US HL-LHC Accelerator Upgrade Project

Q1/Q3 CRYO-ASSEMBLIES PRODUCTION PLAN

Prepared by:
Ruben Carcagno, US HL-LHC AUP Deputy Project Manager, FNAL

Reviewed by:
Giorgio Ambrosio, US HL-LHC AUP Magnets L2 Manager, FNAL
Kathleen Amm, BNL Representative
Mike Anerella, BNL Manager
Soren Prestemon, LBNL Representative
Lance Cooley, US HL-LHC AUP L3 Manager, FSU
Vito Lombardo, US HL-LHC AUP L3 Deputy/CAM Manager, FNAL
Ian Pong, US HL-LHC AUP L3/CAM Manager, LBNL
Miao Yu, US HL-LHC AUP L3/CAM Manager, FNAL
Fred Nobrega, US HL-LHC AUP L3/CAM Manager, FNAL
Jesse Schmalzle, US HL-LHC AUP L3/CAM Manager, BNL
Dan Cheng, US HL-LHC AUP L3/CAM Manager, LBNL
Joe Muratore, US HL-LHC AUP L3/CAM Manager, BNL
Sandor Feher, US HL-LHC AUP L2 Manager, FNAL
Guram Chlachidze, US HL-LHC AUP L3/CAM Manager, FNAL

Approved by:
Ruben Carcagno, US HL-LHC AUP Deputy Project Manager, FNAL
Giorgio Apollinari, US HL-LHC AUP Project Manager, FNAL

Revision History

Revision	Date	Section No.	Revision Description
v0	9-Jan-2017	All	Initial Release
v1	11-Apr-2017	6	Updated shipment assumptions based on PO 632982
V2	14-Jul-2017	various	Provided more clarity to production durations and rates estimates
V3	23-Jun-2018	various	Updates for CD-2/3b Director's review
V4	11-Nov 2018	9	Update peak production estimate
V5	26-Nov-2018	various	Various updates for the DOE CD-2/3b review

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1. Purpose

The purpose of this document is to provide a description of the production plan for the Q1/Q3 Cryo-assemblies scope for the US HL-LHC Accelerator Upgrade project. This plan is used as input for the project Resource Loaded Schedule and Basis of Estimates (BOEs)

2. Reference Documents

All reference documents below can be found in http://us-hilumi-docdb.fnal.gov/

Project Execution Plan: US-HiLumi-doc-93
Key Assumptions: US-HiLumi-doc-78
WBS Chart: US-HiLumi-doc-104
WBS Dictionary: US-HiLumi-doc-39
MQXFA Functional Requirements Specification: US-HiLumi-doc-36
LMQXFA Functional Requirements Specification: US-HiLumi-doc-64
MQXFA Magnets Functional Test Requirements: US-HiLumi-doc-137
MQXFA Final Design Report: US-HiLumi-doc-948
Q1/Q3 Cryo-assemblies Preliminary Design Report: US-HiLumi-doc-974

Basis of Estimates (BOEs) for WBS 302.2 Q1/Q3 Cryo-assemblies:

BOE 302.2.01 Magnet Integration and Coordination: US-HiLumi-doc-122
BOE 302.2.02 Strand Procurement and Testing: US-HiLumi-doc-118
BOE 302.2.03 Cable Fabrication: US-HiLumi-doc-121
BOE 302.2.04 Coil Pars, Materials, and Tooling Procurement: US-HiLumi-doc-125
BOE 302.2.05 Coil Fabrication at FNAL: US-HiLumi-doc-115
BOE 302.2.06 Coil Fabrication at BNL: US-HiLumi-doc-117
BOE 302.2.07 Structure Fabrication and Magnets Assembly: US-HiLumi-doc-127
BOE 302.4.01 Magnets Vertical Test: US-HiLumi-doc-126
BOE 302.4.02 Cold Mass Assemblies Fabrication: US-HiLumi-doc-128
BOE 302.4.03 Cryo-assemblies Fabrication: US-HiLumi-doc-129
BOE 302.4.04 Cryo-assemblies Horizontal Test: US-HiLumi-doc-139

3. Deliverables

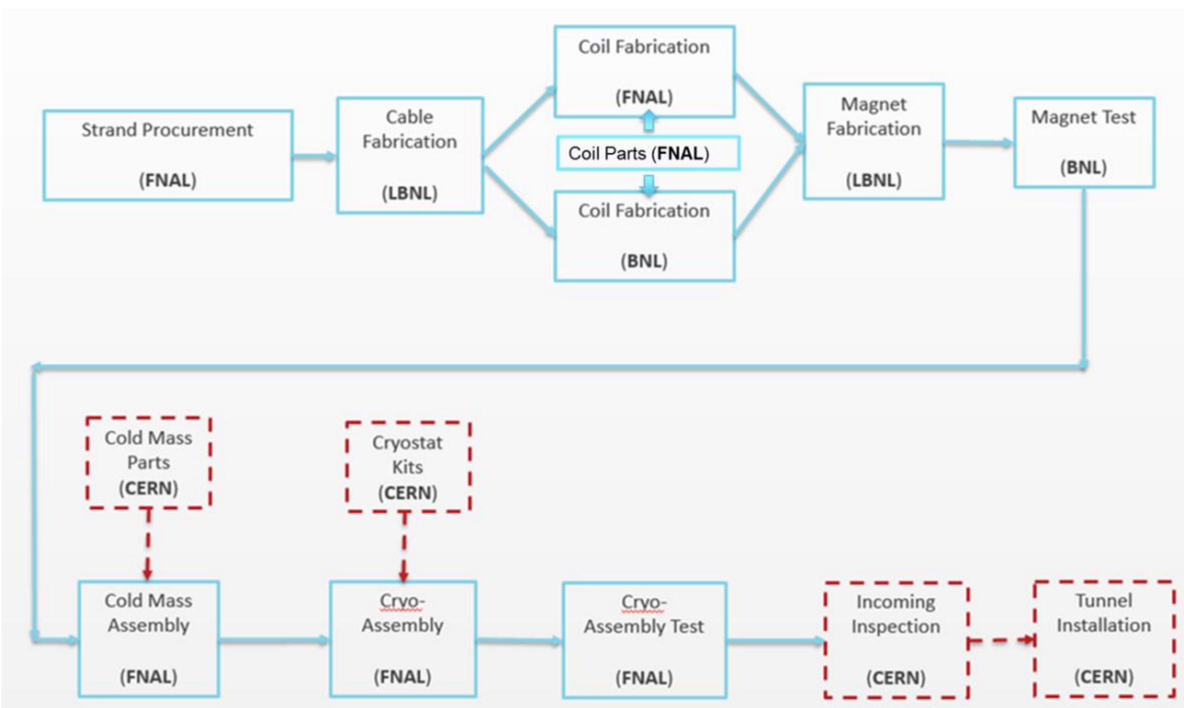
The Q1/Q3 Cryo-assemblies deliverables that this production plan must support are:

- 5 Q1 Cryo-assemblies (LQXFA)
- 5 Q3 Cryo-assemblies (LQXFB)

The Q1/Q3 Cold Mass Assemblies and Cryo-assemblies will be designed to be interchangeable to the extent possible, and for simplicity there will be no distinction made between a Q1 and a Q3 in this production plan.

A critical schedule milestone is delivery of Cryo-assembly #8 by December 2023. This is the last Cryo-assembly for HL-LHC tunnel installation, so it must arrive at CERN on schedule to support installation during CERN's Long Shutdown 3. The rest of the deliverables are for CERN spares.

4. Manufacturing Flow



5. WBS 302.2.01: Final Design and Integration

This WBS is for Level of Effort (LOE) associated with the oversight of the magnet final design, and coordination of the MQXFA Final Design Report; integration of products from other WBS elements into the complete magnet assembly; coordination of all WBS elements regarding MQXFA magnets, for example: analysis of prototype and production magnet test results and feedback into design or fabrication process, magnets assembly re-work, etc. This LOE is distributed across BNL, FNAL, and LBNL, and goes on for the duration of the project. In addition this WBS elements procure accelerometers and shock-sensors for monitoring and recording shocks during shipments, and performs the analysis.

6. WBS 302.2.02: Strand Procurement and Testing

Each unit of cable requires 40 Nb_3Sn strands. The Strand Unit Length (UL) is 500 m, which is the length to be re-spooled onto the cabling machine and accommodate cable pitch and samples (c.f. Cable Unit Length in WBS 302.2.03). A supplier will receive credit for delivering strand ULs. The total length of strand per cable is 40 × 0.5 km = 20 km, and at 5 kg/m this is 100 kg of strand for each unit of cable. The project baseline considers 102 cables (see next section), therefore the total amount of strand needed is 102 x 20 km = 2,040 km or 10,200 kg.

A total of 12 cable ULs of strand (240 km) with their corresponding QC is assumed to be available from an off-project source (LARP), so the project needs to procure an additional 90 Cable ULs of strand (1,800 km)

Strand is shipped by the vendor in “pieces” of continuous length wrapped in a spool. On average, each piece is 2.3 km long, providing enough material for 4 strands of 500 m long each, but this length varies from piece to piece. Each cable therefore requires, on average, strand to be drawn from 10 different spools.

The plan is to place one order by FNAL each year in April (this date is after the first 2 quarters of the FY to mitigate Continuing Resolution funding risks). This annual order is intended to cover the cable fabrication needs of one year with a total float of a few months to mitigate the risk of vendor delays or cable fabrication delays. The plan also assumes that the vendor delivers the first shipment of strand spools 6 months After Receipt of Order (ARO), with bi-monthly shipments continuing for an additional 12 months. The total strand order is assumed to be delivered in approximately equal bi-monthly installments. To support a peak coil production rate of ~ 2 coils per month (see Section 9), bi-monthly deliveries of roughly 80 km strand are needed to support a minimum of 2 UL of cable fabrication per month (40 km = 200 kg of strand in an average of 20 pieces or spools per month).

QC verification testing by a Lab is assumed to be done on 50% of the pieces, to keep uniformity with CERN’s plan, so each cable requires 5 QC verification tests. This QC verification testing is mainly of electromagnetic properties (critical current Ic, residual resistivity ratio RRR, and n-value). Physical properties are spot tested, but most measurements are performed under WBS 302.2.03. A 90% testing yield is assumed for electromagnetic property measurement. Therefore, a total of 5×90/0.9 = 500 pieces are expected to undergo QC verification testing.

In addition, a total of 6 witness samples are taken from each coil, and 3 samples are tested for Ic and RRR. A 90% testing yield is assumed. The plan requires a total of 96 coils (see coil fabrication sections), and 4 coils are to be made with cables received by LARP. The witness samples of the 4 LARP cables will be tested by LARP. Therefore, a total of 3×92/0.9 = 307 witness samples are expected to undergo QC testing.

7. WBS 302.2.03: Cable Fabrication

The Unit Length (UL) of bare cable to be fabricated is 455 m. This includes lengths for samples (insulation vendor and LBNL QC), coil winding leads, and buffer lengths. The minimum length of insulated cable required to fabricate one coil is 431 m. The fabrication of a UL of cable requires 40 strands of 500 m long each. A 90% yield is assumed for the cable fabrication process. The total number of coils required by the project is 96, but 4 UL's of insulated cable are to be received from LARP (see coil fabrication sections). Therefore the plan is to fabricate a total of 92/0.9 = 102 UL of cable, out of which 92 are deliverable to the coil teams.

Bare cable fabrication will be done at LBNL. From past experience, with 2 technicians it takes ~ 10 working days per bare cable fabrication (including preparation and mechanical QC, but excluding RRR measurements on extracted strands). With 3 technicians this can be accelerated to 7 working days. LBNL plans to allocate 10 months per year to this task. The rest is for equipment maintenance and to support other projects. The peak project cable fabrication rate would require ~3 cables per month, and 3 technicians will be needed to support this peak rate.

After a 7-day cable fabrication process, LBNL ships the bare cable to a vendor for cable insulation. This step takes about 4 weeks (including shipment). QC on the insulated cable includes image analysis, low voltage detection of bare spots, and measurement of braiding insulation thickness by the ten-stack method at the vendor. The QC data will be reviewed at LBNL, and a verification sample will also be shipped back to LBNL for ten-stack measurements. This step takes about 2 weeks. Meanwhile, RRR measurements are performed at LBNL on extracted strands as part of the cable electrical QC. Minimum of 5 extracted strand measurements are required per cable, and it is assumed that the sample holders can take at least 5 samples each time. This measurement takes 4 to 6 weeks, including the heat treatment (which lasts about 12 days including cool down), sample preparation, and the room temperature and cryogenic temperature measurements.

The total duration of a UL Cable Fabrication is estimated as follows:

Most likely = 3 months
Optimistic = 2 months
Pessimistic = 6 months

The most likely cable fabrication duration of 3 months is assumed for the project schedule. The peak cable production rate is to begin 1 cable every 7 working days.

The strand order schedule is planned to meet the cable fabrication start schedule, as described in the Strand section. With these assumptions, a few months of cable inventory stock is expected to be generated during project execution. This cable inventory stock mitigates the risks of project schedule delays due to strand vendor delays and unscheduled downtime of the cable fabrication process (estimated to be 3 months maximum). Coil fabrication is in the project critical path, so it is important to avoid having to stop fabricating coils because cable is not available on time. Target minimum float between cable finish and coil start is 3 months.

8. WBS 302.2.04: Coil Parts, Materials, and Tooling

8.1. Coil Parts

The Coil Parts required for coil fabrication are Pole Parts, End Parts, Trace Parts, and Wedges Parts. The total number of coils required by the project is 96 (see coil fabrication sections), so a total of 96 coil parts sets are needed.

A total of 19 coil part sets are assumed to be available from an off-project source (LARP), so the project needs to procure 77 additional sets of coil parts. From past experience, the lead time required for these parts is 12 months for End Parts and Wedges, and 8 months for Poles. This lead time is after the PO is placed, and includes Plasma Coating of End Parts, Cutting of Wedge Parts, and QC activities.

The plan is to place one order by FNAL each year in April (this date is after the first 2 quarters of the FY to mitigate Continuing Resolution funding risks). This annual order is intended to cover the coil fabrication needs of one year plus 20% of the following year to mitigate risks due to vendor delays and parts rejection. Half of the Coil Parts delivered by the vendor will be shipped by FNAL to BNL each year for the fabrication of the BNL coils.

8.2. Coil Materials

The Coil Materials are the consumables required for Coil Fabrication, including interlayer insulation, S2 glass tape, S2 glass sheet, NbTi leads, Epoxy, Binder, etc. The following list of materials will be procured by FNAL for both FNAL and BNL coil fabrication:

- 5 mil thick 3/4" wide Heat cleaned S2 glass tape for pole insulation
- 5 mil thick S2 glass sleeve for wedge insulation
- S2 glass ramp turn shim
- 8 mil thick Heat cleaned S2 glass tape for end parts insulation
- Interlayer insulation (2 x BGF 6781 + 1 x HEXCEL 4522)
- Heat cleaned S2 glass for Reaction Cloth (3 x HEXCEL 4522)
- Impregnation cloth for outer layer (2 x HEXCEL 4522)
- Impregnation cloth for inner layer (1 x BGF 6781)
- L2 Trace LE and RE 2 mil Kapton Insulation
- L2 Quench heater and NbTi Lead (provided by CERN)
- Electric wires for quench heaters - HH1819
- Electric wires for voltage taps - HH2619
- 8 mm Dia. 24 mm Length Dowel Pin
- G11 Midplane shim

The R/I glass, the ramp turn shim, L2 trace Kapton insulation and the interlayer insulation will be laser cut to final size, ready to use on the coil.

Each lab will procure the following additional materials needed for their own coil fabrication:

- CTD-1202 Binder
- Mica sheet - 5 mil thick
- Argon Gas
- Solder Sn96Ag4 and Flux MOB39
- Zyvax Mold release
- CTD-101 Epoxy
- RTV 157
- MYLAR
- Silicone o-rings
- SS tubing
- Nitrogen Gas (FNAL, for vacuum impregnation oven)
- Miscellaneous

8.3. Coil Tooling

One set of coil production tooling is assumed to be available at each coil fabrication site (FNAL and BNL) from the LARP program. Additional tooling needs to be procured on project in FY19 to increase the coil production rate starting in FY20 and meet the project schedule. The justification for this additional tooling can be found in US-HiLumi-doc-95.

The additional tooling includes:

1 Additional Winding Mandrel
4 Additional Reaction Fixtures
2 Additional Impregnation Fixtures
10 Storage Fixtures

FNAL will procure the additional reaction, impregnation and storage fixtures for both FNAL and BNL, and ship the BNL tooling to BNL. BNL and FNAL will procure their additional Mandrel because it is specific to their machine.

8.4. CMM Machine

FNAL will procure 3 CMM machines and coil handling tooling for CMM, 1 for each lab (FNAL, BNL and LBNL).

9. WBS 302.2.05/06: Coil Fabrication at FNAL/BNL

The plan requires two coil production lines to meet the schedule. The project assumes that there will be a fully qualified coil production line at FNAL and another at BNL as a result of prototype coil fabrication initiated under the LARP program and completed by AUP. In order to avoid delays due to coil QC (CMM measurements) a small dedicated CMM system is planned to be procured at both BNL and FNAL by WBS 302.2.04.

Coil Fabrication Process:

The coil fabrication process is described in detail in US-HiLumi-doc-95, “Fermilab Coil Production Analysis”. This note shows a detailed estimate of QXFA 4.2m single coil duration, labor, and equipment occupancy based on Fermilab experience obtained with short model QXFS coils and the first long QXFA coils. Based on this estimate, the note presents an analysis of coil production rate as a function of tooling quantity, including the technician crew required to sustain this rate. The project peak coil production rate with the additional tooling and two coil production lines is ~ 2 coils per month.

Coil Quantities:

A coil production yield of 87.5% (7 out of 8) is assumed. Production must provide enough accepted coils for 21 magnets (each of the cold masses has 2 magnets inside). Each magnet requires 4 coils, therefore the plan is to fabricate a total number of 21*4/0.875 = 96 coils. Rejected coils are assumed to be uniformly distributed during the entire coil fabrication duration.

The project plan is to fabricate a total of 22 pre-series coils for the pre-series magnets and 74 series production coils. The following coils are planned in each coil manufacturing line to support the following magnets (each magnet requires 4 coils):

13 FNAL coils for MQXFA pre-series
9 BNL coils for MQXFA pre-series
36 FNAL coils for MQXFA series
38 BNL coils MQXFA series

Fabrication of prototype coils were done under the LARP program.

Learning Curve:

For the FNAL coil manufacturing line, most of the learning curve already took place during the fabrication of coil prototypes under LARP. For the pre-series coils fabricated under project, two multiplying factors were used. A multiplier of 1.3 x the steady production duration and coil fabrication labor and a multiplier of 2 x the steady state production oversite labor of QA and mechanical/electrical engineering is assumed through coil QXFA-110. No further learning curve is assumed for the series production. However, provisions for training a second FNAL crew in FY19 is included in the plan in order to increase production rate in FY20.

For the BNL coil manufacturing line, there is less coil fabrication experience during LARP, especially for Winding and Curing because the winding and curing infrastructure is planned to be completed in FY18. Therefore, higher multipliers are assumed for BNL in project. For the first two pre-series coils (202 and 203), the same 1.3x multiplier is assumed for all but the winding and curing process. For winding and curing, the multiplier is 2.0x. The following learning curve multipliers are assumed for the other BNL coils:

Coil QXFA-204 - 1.8x
Coil QXFA-205 - 1.5x
Coil QXFA-206 - 1.3x
--- New techs
Coil QXFA-207 - 1.6x
Coil QXFA-208 - 1.4x
Coil QXFA-209 - 1.2x

Production Rate:

From US-HiLumi-doc-95, the total duration for a series coil fabrication is 85 working days. The project assumes that one set of tooling and technician crew is available at each location (FNAL and BNL) from the LARP program. With this existing infrastructure and personnel, some overlap is possible and the production rate at each location is estimated to be 1 coil every 34 working days. However, this production rate is not sufficient to meet the overall project schedule therefore the plan is to procure in FY19 additional tooling and acquire additional manpower to speed up the production rate. Based on the analysis in US-HiLumi-doc-95, with the additional tooling described in the section on Coil Parts, Materials, and Tooling and with additional technicians, the peak project coil production rate is 1 coil every 18 working days at each location.

A production rate of 1 coil every 18 working days at each production line results in a coil set for a magnet (4 coils) every 36 working days in the best case (without rejected coils). With this rate, coil fabrication is in the project critical path. A plan is in place to carefully monitor the actual labor and durations during coil fabrication in FY17-18 to validate the estimates so we can have high confidence in these numbers before freezing the project baseline for CD-2.

BNL Coil and Magnets Shipping Fixtures:

Part of the BNL Coil Fabrication scope is the fabrication of additional coil and magnets shipping fixtures for all Labs.

Coil Shipping Fixtures: assuming coils are delivered at a rate of one every 20 working days from each line at BNL and FNAL, each line needs 1 fixture per month. If total time from preparing to ship (coil or empty fixture) to receipt back and forth is 2 weeks for each of 2 trips, then 4 fixtures total should suffice. Of course, there may be delays such as the inability to immediately remove an incoming coil from the fixture, so it would be wise to have a spare at each location, for a total of 6 fixtures. We already have fixtures as part of LARP, so a total of four (4) additional coil shipping fixtures must be fabricated in project in FY19.

Magnet Shipping Fixtures: a magnet shipping fixture will leave LBNL with the Magnet, then will stay in BNL during the tests waiting for the Magnet and finally it will come (with the Magnet) to FNAL for cold mass assembly. The duration from departing LBNL to returning should be approximately 120 days. Considering the top production rate of 42 days/Magnet, 3+1 spare shipping fixtures should be enough. One shipping fixture is available from LARP, so three (3) additional shipping fixtures must be fabricated in project in FY19.

10. WBS 302.2.07: Structures Fabrication and Magnets Assembly

The project plan is to fabricate five pre-series magnets (MQXFA-03 to MQXFA-07), and 20 series production magnets. The project plan assumes that 1 pre-series and 3 production magnets will fail and need to be re-worked (e.g., disassembly and swapping a bad coil). This re-work effort occurs after the 21st assembly is completed, and most parts are assumed to be reused. The project plan also assumes that 1 magnet will be irreversibly damaged during shipping or handling (therefore 21 magnets are needed for 10 coldmasses).

One additional re-work assembly in this task will be for MQXFAP1, which is the first prototype structure (assembled off-project by LARP). It is assumed it will require a re-work after its vertical test.

The magnet fabrication will be done by LBNL, including procurement of magnet parts. Parts for 21 magnets are needed (5 pre-series and 16 series magnets). From past experience, procurement of magnet parts has a lead time of 6 months ARO. The plan is to place phased procurements at LBNL that are activated each year in April (this date is after the first 2 quarters of the FY to mitigate Continuing Resolution funding risks). This annual order is intended to cover the magnet fabrication needs of one year plus some component spares

To increase production rate and keep up with the coil production rate, additional tooling needs to be procured for use in FY20. This tooling currently includes the following items, timed for production ramp up:

FY18:

- Lifting beams [2x]
- Rollover table
- Rocket pad

- Bladder hydraulic system
- Strain gage monitoring system

FY19:
- Assembly table
- Pivot table [2x]
- Coilpack assembly table
- Winch assembly
- Roller spine
- Tension system

There will not be enough long magnet prototypes fabricated by LBNL to complete the learning curve before series production begins. Therefore, the following learning curve "multipliers" have been assumed for the project plan labor (multipliers are applied to the steady production labor and duration after-learning estimates):

MQXFA-1b:x1.25
MQXFA-3: x1.5 (pre-series and first crew training)
MQXFA-4: x1.25
MQXFA-5: x1.25
MQXFA-6: x1.2
MQXFA-7: x2.0 (train Second Crew to increase production rate)
MQXFA-8: x1.0 (first crew completes learning curve)
MQXFA-9: x1.2 (second crew learning)
MQXFA-10: x1.0 (second crew completes learning curve)

Magnet fabrication can be split into two major sub-assemblies: the Yoke/Shell assembly (which can be done in advance of receiving the coils) and the Coil Pack (which can only be done after receiving the coils). These sub-assemblies are then integrated together into a complete magnet assembly. The project plan will take advantage of this feature to level resources at LBNL consistent with the available funding.

Magnet assembly plan includes measurements for assuring that alignment and field quality requirements are met. Assembly iterations may be needed to meet these requirements.

During peak production, the structure fabrication and magnet assembly process duration for each magnet is estimated to be 60 working days, with a possible overlap of 30 working days. Therefore, the peak production rate is 1 magnet every 30 working days.

The 3 rework assemblies are assumed to only require a coil pack disassembly/reassembly operation—therefore the tasks related to the shell-yoke subassembly are not required in the rework effort.

11. WBS 302.4.01: Magnets Vertical Test

22 magnets that were fabricated or re-worked by LBNL will be vertically tested at the BNL vertical test facility. Testing includes quench training and magnetic measurements. As part of the project scope, some prototypes and pre-series magnets will be tested. The total number of vertical tests planned for the project is 22 (2 prototypes, 5 pre-series, 15 series)

The BNL vertical test facility is assumed to be fully qualified and ready to support production testing. This facility, commissioned in FY16, would have already tested the mirror magnet and the first long prototype, MQXFA-1, as part of the LARP program. The following multipliers are assumed for the prototype and pre-series magnets because the run plan is expected to be longer for these magnets (e.g., may include a thermal cycle).

MQXFA-2: x1.5
MQXFA-1b: x1.8
MQXFA-3: x1.5
MQXFA-4: x 1.8

These multipliers make the total scope equivalent to testing an additional 2.6 production magnets, so the equivalent number of production magnets tests is 24.6

It is also assumed that at the end of every test, the magnet is shipped either to FNAL if accepted or to LBNL for re-work if rejected.

The series production test duration is estimated to be 40 working days. A second top hat and wiring stand is planned to be procured in FY20 to increase the test throughput by preparing a magnet while another one is finished testing. With this second top hat, an overlap of 9 working days is possible, bringing the peak production test rate to 1 magnet every 37 working days.

12. WBS 302.4.02: Cold Mass Assemblies Fabrication

Each cold mass has two magnets inside a stainless steel helium containment pressure vessel. The project plan is to fabricate one cold mass assembly prototype using the first two prototype magnets MQXFA-1b and MQXFA-3, 2 pre-series and 8 series production cold mass assemblies using the 4 pre-series and 16 series production magnets. The project assumes a re-work of one cold mass assembly, so the total number of cold mass fabrication is 12 (1 prototype, 2 pre-series, 8 series, and 1 series re-work). The re-work includes opening the helium vessel and performing internal repairs.

Q1/Q3 cold mass assemblies means that the project plan is to fabricate the cold masses in such a way that the Q1 and Q3 cold mass assemblies are interchangeable so spares work for both quadrupole configurations.

The cold mass assemblies will be fabricated at FNAL. Several cold mass assembly components (e.g., beam tube, heat exchanger tubes, instrumentation, etc.) are expected to be supplied by CERN (see CERN EDMS 1825173). Fabrication includes the pressure vessel fabrication/welding, magnets installation, heat exchangers installation, bus bars installation, sensors, and wiring, alignment, pressure test, etc. Some tooling is assumed to be available from the fabrication of the present LHC IR quadrupoles, and the following tooling is planned to be procured in project:

- Alignment/rolling station
- Welding Station
- End Cover fixture
- Lifting fixture
- Bus bar fabrication fixture
- splice fixture
- Rotation coil MM components
- Welding equipment
- HBM Strain Gauge readout system
- SS shell cutting tool

The most likely Cold Mass fabrication duration is estimated to be 60 working days for the prototype and 40 working days during series production.

13. WBS 302.4.03: Cryo-assemblies Fabrication

Each cold mass will be inserted into a cryostat to deliver a HL-LHC tunnel-ready Q1/Q3 quadrupole (with the exception of the beam screen, which will be installed by CERN after delivery). The cryostat parts will be supplied by CERN and the cryostat will be assembled at FNAL. Assumes re-work of one cryo-assembly, so the total number of cryo-assemblies fabrication is 12 (1 prototype, 1 pre-series, 9 series, and 1 series re-work).

The most likely Cryo-assembly fabrication duration is estimated to be 65 working days for the prototype and 45 working days during series production.

Shipping and Handling of the cryo-assembly to CERN is included in this WBS. After horizontal testing and passing the acceptance procedure, the cryo-assembly is prepared for shipping and shipped to CERN in a dedicated container (one container per cryo-assembly is assumed).

The most likely shipping and handling duration is estimated to be 30 working days.

14. WBS 302.3.04: Cryo-assemblies Horizontal Test

Each cryo-assembly will be tested in the FNAL Horizontal Test Stand previously used to test the present LHC IR quadrupoles. There will be a total of 12 cryo-assemblies tested (1 prototype, 2 pre-series, 8 series, and 1 series re-work).

The FNAL Horizontal Test Stand, Stand #4 in Industrial Building 1, needs to be brought back into reliable operation and upgraded to meet the requirements of the HL-LHC cryo-assemblies.

The project plan assumes that bringing the test stand back to reliable operation is off-project and funded by FNAL. The necessary upgrades are part of the project scope. Upgrades include interconnect and turn around can for interfacing to the new Cryo-assemblies, and magnetic measurement system including a Stretched Wire System, a Probe/Ferret system, Shaft and transport modifications, and a DAQ station. Two CLIQ units (provided by CERN) should be integrated into the protection system. Following is a list of items to be procured in project:

- Bellows
- Helium collection port
- Large Interconnect bellows
- Return can
- Instrumentation components
- All other components
- SSW system
- Probe/ferret
- Shaft and transport modifications
- DAQ station
- 25-ton crane

The test stand must be ready to support testing the cryo-assembly prototype in October 2019.

The most likely Cryo-assembly horizontal test duration is estimated to be 75 working days for the prototype and the first two production cryo-assemblies, and 47 working days for the rest of the series production.