US HL-LHC Accelerator Upgrade Project

MQXFA05 Coil Acceptance Review Report

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Revision History

Revision	Date	Section No.	Revision Description
V0	2/21/2020	All	First release
V1	3/6/2020	5, 7, 8, 9	Updated after coil 209 receiving QC and witness samples

Contents

1 Review Goals and Scope

MQXFA05 is the third pre-series low-beta quadrupole (MQXFA) to be used in the Q1 and Q3 Inner Triplet elements for the High Luminosity LHC. The HL-LHC AUP project is planning to start assembly of MQXFA05 magnet in February 2020. If MQXFA05 meets MQXFA requirements [1] it will be used in a Q1/Q3 cryo-assembly to be installed in the HL-LHC.

QXFA coils 115, 116, 117, 207 and 209 are available for MQXFA05 assembly. Coil 115 was approved for use in MQXFA04 [2] and is assumed approved for use in MQXFA05. If all coils are approved, one of the coils will be reserved as a spare.

The reviewers are requested to assess that coils 116, 117, 207, 209 and their conductor meet specifications [3-4], and to evaluate the impact of non-conformities in strands, cables and coils.

2 Review charges

The committee is requested to answer the following questions:

1. Do the coils under review meet MQXFA coil specifications [3]?
2. Are conductor/coil fabrication and QC data of these coils adequate for allowing MQXFA05 to meet MQXFA requirements [1]?
3. Are there major non-conformities? If answer is yes, have they been adequately documented and processed?
4. Do you have any other comment or recommendation regarding these coils and their conductor for allowing MQXFA05 to meet MQXFA requirements [1]?

3 References

[1] MQXFA Functional Requirements Specification, US-HiLumi-doc-36.

[2] MQXFA04 Coils Acceptance Review, US-HiLumi-doc-2432.

[3] MQXFA Final Design Report, US-HiLumi-doc-948 sections 3 and 5.1.1

[4] QXFA Coil Fabrication Electrical QA, US-HiLumi-doc-521 step 16.

4 Agenda and Presentations

MQXFA05 Coils Acceptance Review

Wednesday, January 29, 2020 from **09:00** to **12:30** (US/Central)
at **by Zoom**

Description Meeting by Zoom, info by email
Material: Charge | Coil Electrical QA | MQXFA Final Design Report | MQXFA Functional Requirements Spec | MQXFA04 Coils Acceptance Review Report

Wednesday, January 29, 2020

09:00 - 09:20 Introduction and Review Charge *20'*
Speaker: Giorgio Ambrosio (FNAL TD/MSD)
Material: Slides

09:20 - 10:10 Strand and Cable data *50'*
Speakers: Dr. Ian Pong (LBNL), Dr. Lance Cooley (Florida State University - NHMFL), Vito Lombardo (Fermilab)
Material: Slides

10:10 - 10:40 Coil 116 and 117 data *30'*
Speaker: Fred Nobrega (FNAL)
Material: Slides

10:40 - 11:10 Coil 207 and 209 data *30'*
Speaker: Jesse Schmalzle (BNL)
Material: Slides

11:10 - 11:30 Measurements at LBNL *20'*
Speaker: Daniel Cheng (LBNL)
Material: Slides

11:30 - 11:40 Coil Ordering based on Conductor Properties *10'*
Speaker: Maria Baldini (FNAL)
Material: Slides

11:40 - 11:55 Questions & Answers *15'*
11:55 - 12:05 Report *10'*

5 Findings

<u>Coil fabrication</u>:

Coil 116 (FNAL)

- Coil 116 had seven non-critical DRs and two critical DRs:
  - Non-critical DRs 11748, 11782, 11818, 1876, 11877 describe equipment malfunctioning issues, defective components or procedural errors that were recognized and corrected before there could cause any negative impact on the coil quality

  - Non-critical DR 11853 was triggered by out-of-specs dimensional measurements following coil impregnation which prompted a disassembly, inspection and re-assembly of the impregnation tooling. It was later found that the dimensional error was not related to the tooling geometry but rather due to bump caused by S2 glass delamination. A small pressure applied to the surface is sufficient to restore the correct geometry, therefore no impact is expected on coil assembly. However, some questions remain on the possible impact of S2 glass delamination in other areas (e.g. electrical insulation) and how to prevent it in future coils.
  - Non-critical DR 11887 describes two instances in which insufficient depth was obtained at a location where bumpers are to be installed on the coil ID. This can be easily corrected at the assembly stage by installing shorter bumpers. However, the reason why installed spacers did not provide the required depth is not clear, and a more formal process may be needed for requesting this corrective action to the assembly L3 (rather than relying only on the coil traveler) and ensure that corrective action is taken
  - Critical DR 11780 reports damage to the cable insulation due to cut for voltage tap insertion being applied at the wrong location. From the picture, we also note that the insulation area affected appears to be larger than required for a voltage tap insertion, possibly due to some error when applying the cut (in addition to the positioning error). The repair however appears to be fully adequate.
  - Critical DR 11903 resulted from a pole key slot being measured to be out-of-tolerance at z=-327 mm (corresponding to the layer jump section). This issue can be corrected at the assembly stage by modifying the alignment key at that location. However, the cause of the error is not clear.

- The coil 116 pole gaps at each stage of fabrication are in line with expectations and results from previous coils. The final coil length is 4527.55 mm or 4.45 mm below target (within but close to the ±5 mm tolerance)
- Coil 116 passed all electrical checks before shipping. A typo is noted in the coil to pole voltage requirement where the old target of 500 V is listed (test was performed to the new target of 100 V)
- Coil 116 passed all electrical checks after receiving at LBNL
- Coil 116 CMM results after receiving at LBNL it would be useful to perform a detailed comparison for those areas where larger deviations were reported by FNAL (DR 11903)

Coil 117 (FNAL)

- Coil 117 had four non-critical DRs and three critical DRs
  - Non-critical DRs 11794, 11854, 11906, 11922 describe equipment malfunctioning issues, defective components or procedural errors that were recognized and corrected before there could cause any negative impact on the coil quality
    - Non-critical DR 11794 indicates a procedural error at the cable insulation step. It is not clear if reporting and discussion with the cable L3 and the vendor took place as part of the resolution. This incident was not discussed in the conductor/cable presentation.
  - Critical DR 11816 reports one instance of cable roping. This happened at the return end, second turn after the first spacer. The damaged cable section appears to be about 20 cm long. There are indications that the winding machine programming or execution may need to be improved at this location (since another issue had been reported at same location for a previous coil). This might require a specific follow-up. A manual repair of the cable and insulation was performed and appears to be fully adequate.
  - Critical DR 11873 reports a failure of the thermocouple DAQ during reaction which resulted in about 12 hours of data loss during the last phase of the 400C plateau and the start of the ramp to 665. The furnace control was not affected but the missing data makes it more difficult to calculate the time of the 400C plateau and confirm it is within specs. This was done by linear extrapolation from the available data and appear to be fully adequate. However, the DAQ reliability needs to be addressed.
  - Critical DR 11929 reports on three locations where the pole key slot deviation from nominal is above a previous tolerance of ±127 mm. After this DR was entered, the tolerance has been increased to ±250 mm and all three locations are within the new tolerance band.

- The coil 117 pole gaps at each stage of fabrication are in line with expectations and results from other coils. The final coil length is 4528.4 mm or 3.6 mm below target (within the ±5 mm tolerance)
- Coil 117 passed all electrical checks before shipping. A typo is noted in the coil to pole voltage requirement where the old target of 500 V is listed (test was performed correctly to the new target of 100 V)
- Coil 117 passed all electrical checks after receiving at LBNL.
- Coil 117 CMM results after receiving at LBNL: it would be useful to be able to perform a detailed comparison for those areas where larger deviations were reported by FNAL (DR11929).

Coil 207 (BNL)

- Coil 207 had 7 DRs. No classification between critical and non-critical DRs was provided. Access to the DR information in the project database was also not provided.
  - DR AM-131 reports that pole gaps were incorrectly set at the start of winding, by 0.25 mm each, or 2.5 mm total. It was not specified at what time the error was recognized, presumably it happened after the start of winding as no correction was applied. A comparison of pole gap measurements from different BNL coils *after reaction* shows that the total gap in coil 207 was between 0.5 and 2 mm larger than in previous coils. Therefore the initial error was somewhat reduced after the various coil processing steps. The coil 207 length is between 2 and 6 mm higher than previous BNL coils, but is also the closest to the nominal length of 4532 mm.
  - DR AM-132 reports a popped strand during winding, which was manually repositioned and further stabilized with binder.
  - DR AM-133 notes a periodic raised wire in the cable while respooling. It is not clear whether there was a follow-up with the cable L3. This incident was not discussed in the conductor/cable presentation.
  - DR AM-140 reports on a damage to the spacer coating after reaction, mitigated by covering with Kapton tape
  - DR AM-143 reports a broken voltage tap flag, repaired by soldering an extension to the flag
  - Coil AM-147 reports multiple areas of poor bonding of outer layer trace after impregnation. It is not clear if there are similarities to the S2 glass delamination noted in coil 116 (DR 11853).
  - DR AM-150 notes a large L-R asymmetry at z=4323 mm (return end region). The value is 0.36 mm compared to a typical range of ±0.15 mm over the entire coil length.
- Coil 207 passed all electrical checks before shipping.
- Coil 207 passed all electrical checks after receiving at LBNL (these results were added after the review)
- Coil 207 CMM results after receiving at LBNL: it would be useful to check/compare LBNL and BNL data in particular for the area described in DR-AM-150

Coil 209 (BNL)

- Coil 209 had 5 DRs. No classification between critical and non-critical DRs was provided. Access to the DR information in the project database was also not provided.
  - DR AM-144 reports a failure of the oven controller during the 665C plateau which is a critical stage of the heat treatment. In addition, the thermocouple DAQ stopped recording data for a period of about 10 hours, including at the

time of the oven controller failure. However, when the DAQ was restarted the coil temperatures were in the range of 630-645C. This indicates that only a relatively short time passed before the oven shut-down was discovered and corrected. This time was estimated to be 1-2 hours by using the cool-down temperature profile measured at the end of reaction.

  - DR AM-146 reports a damage to the spacer coating after reaction, mitigated by covering with Kapton tape. Coil 207 had the same problem in the same spacer (DR-AM-140)
  - DR AM-153 reports an exposed area of the cable at the mid-plane turn near the coil ID. This was covered with Kapton tape. Possible causes were not discussed.
  - DR AM-154 reports an out-of-spec final coil length of 4525.2 mm (1.8 mm lower than the minimum specified length)
  - DR AM-155 notes that some TC recorded temperatures during the reaction stage that are outside the allowed window of 5C (minimum measured was 658C vs. 660C). This was attributed to the use of ceramic insulated TCs, these will be changed to all sealed tube TCs.
- Coil 209 passed all electrical checks before shipping.
- Coil 209 passed all electrical checks after receiving at LBNL (these results were added after the review)

<u>Conductor and Cable</u>

- Incoming strands from OST are all within specification. A few of the strand lengths are close or just above the strand diameter spec. (Cable 1114). Nevertheless, all the cable dimensions are well within specification and very uniform in cable width and thickness along the length of the cable.
- The heat treatment time at the highest temperature stage (665°C) is reduced to 50 hours instead than the 75 hours, which were used in the first part of the program.
- Cable electrical parameters were checked with a minimal number of tests of samples reacted with the coil; one round wire and two extracted strands, which is the present accepted protocol. Witness sample tests confirm that cable performance is well above specifications. However, The RRR variability among billets is quite large which, depending on how wires are selected for cabling, may result in variability of the overall RRR among different coils with potentially negative effects on coil voltages during a quench
- RRR was checked after cable fabrication using extracted strands. These RRR measurements were done for the major and minor edges and the straight section between the edges. These measurements often show significantly larger values than those of witness samples and the round/rolled strand measurements from the vendor. We note that a different definition of RRR is used for different measurements,

however, this difference can only explain a fraction of the differences in the RRR results.

- RRR and Ic measurements of witness samples from coil 209 appear to confirm that the reaction was adequate despite oven controller and DAQ failures during the high temperature stage. This is also consistent with experience from previous programs (e.g. LARP, GARD) when a temperature drop occurred during the reaction phase e.g. due to a power outage.

Coil RRR and expected quench voltages

- The quench voltages were estimated based on coil RRR for both nominal protection and in case of heater failure. The coil RRR was initially estimated using rolled strand data, however, it was found that these data cannot be used for one of the coils due to a mismatch in the heat treatment. The calculation was then repeated (and a revised presentation was submitted) using the minor edge RRR data as measured at LBNL. All these samples used the correct heat treatment, matching the heat treatment schedule of the coils. However, as noted above these measurements are generally not consistent with the results from other RRR tests.
- The voltage calculations were performed using coil 115-116-207-209 as this is the preferred choice and in order to limit the total number of calculations.

Other/general findings:

- All coils under consideration for MQXFA05 should include the new shim configuration at the pole and mid-plane to implement a 5-unit correction of b6. However, this was not specified in the presentations.
- The reaction specification in the design report says: “Soak time shall be longer than target time – 1 hour, and shorter than target time + 3 hours.” According to the data shown for coil 117, dwell1 and dwell3 are out of specification (nominal for dwell1 is 48 hours and for dwell3 is 50 hours). Dwell1 for coil 116 is also out of spec.
- Dimensional measurements after receiving at LBNL were performed for coil 116, 117 and 207. These measurements were performed with the Zeiss Accura CMM system also used in previous coils (a new Leica tracker system is being commissioned and will be utilized for later coils). The results show very good radial uniformity, undersized by 50 micron. Mid-plane size are also undersized by 50 micron on average, but show larger variations. Keyways shifts observed at FNAL and BNL measurements were also generally confirmed at LBNL but no details were provided. The LBNL measurements do not include the return end due to limitations with the present system.

- FNAL coil presentation provides links to the DR documents on the vector database. This is quite useful but the links provided initially did not work. For future reference, the following link should be used for external viewing: https://vector-offsite.fnal.gov/Tools/DiscrepancyReport/DisplayDiscrepancyReportReadOnly.asp?qsDRNo=XXXXX (replace XXXXX with the DR number). Also note that the alternative link https://vector-offsite.fnal.gov/Include/DisplayAllDRs.asp?qsDocID=XXXXX was working intermittently

6 Comments

Coil fabrication:

- Some aspects of the process for DR resolution may need further clarification and/or improvement. Specifically, in many instances the DR has implications for other WBS (L3) tasks besides the one that originated it or requires some follow-up either within or outside the originating task. For the coils under review, at total of 10 DRs (DR 11887, 11903, 11794, 11816, 11873, 11929, AM 133, 147, 150, 144) can be considered as belonging to this category. In these cases, while a DR may be closed from the standpoint of the coil fabrication task, from a project standpoint it cannot be considered to have been resolved until additional actions are taken.
    - Perhaps a mechanism could be established to open follow-up DRs to keep track and ensure adequate follow-up. These would be entered in the register for the appropriate WBS and tracked/resolved there while allowing to formally close the initial DR.
    - Related to this, the process for closing a critical DR is also not completely clear. It is stated that critical DRs require L2 approval for closing, but that this approval is provided at the overall coil level and not specifically to the DR. In fact, the DR documentation in vector does not seem to include a box for L2 approval.
- No classification between critical vs. non-critical DR was provided for the BNL coils. The reviewer's assessment is that a significant fraction of these DRs should have been classified and processed as critical.
- The CMM equipment, procedures and reporting for different labs are still not fully consistent. It was stated that the measurements from the new LBNL system will eventually be used as the main reference for assembly. A comparison and discussion of the results from the different systems would be helpful.

  - The 0.25 mm tolerance for the keyway position also seems large considering that its location should be defined by the coil tooling. It is also possible that the CMM procedure is somewhat contributing to these variations and an improved procedure may provide more consistent results and a better basis for applying a correction at the assembly stage.
- Several non-critical DRs were recorded for each coil. These DRs did not have any effect on coil quality nevertheless they have some impact on coil production with is a critical task both in terms of schedule and cost. Consider possible strategies such as replacing consumable items at regular intervals and/or possible improvements to travelers/procedures to reduce the probability of such events.
- The impregnation quality was deemed acceptable and no discrepancies were reported. However, impregnation quality is critical and should be reported along with details of the impregnation procedures.
- In at least one instance, a cable insulation issue was reported on coil fabrication but not in the cable presentation.
- It appears that BNL reports on pop-strands, FNAL doesn't. Although properly repaired popped strands do not pose a significant risk, their locations should be recorded consistently at both labs for possible correlation with performance issues
- The design criteria require that "The reaction fixture must be sufficiently gas tight to assure internal overpressure with 10 liter/min argon flow. The argon flow during the whole heat treatment must be equal or higher than 20 liter/minute." Since no information was provided on this point, we would like to confirm that argon flow is properly monitored and within specified values.
- Some clarification regarding the coil-to-pole insulation checks would be helpful. We understand that if the leakage current is below1μA at 100V, corresponding to 100MΩ coil to pole, the test is considered successful. Is the leakage current recorded, or only pass/not pass? Recording the leakage current both coil to pole and coil to end saddle would be helpful to check for degradation at later stages e.g. during assembly.
- At least two instances were reported where it appears that bonding between trace and coil was compromised, pointing at the need for improved or better controlled impregnation procedures.
- Damage to the insulation of a spacer was also recorded in more that on DR for different coils. This warrants some further investigation.
- Coil length is generally on the lower side of the allowed range, and in some case close (or outside) the limits. Several corrections may be considered to bring the coil length closer to specifications. For example, an error in selecting the pole gaps resulted in a coil length close to specs.
- With reference to DR AM 150, it is not clear what are the criteria for reporting CMM results that appear to be unusual but not formally out of specs. We agree that this information should be captured but it might be useful to establish some guidelines and apply them consistently at FNAL/BNL and LBNL.

Conductor:

- The reaction used at the supplier was changed from 665C/75h to 665C/50h after billet 143, whereas LARP/AUP changed the HT for verification tests from 75 h to 50h starting with billet 340. This change makes significant impact on the measured RRR with minimal decrease in the critical current Ic. Coil-209/Cable-1114 supplier data are for 665C/75h and so expect the RRR to be higher for the round and rolled wire than what is shown in the Table. Coil 115/Cable-1102 was reviewed earlier and meets all specifications.

- The Table below summarizes the RRR measurements done at various stages at different locations. We note that the criterion used for defining RRR is different for the supplier strands, those measured at LBNL and for the witness samples measured at FNAL. We also note that even with the differences in defining RRR, the data are not very consistent for a single coil and from coil to coil.

Coil	QXFA116	QXFA117	QXFA207	QXFA209	QXFA115
Cable	1105	1107	1106	1114	1102
HT @ OST	665/50	665/50	665/50	665/75	665/50
OST RRR – Round-strand Avg	324	286	258	226	263
OST RRR-Rolled-strand Avg	217	188	168	119	154
% Copper in strand x-section	54.3	54.3	54.7	54.6	55.1
HT @LBNL	665/50	665/50	665/50	665/50	665/50
Avg. RRR_ST-Section	444	342	320	325	305
Avg. RRR_Minor_Edge	336	230	221	230	199
Avg. Witness_RRR_Ext_Strand	234	159	257	239	120

Expected coil voltages during quench:

- The initial calculation was performed assuming coil 115, 116, 207, 209. This appears to be the preferred choice from a coil inventory management standpoint, however, it is understood that technical considerations will be the main driver for coil selection.
- Rolled strand data is generally considered as the best basis to estimate coil RRR, however, it is not reliable for this particular coil selection as a wrong schedule was used for one of the rolled strand HT (coil 209).

- RRR data from the LBNL system (minor edge) was used in the revised calculation, however, this choice is also questionable since the LBNL data is not consistent with rolled strands and witness samples.
- It would be interesting to perform additional calculations assuming coil 115, 116, 117, 207 (this would allow using rolled strand data) and/or using the previous coil selection assumption (115, 116, 207, 209) but with a different way of estimating the coil 209 RRR (e.g. including the witness sample data, or using the LBNL RRR measurements to calculate a relative difference from the other coils. This will allow to get a realistic estimate of the coil voltages at quench with the present level of variability in RRR.

7 Recommendations

- Data was lost during the reaction of one coil in FNAL (117) and one coil in BNL (209). We recommend studying the reliability of the system and implement a backup data storage if it is considered necessary.
- During coil 209 reaction, both the oven and the data acquisition system shut down. In addition, the average temperature is in the lower band 661·C, and the minimum is 658·C, so it is below spec. Taking all this into account, all witness samples reacted with the coil should be measured.
- Some of the reported dwell times appear to be out of specs. We recommend adjusting the reaction cycle to meet specifications or modify acceptance criteria. Otherwise a DR shall be issued.

	Coil 116	Coil 117
Dwell1	45:55	45:50
Dwell2	48:33	50:40
Dwell3	52:18	53:23

- As noted in previous reviews, coil length is generally at the low end of the allowed range and in several cases out of specs. Consider possible adjustments to bring the coil length in production closer to nominal.
- Define and follow a consistent DR classification process as critical/non-critical at all Labs. For future coil reviews, access to DR records should be provided for coils fabricated at both Labs.
- Perform a detailed comparison of the coil mechanical measurements from FNAL/BNL and LBNL in particular for those areas where larger deviations were reported. Establish methodologies to report results and calculate needed corrections at assembly
- Complete the analysis of quench voltages using improved RRR estimates and investigate possible strategies to achieve more uniform RRR at the coil level.

8 Response to Charge Questions

1. Do the coils under review meet MQXFA coil specifications [3]?

The coils meet specifications except for a few dimensional deviations where corrections can be applied during assembly.

2. Are conductor/coil fabrication and QC data of these coils adequate for allowing MQXFA05 to meet MQXFA requirements [1]?

All coils are adequate for use in MQXFA05 based on conductor, cable and coil electrical and mechanical QC data

3. Are there major non-conformities? If answer is yes, have they been adequately documented and processed?

Based on the provided data, none of the reported non-conformities is considered a showstopper for the use of the coils in MQXFA05.

4. Do you have any other comment or recommendation regarding these coils and their conductor for allowing MQXFA05 to meet MQXFA requirements [1]?

Better understand RRR variability and how to obtain a more uniform coil RRR. Also continue to work on how to predict coil RRR based on strand data. Sorting coils based on their expected RRR would cause an additional constraint limiting other strategies such as minimizing voltage on individual coils or optimizing field quality.

9 Summary and Conclusions

QXFA Coils 116, 117, 207 and 209 were reviewed to assess their suitability for MQXFA05 assembly. Based on the provided documentation, no showstopper has been identified for their use in MQXFA05.