therefore the minimum inner radius (with respect to the magnet aperture) is given by the + 0.150 mm tolerance.

When the magnet is assembled about 125 um of insulation is removed from the nominal insulation on the coil OD. This means the inner radius of the coil in the magnet should be slightly outward with respect to the nominal position.

It was also noted that the additional material on the inner radius (0.150 mm max) is on the midplanes, so it doesn't push the pions/coil bumpers inward. Even so, the Committee suggests it may be prudent to measure the coil inner radius where the pions/bumpers will be placed.

5. Recommendations

1) In order to prevent exceeding temperature limits during reaction the Committee recommends that the dwell at 200 ^{0}C should have a maximum of 217 ^{0}C; that at 400 ^{0}Cshould have a max of 405 ^{0}C. Since the spread of temperatures as seen by the thermocouples can be +/- 7 ^{0}C, the Step 4 dwell target temperature should be reduced to 395 ^{0}C.

2) Change the wording in Table 1 from "inner/outer radius" to "inner/outer radius profile" and possibly add an explanation in the caption or text.

3) Perform a thorough review of coil tolerances with respect to the aperture requirement.

6. References

1. MQXFA Final Design Report, US-HiLumi-doc-948.
2. QXFA Series Coil Production Specification, US-HiLumi-doc-2986.
3. MQXFA Functional Requirements Specification, US-HiLumi-doc-36.
4. MQXFA03 Quadrupole Fabrication Report, US-HiLumi-doc-2279.
5. *MQXFA03 Test Report*, US-HiLumi-doc- in progress