



**Report of the MQXFA06
Coil Acceptance Review**

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US HL-LHC Accelerator Upgrade Project

**Report of the MQXFA06 Coils Acceptance Review
November 17, 2020**

S. Izquierdo Bermudez, A. Ghosh, G. Sabbi



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Revision History

| Revision | Date | Section No. | Revision Description |
|----------|------------|-------------|----------------------|
| V1 | 11/17/2020 | All | First release |
| | | | |



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1 Goals and Scope

The HL-LHC AUP project is planning to start assembly of MQXFA06 magnet in October 2020. MQXFA06 is the fourth pre-series low-beta quadrupole (MQXFA) to be used in Q1 and Q3 Inner Triplet elements for the High Luminosity LHC. If MQXFA06 meets MQXFA requirements [1] it will be used in a Q1/Q3 cryo-assembly to be installed in the HL-LHC. For MQXFA06 assembly (including a spare coil) AUP is planning to use QXFA coils: 117, 119, 122, 211 and 123. Coil 117 was approved for use in MQXFA05 [2] and is assumed approved for use in MQXFA06.

The reviewers are requested to assess that coils 119, 122, 123, 211 and their conductor meet specifications [3-4], and to evaluate the impact of non-conformities in strands, cables and coils.

2 Organization

Committee

GianLuca Sabbi (chairperson), LBNL
Arup Ghosh, BNL retired
Susana Izquierdo Bermudez, CERN

Date and Time

September 25, 2020. Start time is 7/9/10/16 (LBNL/FNAL/BNL/CERN)

Link to agenda with talks and other documents

<https://indico.fnal.gov/event/45118/>

3 Charges

The committee was 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 MQXFA06 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 MQXFA06 to meet MQXFA requirements [1]?



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4 References

- [1] MQXFA Functional Requirements Specification, US-HiLumi-doc-36.
- [2] MQXFA05 Coils Acceptance Review, US-HiLumi-doc-2742.
- [3] MQXFA Final Design Report, US-HiLumi-doc-948-v10 sections 3 and 5.1.1 (*)
- [4] QXFA Coil Fabrication Electrical QA, US-HiLumi-doc-521 step 16.

(*) Version 10 was valid at the time when pre-series coils were fabricated

5 Agenda and Presentations

MQXFA06 Coils Acceptance Review

Friday Sep 25, 2020, 9:00 AM → 12:30 PM US/Central

by Zoom ()

Description Meeting by Zoom, info by email



HL_MQXFA_Functi...



MQXFA05-CoilAR-R...



MQXFA06_Coils_A...



MQXFA-FDR_v10.d...



QXFA_Coil_Electric...

9:00 AM → 9:20 AM Introduction and Review Charge

20m

Speaker: Giorgio Ambrosio (FNAL TD/MSD)



Leica_Qualification...



MQXFA06_Coil_Ac...



Record_of_Decision...

9:20 AM → 10:10 AM Strand and Cable data

50m

Speakers: Dr Ian Pong (LBNL), Dr Lance Cooley (Florida State University - NHMFL), Vito Lombardo (Fermilab)



MQXFA06 Coil Rea...

10:10 AM → 10:55 AM Coil 119, 122 and 123 data

45m

Speaker: Fred Nobrega (FNAL)



MQXFAP06 Coil Ac...

10:55 AM → 11:15 AM Coil 211 data

20m

Speaker: Jesse Schmalzle (BNL)



QXFA211 coil revie...

11:15 AM → 11:45 AM Measurements at LBNL

30m

Speakers: Daniel Cheng (LBNL), Katherine Ray (LBNL), Paolo Ferracin (CERN)



200925 A06 Coil R...



AUP_coil-dimensio...



MQXFA06 Coil Rec...

11:45 AM → 11:55 AM Coil Ordering based on Conductor Properties

10m

Speakers: Maria Baldini (FNAL), Vittorio Marinozzi (FNAL)



RRR_analysis_MQX...

11:55 AM → 12:10 PM Questions & Answers

15m

Speakers: Daniel Cheng (LBNL), Fred Nobrega (FNAL), Ian Pong (LBNL), Jesse Schmalzle, Katherine Ray (LBNL), Lance Cooley (Florida State University - NHMFL), Maria Baldini (FNAL), Paolo Ferracin (CERN), Vito Lombardo (Fermilab), Vittorio Marinozzi (FNAL)



200925 A06 Coil R...



200929 Coil 122 V...



Follow up question...



MQXFA06_Coil_Rec...



RRR_analysis_MQX...



RRR_in QXFA coils...



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6 Committee follow-up questions and answers

Conductor and cable

- Revise presentation to include coil 122 and 123 wire and cable data
 - Uploaded
- Write DR for coil 211 10-stack measurement issue at LBNL; add comments in corresponding slide.
 - Done. It turned out DR was in Vector. See latest version of slides, where a screenshot is included.
- Comment on timing of the 10-stack measurement at LBNL (this was discussed at the meeting, but we would like it in writing for clarity).
 - The wording is in Doc 903:
 - 7.3.8 Cable Insulation Vendor QC Prior to braiding the entire cable unit length, the vendor must perform a 10-stack measurement on a startup sample (no longer than 2 m) to determine the insulation thickness. This is a conditional ATPP: if the vendor QC passes, braiding of the unit may proceed. The vendor may make one adjustment and take a second sample. If neither sample passes, the vendor must stop work and contact 302.2.03 task leader or his deputy for a resolution.
 - 7.3.9 Cable Insulation Verification QC The vendor must send a sample of braided cable (no longer than 2 m) immediately adjacent to the qualifying vendor QC sample to LBNL. LBNL will then perform a 10-stack measurement. The results of this verification QC will not interfere with the conditional ATPP of the same cable, because the verification QC cannot be completed without causing unacceptable schedule delay due to the fact that the required peak production rate of AUP will be faster than affordable by shipment duration. 302.2.03 L3 may authorize braided samples (vendor + verification) such that the braided cable length be no shorter than 445 m. 302.2 L2 authorization is needed for further samples.
- Clarify/revise short sample/margin plots: (a) include the reference current used for % short sample, in addition to the % of short sample, since the nominal/ultimate current will be different for MQXFA06; (b) one plot (211) needs to be corrected: margin was calculated using wrong critical current curve (RW vs XS).
 - NOTE: it would be useful for the reviewers to instead request that the L2 charge letter to identify the coils and the cable IDs as well as the reference current used to define %short sample instead of having the L3s look up these values independently, i.e. some important information for the coil acceptance review can and should be pushed down instead of pulled up.
 - Added tables showing updated nominal current and corrected margins
- Provide background/documentation on verification test plan and its rationale in the US and at CERN; in particular, are rolled strand RRR measurements performed as part of US



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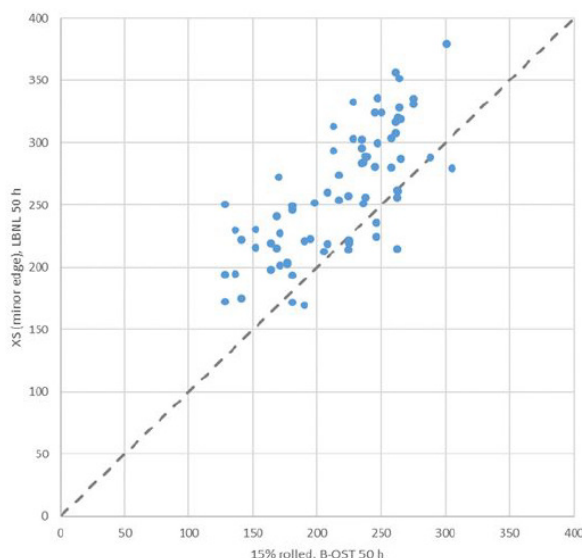
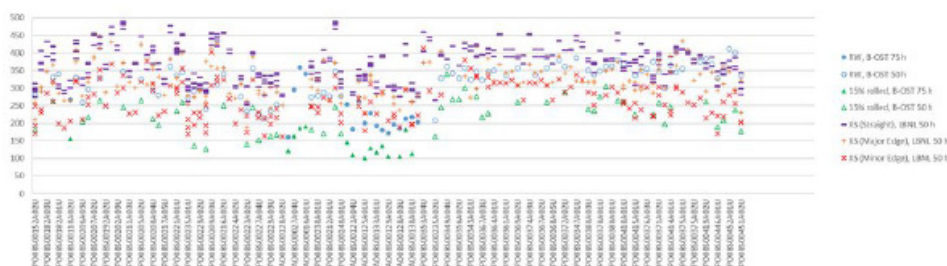
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- verification (it appears that they are included in CERN verification); comment on why verification data is not available for coil 119.
- This is a repeat question from prior coil readiness evaluation committees. Recommend that committee refer to prior documentation or that the charge to committee refer to background documentation such as the AUP conductor Quality Plan QP
 - RRR of XS controls acceptance in the cable MIP; RRR of XS at edges tracks well with the simulation by 15% rolled strand, so the QP did not include verification tests for 15% rolled since the XS edges would provide such verification.
 - Committee should check again that CERN is including rolled strands in their verification; strand task disagrees with this finding.
 - Verification data for coil 119 has not been requested from CERN. AUP QP requires all billets to be verified at both AUP and CERN, which provides assurance that verification has been completed. Does the committee require re-verification of strand already verified by a benchmarked laboratory?
 - V no 15% rolled;
 - CERN did not provide V data for strands used in coil 119.
 - Clarify and add comments in the slides regarding the heat treatment schedule issue for coil 119 supplier data. Does this affect both Ic and rolled strand RRR?
 - Clarify - what is the “heat treatment schedule issue”?
 - Recommend that L2 charge the committee with refreshing from DOE reviews as background information. Recommend that a single “history” commentary be provided since these comments will likely arise every coil review.
 - CD2-3b review slides and commentary identified that PO624035 (LARP) strand used 665/75 at supplier, US verification lab and CERN, PO632982 (LARP) strand used 665/50 at supplier and CERN but 665/75 at US verification lab, and 646116 (AUP) onward used 665/50 everywhere.
 - Coil 119 used cable made from strand from billets 126, 128, and 134 delivered to CERN. That vintage corresponds to the period between PO624035 (US deliveries end at billet 120) and PO632982 (US deliveries begin at billet 147). Supplier and verifier HT were probably 665/75. Billets during that run period had RRR - 15% roll at the low end of the LARP production run, ranging from 131 to 168 for LARP billets 109 to 120.
 - Provide background/documentation on the strategy for measuring witness samples and how it was applied to the A06 coils
 - Recommend that L2 charge the committee with review of background documents, in this case the cable PRR outcome doc 2080.
 - Cable PRR identified the cable number at which witness testing changed from XS and VS (6 total samples, 4 XS and 2 VS) to witness samples coming from a reference VS spool and XS being used to qualify the cable.
 - All the cables presented at this review are before the PRR change (BCR 070) is implemented.

- LBNL RRR measurements still appear to give consistently higher results than those from witness samples, rolled strands, and magnet cold test. Please comment on this. There was some discussion during the presentation, but no convincing argument was made to show that we understand this difference and how to improve.
 - The committee appears to imply that the measurement technique is at fault. Let's be clear: the LBNL measurements are accurate and are not biased based on the outcome of numerous inter-comparisons. The differences are actual differences in the samples based on HT and sample preparation or state. We understand the difference fully and it is related to (a) coil reacted over temperature, which affects the witness samples; (b) pedigree of the billet material and the billet manufacturing; (c) agreement between rolled strand data and the data for segments incorporating cable edges
 - RRR depends on the HT and sample preparation
 - Coil 211, for example, showed excellent agreement between witness and XS RRR.
 - Coil 119 HT overcooked the coil, so witness RRR is low. LBNL RRR has been consistently with BOST 15% rolled data.
 - See below presentation at the 2020 06 03 Conductor Status with CERN





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- Clarify strategy for selection of spools to be used in the cable: what is the priority between RRR and other possible goals
 - The general philosophy of our strand mapping is by minimizing spool splitting while aiming to limit the number of billets blended to about 5, unless we are otherwise restricted by strand delivery. Cable P43OL1120 was one of the special cases where we used up all the short pieces.

Coil fabrication/FNAL

- Add measured data for coil reaction. Show how average temperature and times were calculated.
 - Addressed in response slides, file name:
Follow_up_questions_MQXFAP06_Coil_Acceptance_Review_FNAL_Coils_119_122_123
 - Average temperature is calculated within the spreadsheet at each timestamp. Each line in the spreadsheet is a timestamp that are in 1-minute increments and include the temperature for each of the 10 thermocouples used on the tooling. The plot of the average temperature is typically flat, and the reported temperature is selected from the last 25% of the plot, e.g. before the end of the plateau.
 - Time duration is the timestamp at +/- 5° C of the target temperature. For example, to find the duration of the 210° C plateau, use the timestamp at 205° C and the timestamp of 215°. The difference between the two timestamps is the duration of the 210° C target temperature.
 - Temperature plots were also included
- Correct coil to pole hi pot table, still shows 100/500 V, should be 100/100.
 - Corrected in updated presentation
- Add leakage currents to hi-pot tables (as in BNL table)
 - Tables were included in response slides.

Coil fabrication/BNL

- Include in the slides an explicit comment that measurements are within specs (there are many details in the reaction and impregnation that we are not able to evaluate)
 - Updated in presentation v4

Coil dimensions/LBNL

- Clarify plan/timeline for dealing with inner pole deviations
 - Not addressed



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Coil electrical QA/LBNL:

- Out of sequence resistance measurement for Vtap B07 in coil 122: addressed in follow up slides file name: 200929_Coil_122_VTB07
 - Fabrication data shows same out of sequence values from trace installation
 - Data was remeasured and confirmed at LBNL
 - Photos presented
 - Measurement data suggests that the VTB07 VT flag was placed on the 2nd turn from the pole
 - Actual order of the outer layer voltage taps are: B01, B02, B03, B07, B04, B05, B06, B08, A08, etc...
- Sequential R measurements for coil 211:
 - Re -measured and update slides 200925_A06_Coil_Reception_EQC_v2

7 Findings

Coil fabrication:

Coil 119 (FNAL)

- Coil 119 had 8 non-critical DRs and 2 critical DRs:
 - Non-critical DRs 11911, 11932, 11939, 11942, 11952, 11967 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 11941 was due to an error during part preparation, resulting in one of the side rails not meeting specifications.
 - Non-critical DR 11943 was due to a larger than expected gap between a saddle and coil, corrected by filling with fiberglass
 - Critical DR 11904 was due to a failure of the Selva winding machine, which required to move the coil to a backup station to complete the winding
 - Critical DR 11963 was due to an out of tolerance keyway shift, to be corrected by modifying the pole key during magnet assembly. Communication between the coil L3 and the structure L3 is through a note in the interface traveler, and DR is defined as critical because it affects an interface.
- The final coil length is 4531.2 mm which is well within the ± 5 mm tolerance band for both the pre-series target of 4532 mm and the series target of 4529 mm
- Coil 119 passed all electrical checks before shipping.



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- Coil 119 passed all electrical checks after receiving at LBNL
- Coil 119 dimensional measurements after receiving at LBNL confirmed the out of tolerance key slot deviation at position 465 mm as indicated by FNAL (DR 11963). In addition, the measurements indicated an out of tolerance inner radial position of the coil blocks at 665 mm, which was attributed to measurement error due to difficulties in positioning the probe; and out of tolerance deviation of the inner radial pole position, which were attributed to delamination.

Coil 122 (FNAL)

- Coil 122 had eleven non-critical DRs and one critical DR
 - Non-critical DRs 11972, 11975, 11991, 12016, 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 12079, 12080, 12081, 12082, 12083 report on lower than specified quality factor values during electrical testing.
 - Non-critical DR 12019 reports on multiple shorts between pole pieces after winding. No corrective action was taken at this stage, with the expectation that shorts would be resolved after reaction and impregnation
 - Non-critical DR 12021 reports a short between coil and tooling. Measurements indicate that contact is located at the center of the coil, possibly caused by a pin. No corrective action was taken at this stage.
 - Critical DR 12014 is due to calibration issues in the reaction furnace thermocouples. This, along with temperature controller issues, may have resulted in reaction temperatures higher than specified for the final (665C) step. Corrective actions include: (1) TC recalibration and replacement of the reaction tooling and control TC; (2) reducing the temperature setpoint by about 4C in the next coil (123); performing a reaction with dummy load after coil 123.
- The final coil length is 4531.3 mm which is well within the ± 5 mm tolerance band for both the pre-series target of 4532 mm and the series target of 4529 mm. It is also very close to the measured length of coil 119.
- Coil 122 passed all electrical checks after receiving at LBNL
- Coil 122 dimensional measurements after receiving at LBNL indicated an out of tolerance inner radial position of the coil blocks at 665 mm, which was attributed to measurement error due to difficulties in positioning the probe; and out of tolerance deviation of the inner radial pole position, which were attributed to delamination.



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Coil 123 (FNAL)

- Coil 123 had 12 non-critical DRs and one critical DR. Coil presentation did not include 3 of the non-critical DRs
 - Non-critical DRs 11990, 12068 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 11976 described an incident during coil winding which resulted in insulation damage and cable roping. Cable was manually repaired and new insulation was added and cured in place with binder.
 - Non-critical DR 11986 resulted from an error in following the procedure – moving to a new step before the previous step was completed. This was corrected by backtracking and completing the missing portion.
 - Non-critical DR 12034 resulted from an unexpected dark coloring found on a section of the coil.
 - Non-critical DR 12036 reports on a voltage tap damage during installation of the insulation layers. Broken flag was left in place and a new VT was installed
 - Non-critical DR 12049 is due to out of spec temperature readings from individual thermocouples during all steps of the reaction phase. It is related to DR 12014 in coil 122.
 - Non-critical DR 12063 reports multiple shorts between coil and tooling after reaction and prior to impregnation. It appears that there the electrical path goes through the pole pieces, i.e. there is a short between coil and pole, and another one between pole and tooling (through pins). No action was taken. It is not clear if these shorts were further investigated in later phases.
 - Non-critical DR 12101, 12147, 12148, 12149 report on lower than specified quality factor values during electrical testing. This is similar to coil 122 findings (non-critical DR 12079, 12080, 12081, 12082, 12083).
 - Critical DR 11992 resulted from a decision to shut down the reaction during the initial ramp to 210 C due to suspension of on-site activities to comply with COVID mitigation directives at Fermilab. Reaction cycle was restarted from the beginning when on-site activities were resumed.
- The final coil length is 4529.9 mm which is well within the ± 5 mm tolerance from the pre-series target of 4532 mm, and very close to the series target of 4529 mm.
- Coil 123 passed all electrical checks before shipping.
- Coil 123 is a series coil with fewer voltage taps.
- Coil 123 dimensional measurements showed out of tolerance deviation of the inner radial pole position, which were attributed to delamination. This is similar to other coils. All other measurements including coil block inner radius were within tolerance.



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Coil 211 (BNL)

- Coil 211 had 5 DRs:
 - DR AM-148 reports that part coatings exhibited chips upon inspection. This is similar to findings from previous coils. Resolution was to use as is per US-HiLumi-Doc-1240. (Note: HiLumi document number is actually 2140)
 - DR-AM-149 reports on markings found on the traces that did not match the drawing number. Traces were used after consulting with Fermilab.
 - DR-AM-151 reports that a spacer was found to be shorted to the coil after installation. This is one of the spacers that exhibited chips in the plasma coating. It was replaced with a new part and new insulation was installed around it.
 - AM-161 reports on damage to the cable insulation found prior to impregnation at the first turn of L1, possibly due to rubbing against the corner of the pole part. Kapton was added at this location between the part and the cable.
 - AM-162 reports on an oil drop affecting the cable insulation. Some cleaning was attempted.
- The final coil length is 4527.2 mm which is at the lower limit of the ± 5 mm tolerance from the pre-series target of 4532 mm, but well within the tolerance band for the new target of 4529 mm.
- Coil 211 passed all electrical checks before shipping and after receiving at LBNL.
- Coil 123 dimensional measurements showed out of tolerance deviation of the inner radial pole position, which were attributed to delamination. This is similar to other coils. All other measurements including coil block inner radius were within tolerance.

Conductor and Cable

- A few of the strand lengths are close or just above/below the strand diameter spec. (Cables 1116, 1117). These are documented in DR-12136 and DR-12145 reports for the cables. Nevertheless, all the cable dimensions are well within specification and very uniform in cable width and thickness along the length of the cable.
- 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.
- The Table below summarizes the RRR measurements done at various stages at different locations. We note that the data are not very consistent for a single coil and from coil to coil.



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- 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 I_c . Coil-119/Cable-1117 used CERN procured wires and 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 | QXFA117 | QXFA119 | QXFA122 | QXFA123 | QXFA211 |
|------------------------------|---------|---------|---------|---------|---------|
| Cable | 1107 | 1117 | 1126 | 1130 | 1120 |
| HT @ OST | 665/50 | 665/75 | 665/50 | 665/50 | 665/50 |
| OST RRR – Round-strand Avg | 286 | 204 | 354 | 347 | 313 |
| OST RRR-Rolled-strand Avg | 188 | 131 | 267 | 229 | 234 |
| % Copper in strand x-section | 54.3 | 54.3 | 53.3 | 53.6 | 54.5 |
| HT @LBNL | 665/50 | 665/50 | 665/50 | 665/50 | 665/50 |
| Avg. RRR_ST-Section | 346 | 312 | 346 | 329 | 400 |
| Avg. RRR_Minor_Edge | 233 | 220 | 233 | 227 | 369 |
| Avg. Witness_RRR_Ext_Strand | 159 | 122 | 149 | 183 | 356 |

- The coil reaction at FNAL was modified after coil 122 as it was observed that the plateau temperature at 665 C was high (DR 12014). The plateau temperature for Coil 123 was reduced by 4°C. As expected, the RRR of extracted strands for 123 show a higher value as compared to previous coils (see Table).
- We estimate that the coil reaction at 665C at FNAL is at a higher temperature than that at BNL. This observation is based on witness sample measurements at FNAL of the RRR for these and earlier coils that were reviewed previously. This is shown below for BNL and FNAL coils:

BNL Coils

| Coil | Average | STD | Witness Extracted samples | | | |
|---------|---------|-----|---------------------------|-----|-----|-----|
| QXFA203 | 313 | 16 | 317 | 290 | 320 | 325 |
| QXFA204 | 453 | 36 | 432 | 495 | 432 | |
| QXFA206 | 225 | 17 | 236 | 241 | 204 | 217 |
| QXFA207 | 257 | 37 | 253 | 228 | 310 | 236 |
| QXFA209 | 239 | 15 | 221 | 233 | 250 | 252 |
| QXFA210 | 223 | 15 | 216 | 231 | 238 | 205 |
| QXFA211 | 356 | 57 | 414 | 319 | 395 | 297 |

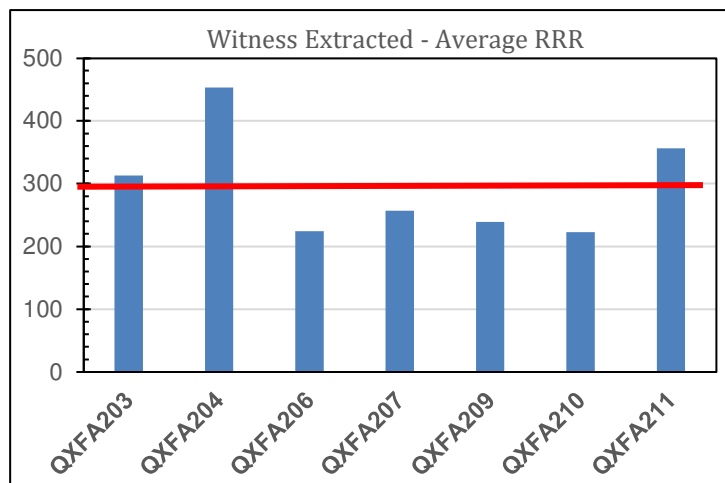


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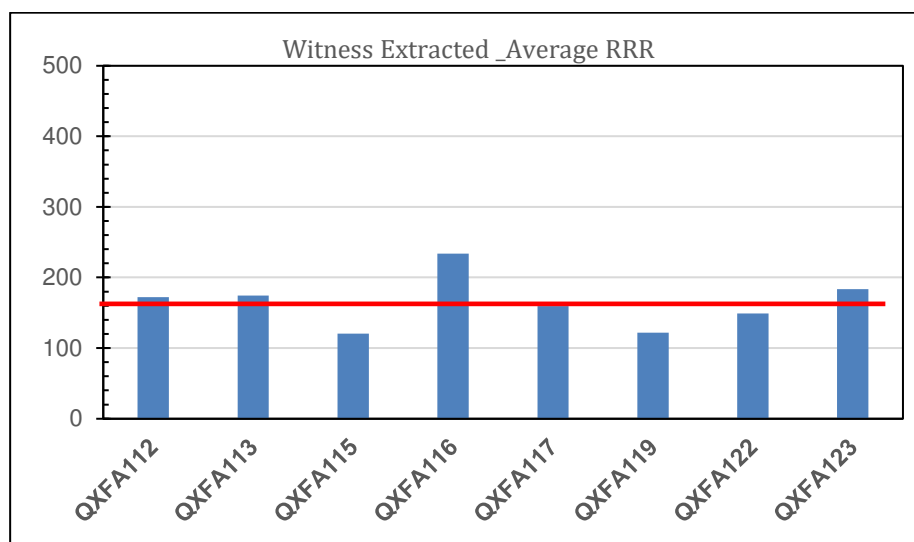
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FNAL Coils

| Coil | Average | STD | Witness Extracted samples | | | |
|---------|---------|-----|---------------------------|-----|-----|-----|
| QXFA112 | 172 | 18 | 190 | 179 | 171 | 148 |
| QXFA113 | 174 | 12 | 166 | 184 | 162 | 185 |
| QXFA115 | 120 | 11 | 127 | 125 | 125 | 104 |
| QXFA116 | 234 | 48 | 189 | 285 | 265 | 196 |
| QXFA117 | 159 | 28 | 149 | 125 | 189 | 174 |
| QXFA119 | 122 | 16 | 121 | 143 | 105 | 119 |
| QXFA122 | 149 | 9 | 149 | 158 | 140 | |
| QXFA123 | 183 | 12 | 201 | 181 | 176 | 175 |





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Coil RRR and expected quench voltages

- The quench voltages were estimated for both nominal protection and in case of heater failure. The coil RRR was initially estimated using rolled strand data, however, rolled strand samples for coil 119 received the wrong heat treatment (see comments above). Using these RRR values results in pessimistic quench voltage estimates, above established limits for most coil ordering solutions. 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 in the above sections, these measurements are significantly higher than the results from other RRR tests. Using this high RRR data results in optimistic estimates for the coil voltages. A third estimate was performed using the rolled strand data, but correcting coil the coil 119 data based on the LBNL measurements. This third approach results in a more reliable voltage calculation compared to the other two, however, it still has significant limitations in particular by not reflecting the actual heat treatment experienced by the coil.

8 Responses to recommendations from MQXFA05 coil acceptance review

- 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.

FNAL: The SpecView software and PC reliability has had 1 spontaneous system crash in 14 years. A 2nd PC with software is available as a backup. A group was formed to examine a variety of backup data recording systems. It was determined that any system selected would require rework or preplacement of the furnace PLCs at significant cost and time. No further action was taken.

BNL: The data collection system is reliable, and the computer is on a UPS. We concluded that backup data storage is not 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.



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Addressed shortly after the A06 review. Samples were measured and results were within specs.

- 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.

Furnace trouble shooting is in progress to resolve the out of spec issues. DR's are written when parameters are out of spec.

- 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 series coils closer to nominal.

Series coil specifications for coil length was changed from 4532 mm to 4529 mm (US-HiLumi-doc-2986). The 4532 mm length specification was current during A06 coil fabrication and is still listed as reference in the presentations.

- Define and follow a consistent DR classification process as critical/non-critical at all Labs.

Critical DR's are those that effect coil form, fit, or function and require L2 notification. Non-critical DR's are nonconformities during coil fabrication written against a specific step in the traveler that do not effect coil form, fit, or function.

- 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

A record of decision was presented concerning the use of the new LBNL Leica laser tracker system as the main reference for coil fabrication and magnet assembly. Coil fabrication L3s may still use BNL/FNAL CMM systems if that does not cause magnet-assembly schedule delay

- Complete the analysis of quench voltages using improved RRR estimates and investigate possible strategies to achieve more uniform RRR at the coil level.

A06 showed similar issues as A05, however, it is understood that improvements can only be realized over the cycle of cable and coil fabrication. A06 coils were already in an advanced state of processing at the time of the A05 review.



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- For future coil reviews, access to DR records should be provided for coils fabricated at both Labs.

Links to DR were provided for both Labs, however, there is some new challenge due to increased security requirements for access to the DRs which should be taken into consideration for future reviews.

9 Comments

Coil fabrication:

- A total of 9 DR (coil 122 non-critical DR 12079, 12080, 12081, 12082, 12083, and coil 123 DR 12101, 12147, 12148, 12149) report on lower than specified quality factor values during electrical testing. The cause was not discussed in detail in the presentations or DR, except for comments pointing at possible equipment malfunction. No corrective actions were taken, and disposition was to continue with coil fabrication. Follow up should include verification of the instrument, review of the tolerances, and other possible factors influencing this measurement. It is possible the tolerance of this measurement may be safely increased, but once a tolerance is established, a process should be defined for addressing out of tolerance measurements.
- Coil 122 non-critical DR 12019 reports on multiple shorts between pole pieces after reaction. Comments indicate that “The cause of the pole to pole shorts are a result of the poles shifting during the heat treatment process. Often, once heat treatment is complete, some of the poles remain in contact as seen on QXFA 122”. Disposition is that “each of the poles listed above should be inspected again after impregnation to confirm that they are no longer in contact with one another”. However, it is not clear if and how this inspection was performed, and what were the results.
- Coil 123 non-critical DR 12063 reports shorts between coil and tooling after reaction and prior to impregnation. It was determined that this was due to combination of a pole to tooling short through a pin, and a coil to pole short. The latter is the main concern. It appears that extra binder covering both coil and pole could be the source of this short. Corrective action for future coils will be to limit the amount of binder in proximity of the pole using masking tape. However, for coil 123, it is not clear if the coil to pole short was still present in later stages of the fabrication, and in the completed coil. For future coils, insufficient binder in the pole area resulting from the new procedure may also be a concern and should be closely monitored.
- Coil 122 DR 12021 appears similar to coil 123 DR 12063 above (short between coil and tooling). In DR 12063, it is mentioned that “While the coil dwells in the tooling, there are likely no other means for which the coil can contact the tooling other than



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through the pole”. In DR 12021, while a possible tooling to pole short through a pin is mentioned, a coil to pole short is not mentioned or investigated.

- DR-AM-148 (BNL coil 211): considering that the number of chips on this part is at the limit of what is considered acceptable some additional comments, e.g. to report at which stage and under which circumstances these defects occurred, may be useful to help mitigate this issue. The reference to HiLumi-Doc-1240, Disposition of Non-Conforming Plasma Coated Parts should be corrected in both the presentation and the DR - it is HiLumi-Doc-2140.
- Positioning error for Voltage tap B07 of coil 122 needs to be communicated to the testing team. The approach should be based on the process that was defined for DRs which affect an interface (e.g. keyway shift out of tolerance): (1) fill in a DR, classified as critical; (2) direct communication among relevant L3 (in this case assembly L3 and test L3); (3) add a note in the interface traveler. It was not clear from the presentation if these steps were taken.

Coil reaction:

- Witness sample RRR confirms earlier observations that the temperature of the final HT step at FNAL was higher than specified. The plateau temperature for Coil 123 was reduced by 4°C. Additional verification with a dummy load is planned after coil 123.
- The heat treatment of coil 122 is above specification. However, impact on I_c and RRR is minimal. Witness sample tests show data well above specification

Coil QA

- While the MQXFA06 coils were originally fabricated to a target length of 4532 mm, this target has been changed to 4529 mm for series coils. The latter number appears to be more relevant in evaluating the coil length. As was observed in previous coils, the length measurements are within the tolerance band relative to the new target, while with the original target, some coils are close or outside the lower tolerance band. No change was made to the parts of fabrication process. As-built coil lengths for MQXFA06 appear to remain consistent with previous assemblies, and overall uniformity is good.
- Measurements of coil inner radii are often out of tolerance. This is attributed to delamination or difficult to reach locations. In this case the measurements do not provide useful information. Project needs to define an approach to deal with these issues. Independent verification of the magnet aperture at the end of the assembly should guarantee that functional requirement is fulfilled.
- Sequential R table for new coils with fewer voltage taps should clearly indicate that these taps are not present rather than simply leaving the cells blank.

RRR estimate to compute the expected coil voltages during quench:

- For both MQXFA05 and MQXFA06, several iterations were needed in order to select the best approach to estimating coil RRR to be used for the quench voltage analysis. Considering that (a) rolled strands measurements from samples that received the wrong HT are still affecting billets that are being used in coils; (b) even for the correct HT, there is no strong evidence of the validity of rolled strand measurements for this purpose; and (c) here are still open questions regarding the actual HT temperature during coil reaction; the RRR measurements from witness samples reacted with the coils appears to be the most reliable data source for quench voltage estimates.
- With increased experience on quench voltage analysis, the scope of this analysis for future coil reviews may be reduced to confirming that the RRR of each coil will not prevent its use in the magnet assembly, rather than determining the optimal coil ordering. This analysis however should include all coils being considered for the assembly (the coil intended as spare was not covered in MQXFA05 and 06). Optimal coil ordering may be addressed during the magnet assembly review.

DR classification:

- Criteria for classification between critical vs. non-critical DR have been stated as requested. However, it is possible that some DR that were classified as non-critical may have to be classified as critical under these definitions. Examples for MQXFA06 include DR 12019, 12021, 12049, 12063. The criteria states that a DR is critical if it affects coil form, fit, or function. In some cases where an issue has the potential to affect form, fit or function, it may be prudent to classify as critical until proven otherwise. This would also ensure that proper follow up and oversight is triggered.

10 Recommendations

- Check the RRR and I_c of the reference wire that is heat-treated with the coils at BNL and FNAL. This will indicate whether there is a systematic difference in the coil temperatures at 665C.
- For quench voltage calculations used to optimize the coil ordering use RRR of extracted strands rather than rolled strand data. In addition, quench voltage analysis should address the possibility that the spare coil will be used.



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- Address out of tolerance DRs for electrical tests: review and possibly refine tolerance band, check instruments, and define additional tests and/or corrective actions that should be undertaken following out of tolerance measurements.

11 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 MQXFA06 to meet MQXFA requirements [1]?

All coils are adequate for use in MQXFA06 based on conductor, cable, 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 MQXFA06.

4. Do you have any other comment or recommendation regarding these coils and their conductor for allowing MQXFA06 to meet MQXFA requirements [1]?

See recommendations section.

12 Summary and Conclusions

QXFA Coils 119, 122, 123, 211 were reviewed to assess their suitability for MQXFA06 assembly. Based on the provided documentation, no showstopper has been identified for their use in MQXFA06.