AUP Superconductor Quality Plan

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Revision History

Rev.	Date	Description	Section	Author
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1 SCOPE AND SUMMARY

This document describes the quality assurance (QA) and quality control (QC) management related to the acquisition of the superconductor for the MQXFA quadrupole magnets to be produced by the U.S. HL-LHC Accelerator Upgrade Project (AUP). In this context, "superconductor" or "Conductor" refers to the Nb_3Sn RRP® strand under the strand procurement task (302.2.02) and the Rutherford cable and cable components including the stainless steel core and braiding insulation under the cable fabrication task (302.2.03). The quality plan presented here covers the workflow, reporting, and controls management for manufacturing, inspection, and acceptance under both normal and unusual situations.

The task leaders and their deputies and the control account managers of the two AUP superconductor tasks are:

	Task Leader	Deputy Task Leader	Control Account Manager
302.2.02 *Strand Procurement*	Lance Cooley (FSU)	Vito Lombardo (FNAL)	Vito Lombardo (FNAL)
302.2.03 *Cable Fabrication*	Ian Pong (LBNL)	Charlie Sanabria (LBNL)	Ian Pong (LBNL)

2 APPLICABLE DOCUMENTS

The following documents form a part of this specification to the extent specified herein:

US-HiLumi.doc.36	MQXFA Functional Requirements Specification
US-HiLumi.doc.37	Advanced Acquisition Plan for Quadrupole Magnet Conductor
US-HiLumi.doc.40	Quadrupole Magnet Conductor Specification
US-HiLumi.doc.41	Material Naming Scheme
US-HiLumi.doc.74	Cable Specification
US-HiLumi.doc.75	Cable Insulation Specification
US-HiLumi.doc.138	Production Plan
US-HiLumi.doc.885	Design Criteria for MQXFA Superconducting Elements

3 SUPPLIERS AND VENDORS

Nb_3Sn Strand Supplier	Bruker-OST, 600 Milik St., Carteret , NJ 07008, USA
Stainless Steel Core Vendor	Brown Metals Company, 8635 White Oak Ave, Rancho Cucamonga, CA 91730, USA
Braiding Insulation Vendor	New England Wire Technologies, 130 North Main Street, Lisbon, NH 03585, USA

4 NOMENCLATURE

Supplier QC	The quality control tests performed at the supplier or vendor
Verification QC	The quality control inspection performed at the national laboratories for verifying the supplier QC system by means of comparing QC data, on samples adjacent to the supplier QC samples
Witness QC	The quality control tests performed to validate the coil heat treatment (HT)
Virgin Strands	Round wires without suffering cabling deformation, including remainder round wires left on the spools (a.k.a. "spindles") after a cable run
Rolled Strands	Round wires rolled to a height reduction (of 15% in this document unless otherwise specified) to simulate the deformation at the cabling edges (or "kinks" when the differentiation between major and minor edges is ignored)
Extracted Strands	Strands extracted from a Rutherford cable – hence by definition deformed. They are representative of the degraded performance of cabled strands compared to round wires
Startup Sample	Cable samples fabricated for the purpose of making controlled adjustments to the machine setting, typically out of specification
Qualification Sample	Cable samples fabricated after controlled adjustments for validating the machine setting, must pass before production may proceed
Archive Samples	Wire or cable samples kept for future uses

5 CONTROL POINTS AND PRODUCTION FLOW CHART

Laboratory review and approval is required at certain steps to ensure product quality. Authorization to proceed will be required at the following points:

5.1 Strand Procurement Control Points

- **Authorization to begin work** shall be given after reviewing the response (including the QA package, see 6.2.1) to the request for proposal (RFP). This authorization is expected to occur concurrently with, or shortly after, the award of the contract. The supplier will be selected by a source evaluation board (SEB), based on a range of criteria such as past performance of conductor products, manufacturing capability, ability to delivery according to timetable, and the QA package.

- **Authorization to deliver**: The supplier is instructed in US-HiLumi.doc.40 Quadrupole Magnet Conductor Specification to not deliver product upon the completion of manufacture. Rather, the supplier will prepare a full report ("QA Package" see 6.2.2) and issue a written delivery request, along with verification samples of the pieces to be delivered (if not already delivered, see below in this paragraph). Upon satisfactory review of the information in the delivery request, and possible completion of verification testing at the national laboratories, the 302.2.02 task leader or his delegates may issue a delivery approval and formally accept the conductor. The process to issue an authorization to deliver may require 60 days. The supplier is further instructed to deliver verification samples as reasonably close to the onset of the supplier's own QC process as possible, to minimize the time required to conclude the authorization process. The authorization to deliver constitutes a clearance for strand usage in cable, subject to any attached conditions.

- **Discrepancy resolution** shall be issued when a significant discrepancy has caused managers to hold production. The resolution may result in changes to the manufacturing plan, QA plan, or management plan, which will be documented in a change order. This may require a significant amount of time.

5.2 Cable Fabrication Control Points

- **Work order** shall be required from the cable task leader or his deputy prior to any strand usage. The issuance of a Cable Fabrication Procedure with a strand map constitute a work order.

- **Authorization to proceed points (ATPP's)** are placed (1) after the cabling machine is strung and before any cable samples are made, (2) after the cable qualification is made and before the production unit length is fabricated, and (3) after the production unit length is made and before QC samples and archive lengths are cut. An ATPP requires the technicians to stop work until a clearance is issued by the 302.2.03 task leader or his deputy. ATPP's are procedural, i.e. they take place every time.

- **Conditional ATPP** is placed when an ATPP clearance will be automatically granted if certain conditions are fulfilled. Work must stop only if any of the qualifying conditions does not pass. Conditional ATPP's are also procedural. They are only placed in special circumstances where there are compelling justifications.

- **(Conditional) hold points** are *ad hoc* control points, placed to respond to irregular situations.

- **Authorization to ship** a bare cable to the insulation vendor is granted when the 302.2.03 task leader or his deputy issues a shipping document according to US-HiLumi.doc.74 requirements.

- **Cable release approval** is the final sign off certifying that the cable meets all requirements per US-HiLumi.doc.74 and US-HiLumi.doc.75, or where the requirements are not met, a deviation or non-conformance report has been submitted and approved.

5.3 Production Flow Chart

Below are three flow charts showing the strand procurement contract award process (Figure 1), the strand manufacture process (Figure 2), and the cable fabrication process (Figure 3), with the responsible parties demarcated and the main control points highlighted. All the control points for conductors are internal to AUP (i.e. none due to CERN), but may apply to AUP subcontractors.

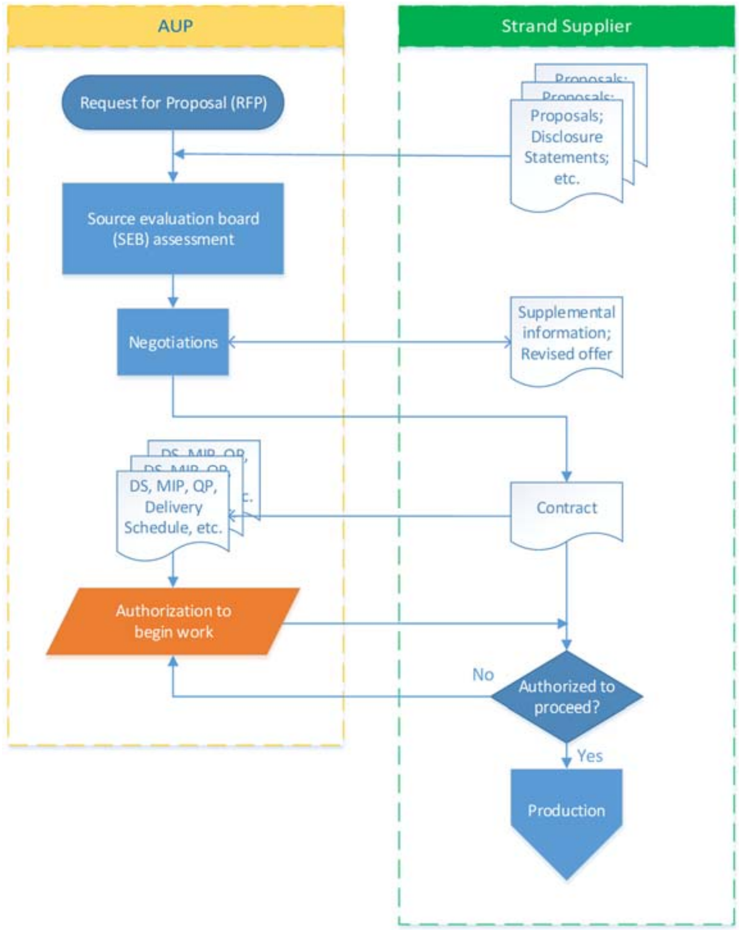

Figure 1 Flow chart showing the process of strand procurement contract award, the responsibilities of AUP and of the supplier, and the control point (in orange).

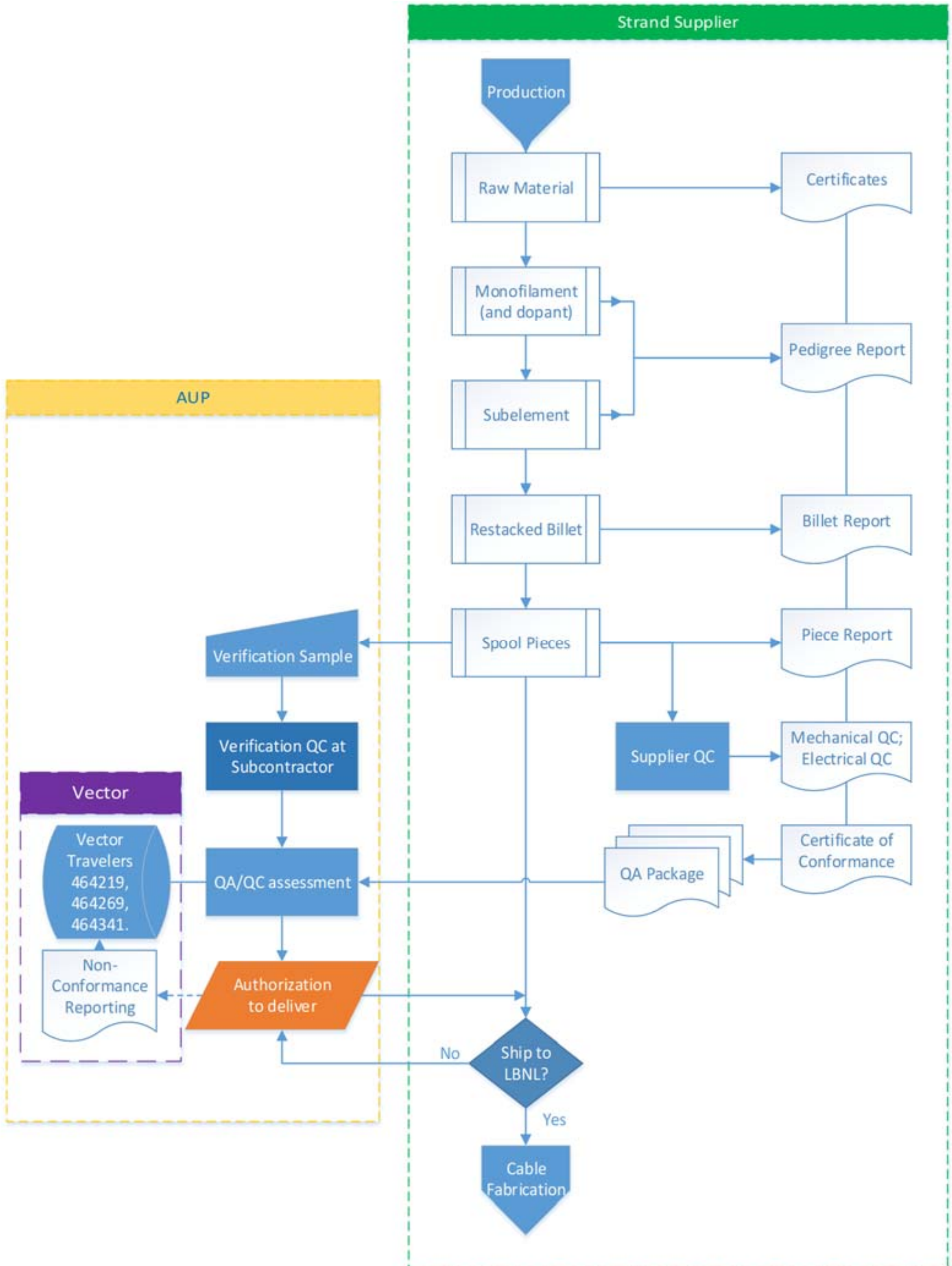

Figure 2 Flow chart showing the process of strand manufacture, the responsibilities of AUP and of the supplier, and the control point (in orange). Vector is the traveler system used by AUP.

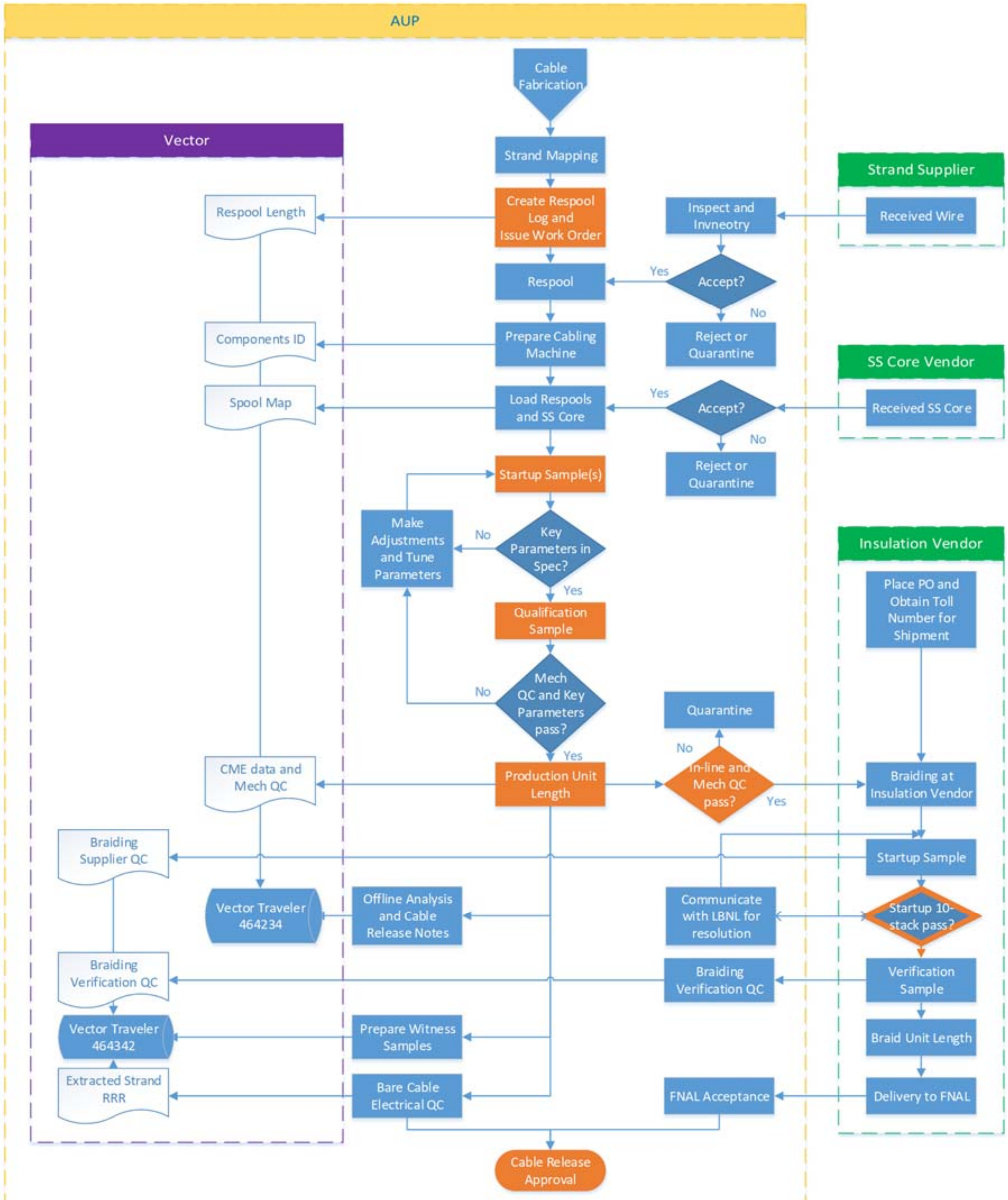

Figure 3 Flow chart showing the process of cable fabrication, the responsibilities of AUP and of the suppliers / vendors, and the control points (in orange) and conditional ATPP (orange outline). Vector is the traveler system used by AUP.

6 QUALITY ASSURANCE

6.1 Conductor and Project Reviews

6.1.1 FNAL Director's Reviews

Approximately three months before the DOE Reviews (see 6.1.2), the FNAL Director would call a review. The ones relevant to superconductors are:

1) The Hi Luminosity LHC Accelerator Upgrade Project CD1/3a Director's Review held at FNAL between the 13th and the 15th of June, 2017. For details, see Appendix A: FNAL Director's Review 2017.
2) The Hi Luminosity LHC Accelerator Upgrade Project CD2/3b Director's Review to be held at FNAL, provisionally between the 17th and the 19th of July, 2018.

6.1.2 DOE Reviews

As a 413.3b project, there will be DOE reviews for critical decisions (CD). The ones relevant to superconductors are:

1) CD-1/3a – Approve alternative selection and cost range ("CD-1") for both strand procurement (302.2.02) and cable fabrication (302.2.03), and Approve purchase of long-lead items ("CD-3a") for strand procurement (302.2.02) only.
2) CD 2/3b – Approve performance baseline ("CD-2") and approve start of construction ("CD-3b") for cable fabrication (302.2.03).

6.1.3 International Reviews

There have been two international reviews:

1) The HiLumi-LHC/LARP International Review of the Superconducting Cable for the HL-LHC Inner Triplet Quadrupoles (MQXF) was held at CERN between the 5th and the 7th of November, 2014. For details, see Appendix B: International Review 2014.
2) The International Review of the Inner Triplet Quadrupoles (MQXF) for HL-LHC was held at CERN between the 7th and the 10th of June, 2016. For details, see Appendix C: International Review 2016.

6.2 Strand Procurement

The specification is described in US-HiLumi.doc.40. The requirements were established to be technically identical between CERN and AUP. Contracts are placed in phases by FNAL on behalf of AUP, and deliveries are made in multiple shipments identified with an incremental letter (viz. A, B, C…) under the corresponding purchase order ("PO") directly to LBNL, who performs acceptance inspection (see 7.3.3).

At the supplier, Michael Field, the project manager / technical responsible officer (TRO), and Joshua Harnanto, Director of Safety & Quality / QA manager, shall be the main points of contact (POC) for AUP strand procurements. Figure 4 outlines schematically the channels of interaction at high level – between HL-LHC AUP and the supplier's project manager – and at lower levels – between lead representatives in different areas at the supplier and in the HL-LHC AUP organization – to enable prompt information transfer and efficient operation. Items that require discussion, decision, action, or approval should be escalated up to the project managers for discussion at periodic meetings.

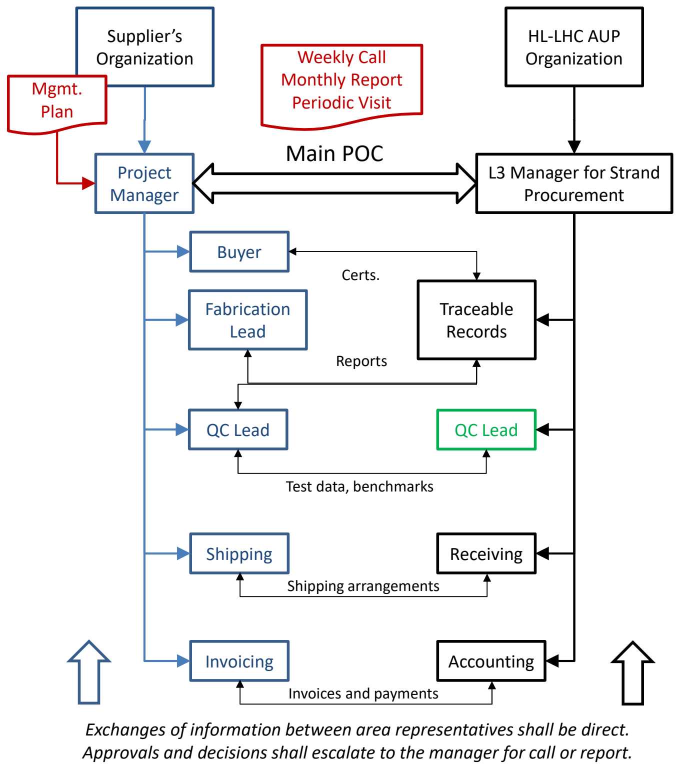

Figure 4 Schematic depiction of the relationships between a supplier and HL-LHC AUP.

6.2.1 QA Package Requirement Prior to Contract Award

As described above in 5.1, the bidding strand suppliers are required to submit a QA package. This QA package shall include a disclosure statement (DS), proof of manufacturing capability, a manufacturing and inspection plan (MIP), a management plan, a quality plan (QP), safety plan, and a manufacturing and delivery schedule.

The DS, MIP, and QP will be reviewed and approved by AUP. Modification to anything described in the DS, MIP, or QP is not allowed after contract signing unless a change request has been submitted by the supplier and has received re-approval from AUP.

The items to be covered by the **disclosure statement** (DS) include:

- The proposed conductor design and a layout of its cross-section
- Identification of all materials and their location and intended function in the proposed design
- The sources of all raw materials, including back-up or secondary sources
- The providers of all sub-contracted services, including back-up or secondary providers
- Standards or other specifications used to control the composition, wrought form, and temper of raw materials
- A proposed heat treatment schedule for the disclosed conductor design

The items to be covered by the **manufacturing and inspection plan** (MIP) include:

- Work flow and applicable documents, procedures, or standards
- Work locations on a floor plan
- The sites where proposed manufacturing will take place (address, city, state)
- Equipment or facilities used at each location, as well as back-up equipment

- Responsible persons or roles in charge of work locations

The items to be covered by the **quality plan** (QP) include:

- In-process tests
- Final product tests
- Proposed test frequency (if different from specification)
- Facilities and equipment used to perform the tests
- Persons who perform the tests
- Certificates of qualification or validation of tests
- Calibrations traceable to standards or nationally-recognized testing laboratories
- Calibration cycles or frequency
- Recordkeeping and data transmission

6.2.2 QA Package Requirement Prior to Shipment

As described above in 5.1, the strand supplier must submit a QA Package for review to obtain authorization for delivery. The QA Package shall include:

- A **certificate of conformance (CoC)** for delivery, with
  - PO number
  - Shipment Number
  - Specification (and revision number, where applicable)
  - Signatures and dates of the supplier Technical Responsible Officer (TRO) and QA Manager
  - Any deviation or non-conformance
  - Details of all the spools under consideration for authorization to ship
    - Spool ID (conforming to US-HiLumi.doc.41)
    - Length (invoiced as well as inspected)
    - Invoiced units
    - Weight
- **Billet report**, providing data of all the billets under consideration for authorization to ship:
  - The billet ID (conforming to US-HiLumi.doc.41)
  - Certification Date
  - Nominal 100% yield length
  - Billet yield
  - Number of superconducting subelements (in lieu of subelement diameter, see US-HiLumi.doc.40)
  - Number of unintentional breaks
  - Raw material Cu RRR
  - Transverse cross sectional micrographs of the Point (P) and Tail (T) ends, and of 15% rolled strands
  - A pass / no pass check on barrier fracture
- **Piece report**, providing data of all the spools under consideration for authorization to ship:
  - The spool ID (conforming to US-HiLumi.doc.41)
  - Length (inspected)
  - Diameter (number of measurements, average, standard deviation, axis-1 average, axis-1 standard deviation, axis-2 average, axis-2 standard deviation, ovality average, ovality maximum)
  - A pass / no pass check on whether wire twist is applied

  - A pass / no pass check on the wire twist direction
  - A pass / no pass check on eddy current test
  - A pass / no pass check on surface cleanliness
- **Pedigree report**, providing identification of all the materials under consideration for authorization to ship:
  - The subelements
  - The key components in the subelements, e.g.
    - Sn core
    - Dopant
      - Nb-Ti
      - Nb barrier
    - Nb barrier
    - Cu element
    - Cu can
    - Cu fillers (identified separately if different sizes are used)
    - Monobillet
      - Nb billet
      - Cu can
- A copy of all the certificates of the raw materials that go into the strands under consideration for authorization to ship
- **Mechanical QC**, providing
  - Sample ID
  - Cu:non-Cu ratio
  - Twist direction
  - Twist pitch
  - Number of cracks under sharp bend test
  - Number of breakages under sharp bend test
  - Number of turns or turns in degrees under spring back test
  - Spring back diameter
- **Electrical QC**, providing
  - Sample ID, with an indication whether it is a round wire or 15% rolled strand
  - Applied HT cycle
  - Identification of the furnace
  - The start date of the HT
  - HT atmosphere
  - The room temperature (RT) resistance per unit length, the low temperature (LT) resistance per unit length, and the residual resistance ratio (RRR)
  - The critical current and the temperature and magnetic field (at least at 15 T and 12 T) at which it is measured
  - The critical current after temperature correction is applied
  - The critical current measurement transition index (a.k.a. *n*-value)

6.2.3 Frequency of Meetings and Progress Reports

The list below outlines the intended frequency of meetings between the main points of contact, and transmission of progress reports. The frequency shall apply fully at the beginning of the work period. The frequency can be sustained throughout the contract period, or can be reduced, by mutual agreement between the supplier(s) and HL-LHC AUP.

Table 1 Meetings with and reports from strand supplier

Meeting	Timing
Kick-off meeting	At start of contract
Budget meeting	At start of procurement phase
Phone or video meetings between points of contact:	Weekly
Progress reports, with reference to schedules:	Monthly
Manufacturing and delivery schedules for next 3 months:	Monthly
Summary reports with all tests performed:	Prior to each delivery
Raw data	Prior to each delivery
Visits to supplier	Quarterly, and if need be
Wrap-up meeting	At end of contract

6.3 Cable Fabrication

The specifications are described in US-HiLumi.docs 74 (cable) and 75 (insulation). The key cable parameters are identical between CERN and AUP, as they are based on the same functional requirements. However, minor technical details may be different, as the machines and their operations are not identical. Some such differences are reflected in the QC requirements.

The cable will be fabricated at LBNL. No disclosure statement is required.

6.3.1 Manufacture and Inspection Plan

As described in 5.2, there are a number of control points. The work flow documentation, including monitoring processes, control points for inspections and testing, and the applicable standards and procedures, are captured in a Manufacture and Inspection Plan (MIP). The MIP is under version control and must be reviewed and approved by both AUP and CERN.

6.3.2 Stainless Steel Core Supplier CoT

The stainless steel core supplier must submit a certificate of test (CoT) with the delivery. The CoT must include:

- The material classification and source information
  - UNS number and specification (316L Stainless Steel, AMS-5507G)
  - Width (12 mm) and thickness (0.001” or 25.4 μm)
  - Supplier Source
  - Melt Mill Source
  - Heat Number
  - Lot number is optional but preferred
- Mechanical properties
  - Condition / Temper
  - Hardness
  - UTS
  - Proof stress (a.k.a. yield strength at 0.2% strain)
  - ASTM grain size is optional but preferred

- Chemical composition
    - Co
    - Cr
    - Other elements optional

6.3.3 Braiding Insulation

LBNL subcontracts an outside company ("vendor") to perform the braiding of S-2 Glass® on the superconducting cable. The vendor is required to have a version controlled procedure available for inspection on-site. No DS or MIP is required.

6.3.3.1 Frequency of Meeting

The list below outlines the intended frequency of meetings between the main points of contact, and transmission of progress reports. The frequency of meetings is not to be applied literally, but should respond promptly to any necessary event, such as quality or contractual issues.

Table 2 Meetings with and reports from insulation vendor

Meeting	Timing
Kick-off meeting	At start of contract
QA reports	Every cable
Manufacturing and delivery schedules for next 3 months:	Every PO
Procurement of raw materials directly from AGY	Once only: 6 months prior to exhaustion of existing stock
Visits to supplier	Quarterly, and if need be
Wrap-up meeting	At end of contract

7 QUALITY CONTROL MANAGEMENT

AUP will adopt a cost-saving and graded approach to QC management. AUP will strive to reduce costs and mitigate cost risks whenever possible. For example, the LHC Accelerator Research Program (LARP) experience has shown that the quality risk associated with the cabling process lies with RRR, not critical current. Therefore AUP will not seek to implement critical current measurements of either the full-size cable or extracted strands as an essential part of cable electrical QC.

The national laboratories and the strand supplier may seek qualified third-party contractors such as a university research group to provide QC testing (see 7.1). The national laboratories shall not select the same contractor as the supplier in the event both parties elect to pursue this option.

When the test facilities at the supplier's location, or under subcontract to the supplier, are operating smoothly and producing test results with required accuracy, verification testing by the national laboratories (or their contractors) need not be performed at the same frequency as the testing activities performed by the supplier (or the supplier's contractor). A graded approach may be applied, where verification testing frequency may be reduced at intermediate phases of the conductor acquisition, and to a lower spot-checking rate during later phases.

It is the philosophy of AUP that the verification tests are not carried out to verify *individual* measurements, but rather to verify the consistency of the supplier's QC facilities and measurement techniques. The primary QC of strand will be the privilege of the conductor supplier. This privilege may be retracted in case of violation of trust. Statistical process control (SPC) is applied to supplier QC data. Correlation between supplier QC and verification QC data will be monitored. AUP may call for additional on-demand testing whenever justified, such as when a conductor billet is processed with an unusual number of breaks. AUP may also request *ad hoc* investigation whenever necessary, such as when an unusual discrepancy arises between supplier QC and verification QC results.

7.1 Qualification of test facilities

Laboratories—including subcontractors—participating in AUP QC campaigns must first be qualified. Qualification paths include having participated in AUP recognized benchmark or round-robin tests, or other activities related to the development of the International Standards used to determine compliance with the specified requirements. Such tests ensure that the laboratories have definitive test protocols with high reproducibility and low uncertainty, as defined by the target accuracy and uncertainty thresholds of the International Standards. Cross-checking between laboratories ensures that this status is maintained.

Qualification of facilities that do not participate in inter-laboratory comparisons can take place by benchmarking. Reference samples, which have been previously measured at a HL-LHC AUP laboratory, are given to the test facility seeking qualification. Testing is done according to the proposed method provided by the specification document. Comparison of results with measurements by the reference laboratory can isolate any deficiencies in the test facility that lead to inaccuracy or increased uncertainty. Periodic re-checking assures that modifications to the test facility, wear and tear on equipment, changes in shift or personnel, or other factors do not result in process creep or accumulation of undetectable uncertainties that lead to errors.

All test facilities shall be calibrated and cross-checked at least annually.

7.2 Specifications and Relevant Documents

The standards, by which specified properties or characteristics are validated, are defined in the technical specification US-HiLumi.doc.40. Generally, approved international standards, such as IEC or ISO standards, or US standards, such as ASTM and ANSI standards, shall be used for test procedures.

When a laboratory uses their own documented procedures, or where there is an absence of applicable standards, the AUP management shall have the right to decide if the process is deemed qualified.

7.3 Quality Controls and Frequency of Tests

A summary of the QC tests for round wire and extracted strand and the location where they take place is shown below in

Table 3. The detailed QC and frequency of tests are shown in the relevant sub-sections.

Table 3 A summary of the key QC for wires and extracted strands only against the test location.

	RRR	I_C at 4.2 K 12 T & 15 T	Diameter	Other LT tests	Other RT tests
Round Wire Supplier QC at supplier	Y	Y	Y		Y
Round Wire Verification QC at AUP subcontractor	Y	Y			
Round Wire Verification QC at LBNL			Y		
Extracted Strand Electrical QC at LBNL	Y				
Round Wire Witness QC at FNAL	Y	Y			
Extracted Strand Witness QC at FNAL	Y	Y			

7.3.1 Strand Supplier QC

7.3.1.1 Raw Material

The supplier should provide the following testing of raw materials. It should be noted that the supplier's Disclosure Statement will detail the names of raw material vendors.

Table 4 Strand supplier's frequency of test on raw material

Material and test	Trusted vendor	New vendor
Copper, RRR	Spot check	Every lot*
Copper, chemical assay	Spot check	Every lot
Niobium, RRR	Every lot	Twice per lot
Niobium, mechanical	Every lot	Twice per lot
Niobium, microstructure	Every lot	Twice per lot
Tin, chemical assay	Spot check	Every lot
Other additives	(depends on form)	(depends on form)
Material condition	Each piece	Each piece

* A Lot is defined as all material having the same parent ingot or billet and having been annealed in the same furnace charge.

The rationale for higher frequency testing of niobium raw materials is based on its dominance of wire-drawing properties and relative difficulty of cleaning and processing, relative to the other metals.

7.3.1.1 Strand

The supplier should provide the following testing of the product ("strand") at the rate specified below.

Table 5 Strand supplier's frequency of mechanical property tests on their product ("Mechanical QC")

Parameter or characteristic	Testing rate
Strand diameter	Each piece
Ovality	Each piece.
Twist direction and pitch	2 per billet (1 point, 1 tail) if billet drawn down in one piece, otherwise 3 per billet
Length	Each piece
Strand spring back	3 per billet
Sharp bend test	3 per billet
Cu : Non-Cu volume ratio	2 per billet (1 point, 1 tail) if billet drawn down in one piece, otherwise 3 per billet
Photomicrographs	3 per billet: 1 point, 1 tail, 1 either end 15% rolled

Table 6 Strand supplier's frequency of electromagnetic property tests on their product ("Electrical QC")

Parameter or characteristic	Testing rate
Critical current	2 round wires per billet (1 point, 1 tail) if billet drawn down in one piece, otherwise 3 per billet; plus 1 either end 15% rolled 12 and 15 T, 4.2 K (required) 13 and 14 T, 4.2 K (for information)
n-value	(with tests above; 15 T required)
RRR	2 round wires per billet (1 point, 1 tail) if billet drawn down in one piece, otherwise 3 per billet; plus 1 either end 15% rolled

7.3.2 Strand Verification QC

Strand verification, under the purview of 302.2.02, only includes Electrical QC. The QC results contribute significant opinion to the authorization to deliver.

Strand verification test frequency is tied to the supplier's rate. If the supplier's obligation test rate is 3 or fewer per billet, then one verification test is required, usually using the verification sample from the tail end of the billet. If the supplier's obligation tests rate is 4 or greater per billet, then the verification test rate is 50% of the supplier.

7.3.3 Strand Acceptance

Strand acceptance, performed by LBNL under the purview of 302.2.03, which takes place after the authorization to deliver but before payment certification, includes the following:

- Visual inspection
- Weight inspection

Spools authorized to deliver to and accepted at LBNL may still be placed under quarantine or diameter scrutiny request per instruction of 302.2.02 task leader. 302.2.03 task leader should place a conditional hold point for respooling in response to a diameter scrutiny request from 302.2.02.

7.3.4 Respooling Diameter QC and Length

Diameter shall be inspected during respooling of strand in preparation for cabling at LBNL. Significant out-of-tolerance events or unusual periodicity suggestive of possible strand production issues shall be reported to 302.2.02, and elevated to L2 where appropriate. Out-of-tolerance events beyond experimental uncertainty shall be documented (see 7.4).

Nominal respooling length is 500 m. When the number of pieces that can be mapped is not in jeopardy, the respooling length may be increased to provide additional margin for insulation and coil winding. At 302.2.03 L3 discretion, the respooling length may go down to 490 m but not more. Authorized by 302.2 L2, the respooling length may go down to 485 m.

7.3.5 Cable Qualification QC

Prior to fabricating the cable unit length, a cable qualification sample (2 m or longer) must pass the following QC tests. There is only mechanical QC requirements, since electrical QC would cause unacceptable schedule delay due to the duration of Nb_3Sn reaction heat treatment.

Table 7 Cable qualification QC (Mechanical QC only)

Parameter or characteristic	Testing rate
Cable width by CME	Every 1 m or more frequently
Cable mid-thickness by CME	Every 1 m or more frequently
Cable keystone angle by CME	Every 1 m or more frequently
Residual twist	1 measurement per sample
10-stack	1 measurement per sample
Metallography	1 measurement per sample
Facet size	No specified rate
Lay pitch and direction	No specified rate
Surface quality	No specified rate

7.3.6 Cable Production Mechanical QC

Prior to releasing the <u>bare</u> cable unit length for insulation, it must pass the following QC tests.

7.3.6.1 In-line QC

Table 8 Cable production in-line mechanical QC

Parameter or characteristic	Testing rate
Cable width by CME	Every 3 m or more frequently
Cable mid-thickness by CME	Every 3 m or more frequently
Cable keystone angle by CME	Every 3 m or more frequently
Facet and broad face real time image analysis	Entire production unit length*

* A negligible amount of "lost data", due for example to occasional and momentary software memory buffer overload, is acceptable.

7.3.6.2 Post-production QC

Table 9 Cable fabrication post-production mechanical QC

Parameter or characteristic	Testing rate
Residual twist	1 measurement per production unit
10-stack	1 measurement per production unit
Metallography	1 measurement per production unit
Lay pitch and direction	No specified rate

7.3.7 Cable Production Electrical QC

Prior to releasing the insulated cable unit length for coil winding, it must pass the following QC tests. Electrical QC on a sample cut from the production unit length may take place concurrent with shipment and/or braiding of the production unit length, since it would otherwise cause unacceptable schedule delay due to the duration of Nb_3Sn reaction heat treatment.

Table 10 Cable fabrication post-production electrical QC

Parameter or characteristic	Testing rate
Extracted Strand RRR	Minimum 5 representative extracted strands per cable

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.

7.3.10 Coil Heat Treatment Witness QC

To validate the coil heat treatment (HT), witness samples representative of the conductor in the coil shall be included with every coil HT. To ensure there will be a spare set of samples in case of measurement issues, the number of samples heat treated must double the minimum number of samples measured.

Table 11 Coil HT Witness QC

Parameter or characteristic	Testing rate
Round wire HT	Minimum 2 representative strands per coil
Extracted strand HT	Minimum 4 representative strands per coil
Round wire critical current	Minimum 1 12 and 15 T, 4.2 K (required) 13 and 14 T, 4.2 K (for information)
Round wire *n*-value	(with tests above; 15 T required)
Round wire RRR	Minimum 1
Extracted strand critical current	Minimum 2 12 and 15 T, 4.2 K (required) 13 and 14 T, 4.2 K (for information)
Extracted strand *n*-value	(with tests above; 15 T required)
Extracted strand RRR	Minimum 2

The responsibilities related to witness QC are as listed below. The interfaces are controlled by the appropriate Interface Control Documents (ICD's).

Task	Responsible party
Preparation of samples	Strand Team
Heat treatment	Coil team
QC measurements and reporting	Strand Team

7.4 Reporting in Vector

All AUP acquired and AUP generated data appropriate for transfer to CERN will be kept in Vector. While the exact fields are not explicitly known, AUP endeavours to retain at least as many fields as reasonably likely be required. The Master Document Travelers relevant to conductors are as follows:

- 464219 – Billet pedigree report. This traveler captures the trace of materials and manufacturing records that are associated with a **billet** of wire strand supplied to AUP. One or several spools of strand may be derived from a single billet, and cross-reference is made between strand and billet reports.
- 464269 – Strand spool report and certification. This traveler captures the mechanical and electrical QC data (both supplier QC and verification QC) for a **spool** of wire supplied to AUP.
- 464341 – strand shipment traveler. This traveler is generated each time a strand supplier produces a **shipment** of strand for delivery to the project. The traveler tracks the actions for delivery authorization, verification testing, and acceptance of strand for subsequent cable manufacturing.
- 464234 – cable manufacturing summary. This traveler is generated each time a **bare cable** is fabricated and covers the spool map and **mechanical QC**.
- 464342 - Cable QC and witness sample preparation traveler. This traveler is generated each time a report is created in 464234, either concurrently or some time after. It tracks the actions for **bare cable electric QC, insulated cable mechanical QC, and witness sample preparation**.
- 464312 – coil reaction traveler. This is not a conductor traveler, but the witness sample measurements are reported here. It is not reported in any of the above because of scheduling and logistics reasons. There is > 3 months' float between conductor and coil finish. Witness sample measurements should not delay traveler closure which releases the cable. Coil fabrication has an assumed yield, and a coil failure should not impact the completion of the cable used.

Note:

- Strand usage for cable fabrication is authorized through the authorization to deliver, not the completion of the strand travelers.
- Cable usage for coil winding is authorized through the cable MIP, where the completion of the cable travelers leads to cable production unit approval.

7.5 Accepting Non-conformance

All non-conformances are reported in Vector. The terminology in Vector for non-conformance reports is "Discrepancy Reports". Each instance is generated from the relevant Vector Master Document Traveler (see 7.4), has a unique identifier, includes a description, and requires disposition and corrective actions to prevent recurrence.

7.6 Change Control

Data are stored on Vector, with QA control (i.e. limited to AUP QA manager and the Vector team) once process completeness verification (i.e. traveler completion signed off by the task leader or his deputy) is signed.

Most project QA documents are stored on DocDB, with version and metadata controls as well as digital certificate for uploading, modifying, reviewing, approving, and signing off documents. Conductor QA documents include specifications (Doc 40, 74, 75), MIP, and certain procedures.

Some conductor QA documents are not stored on DocDB, such as business sensitive documents including strand supplier DS and insulation vendor procedures, which are however available on-site or else kept confidential.

7.7 Archives

Archive samples of strands and bare cables are required. The amount of samples kept must be sufficient for at least a set of witness QC used in regular production.

8 APPENDIX A: FNAL DIRECTOR'S REVIEW 2017

Fermilab

Fermi National Accelerator Laboratory

MEMORANDUM

May 11, 2017

To: Mike Lindgren, Chief Project Officer

From: Nigel Lockyer, Director

Subject: Director's CD-1 Review of the HL-LHC Accelerator Upgrade Project

Please organize and conduct a Director's Review of the HL-LHC Accelerator Upgrade Project on June 13-15, 2017 to assess the project's readiness for the DOE CD-1 review and approval process. The purpose of the Review is to assess all aspects of the project's conceptual design and associated plans.

The review committee should respond to the following questions:

1. **Design and Scope.** Have performance requirements been appropriately and sufficiently defined for this stage of the project? Is the conceptual design sound and likely to meet the performance requirements? Is the U.S. project scope well defined within the CERN HL-LHC project? Does the conceptual design support the stated cost range and duration? Is the need, technical justification and schedule justification sufficient to approve early materials procurement?
2. **Cost and Schedule.** Has a credible and sufficient alternatives analysis been performed? Are the estimated cost and schedule ranges credible and realistic for this stage of the project? Is adequate scope, cost, and schedule contingency included?
3. **Management.** Is the project being appropriately managed? Is the Integrated Project Team established and functioning? Are the management structure and resources adequate to produce a credible technical, cost and schedule baseline? Is the required DOE Order 413.3b documentation on track to be complete for CD-1?
4. **Environment, Safety, Health, and Quality (ESH&Q).** Is ESH&Q being appropriately addressed for this stage of the project? Are Integrated Safety Management Principles being followed?

The committee is asked to present a draft of their report at the review closeout and to issue the final report within two weeks of the review's conclusion.

Nigel Lockyer
Director
Fermi National Accelerator Laboratory

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9 APPENDIX B: INTERNATIONAL REVIEW 2014

High Luminosity LHC

LARP

HiLumi-LHC/LARP International Review of the Superconducting Cable for the HL-LHC Inner Triples Quadrupoles (MQXF)

CERN, Switzerland – November 5th to 7th, 2014

Charges

The High Luminosity LHC project has been approved as first priority by the special CERN Council held in Brussels on 30 May 2013. In May 2014 HL-LHC has been rated among the priority project for US HEP in the next decade by the P5 committee and in June 2014 the CERN Council has approved its financing in the years 2015-2025.

HL-LHC is entering in the final stage of design and prototyping: all technologies for the hardware upgrade must be fully proven by 2016-2017. The replacement of the present Inner Triplet (IT) quadrupole magnets with new quadrupoles (MQXF), featuring much larger aperture and higher peak field, is the cornerstone of the upgrade plan. Tests of the short models of final design, foreseen in 2015-16, and of the long prototypes, planned for 2016-17, are on the critical path. US-LARP program has worked steadily for ten years to reach the present maturity in cable and quadrupole for the LHC upgrade.

As it is well known the SC cable is the component with the longest design, validation and procurement time for SC magnets. This characteristic is even more accentuated with a complex conductor such as Nb_3Sn. In particular the Nb_3Sn cable for HiLumi (LARP) magnets has unique characteristics: a J_c about three times the one specified by ITER; limited degradation and high stability despite strong plastic cabling and deformation. Therefore this relatively large size procurement (approximately 20 metric tons including prototypes and production amgnets) will be the real test of Nb_3Sn industrial maturity for Collider Magnets.

The HL-LHC Project Leader and the LARP Director call an International Review with the following goals:

1. Are the Functional or Technical Specification for conductor strand and cable adequate to the scope of the MQXF ? Are they sufficiently developed and reasonably finalized ?
2. Does the design of strand and cable meet the specifications in terms of minimun I_c, maximum allowed degradation, minimum RRR, maximum D_{eff}, stability request, cable size, and unit length ?
3. Assess the likelyhood of meeting – with adequate margin – the chosen specifications and requirements based on the decade long experience acquired by LARP in cables and magnet construction and the most recent experience in Europe.
4. Is the plan for two types of strand architecture (RRP and PIT) correctly managed inside the program?
5. Is the procurement schedule, with associated QA and test plan, credible and adequate for the prototyping phase (where applicable) and for the construction phase?

The review is schedule for November 5th-6th with the close-out on the 7th at CERN.

We would appreciate a presentation with the main comments and recommendations at the close-out of Nov. 7th, with a written report few weeks later.

10 APPENDIX C: INTERNATIONAL REVIEW 2016

International Review of the Inner Triplet Quadruples (MQXF) for HL-LHC

CERN, Switzerland – 7th to 10th June, 2016

OBJECTIVES

HL-LHC is in the final stage of design and prototyping: all technologies for the hardware upgrade must be fully proven by beginning of 2017. This review covers the cornerstone of the upgrade plan, the new IR quadrupoles (MQXF), featuring 150 mm aperture and peak field in the range of 11.5 T. The previous technical reviews addressed the conductor, the preliminary design, including the engineering concepts and the cost and schedule (within the overall scope of HL-LHC). A review in March 2016 will address the topics concerning the circuit system.

The scope of this review is to examine:

1. The magnet requirements and design status, including the cold mass with its interfaces (cryostats, electrical, hydraulic, mechanical, vacuum) and integration issues (cold mass and integration will be assessed at the level of preliminary design stage);
2. The major design alternatives considered (conductor, aperture, length, operating temperature, etc.);
3. The results of model magnets (including previous smaller aperture ones) and the status of prototype magnets;
4. The conductor performance, procurement status and plans;
5. The status of production tooling, finalization of design and procurement;
6. The components' procurement, status and plans;
7. The test plan, QA/QC, and safety aspects;
8. The strategy for magnet construction and/or procurement and the overall schedule (assuming the US contribution for Q1 and Q3 magnets);
9. The risk registry and mitigation measures.

MANDATE

The review committee is invited to assess the progress since the last reviews (MQXF superconducting cables and MQXF magnet design), the soundness of the design and technical choices, the readiness of the various components and of the procurement plan (including QA/QC) and test plan, and the status of the integration. A detailed resources analysis is beyond the scope of the review. However, comments on the credibility of the plan, also with respect to the available resources, are welcome.

The project is a joint venture between CERN and the US DOE laboratories BNL, FNAL, LBNL, federated under the US-LARP program (now transforming into the construction project called US HL-LHC Accelerator Upgrade Project). The share of contribution between CERN and US HL-LHC AUP is at present approximately equally shared. The committee is invited to comment on the level of integration of the teams, on the collaboration interface and on measures that could be pursued to take advantage of the work distribution.

Following the close-out by the review chair, the committee is required to compile a short report with findings, comments and recommendations within one month. The report will be delivered to G. Apollinari, US HL-LHC AUP Project Manager, and to L. Rossi, HL-LHC Project leader.

REVIEW PANEL (current composition):

Akira Yamamoto (KEK/CERN) Chair

Joe Minervini, MIT (Co-Chair)

Arnaud Devred, ITER

Pasquale Fabbricatore, INFN

Mauricio de Lima Lopes, FNAL

Pierre Vedrine, CEA

DATES AND PLACE: 7th to 10th June 2016 at CERN

PROGRAMME (draft): organized on 4 days (general lines, if possible the review will last 3 days only)

Day 1

- Introduction and outline of the MQXF program
- Magnet design, cold mass and interfaces/integration
- Tooling status
- Model magnet production
- Model magnet test results and analysis

Day 2

- SC performance and production status and plan, QA/QC
- Components procurement, status and plan, QA/QC
- Special issues: protection, FQ, etc.
- Test plan (including IR string)

Day 3

- Safety and codes
- Construction plan and global schedule
- Alternative considered
- Risk registry
- Committee closed session (Q&A)

Day 4

- Committee closed session, report writing
- Close-out

G. Ambrosio LARP (FNAL) and Ezio Todesco (CERN) will be the link persons to propose and finalize the detailed program.