U.S. HL-LHC Accelerator Upgrade Project

SPECIFICATION FOR QUADRUPOLE MAGNET CONDUCTOR

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Revision History

Rev.	Date	Description	Section	Author
DRAFTv0	28-Jan-2015	Original draft.	All	L. Cooley
DRAFTv1	29-Jan-2015	Coordination with US-HiLumi docs 37, 41, and 42	All	L. Cooley
DRAFTv2	12-Feb-2015	Modification of RRR and sub-element spec	6	L. Cooley
DRAFTv3	19-Mar-15	Modification of delivery specifications; Removed "excessive breakage" lang.	11 4,5,6 Annex	L. Cooley
DRAFTv4	20-Mar-15	Further modification of parameters in response to LARP video conf.	4,5,6 Annex	L. Cooley
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Original Release	22-Apr-15	Revision of spec per CERN – US phone discussion	Annex	L. Cooley
Original Release_v2	04-May-15	Incorporation of comments from reviewers	All	L. Cooley
Original Release_v3	04-May-15	Correction of section 11 heading, addition of sub-element diameter to Annex A	11, TOC, Annex	L. Cooley
Original Release_v4	05-May-15	Addition of rolled strand Ic spec. Addition of testing frequency statement. Test frequency removed. Correction to QC document. Rolled thickness changed Modifications of magnetization Summary changes	6.1.4 9.3 9.6 11.1 6.2.2 6.3.1 Annex A	L. Cooley
Original Release_AUP	19-July-16	Conversion to the HL-LHC AUP project template Updated terminology Clarified requirements	All 4 5, 6, 7, 8, 9	L. Cooley
Rev AUP_1	08-May-2017	Added the US HL-LHC AUP logo Changed testing requirements per CERN and 29 March 2017 procurement PO 632982	6, 9, Annex A	L. Cooley

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1 SCOPE

The objective of the specification is the supply of long lengths of strand conductor with uniform properties according to the functional requirements of the MQXFA 150-mm aperture superconducting quadrupole magnets under the HL-LHC Accelerator Upgrade Project. The magnets are to be installed at critical locations near the intersection regions of the LHC during the High Luminosity Upgrade. Prototype magnets are being fabricated by LARP, using the same specifications. The strand will be used to fabricate flat, compacted 40-strand Rutherford cables, from which the MQXFA magnets are wound. Property uniformity along the continuous strand length from any billet, as well as consistency of properties across different billets, thus directly relates to performance and uniformity of cables. In turn, the provision of long cables with the required properties and uniformity ensures the operation of the MQXFA magnets with the target parameters. Margin for degradation during cable compaction and other losses are accounted for by the specified parameters. Each cable must be more than 500 meters long to provide sufficient length for winding a magnet, so long strand pieces would be highly desirable. The strand procurement seeks characteristics in manufactured Nb_3Sn composite superconducting strands that exemplify the best present state of the art, including an addition of Ti to improve properties of Nb_3Sn at high magnetic fields.

2 APPLICABLE DOCUMENTS

The following documents apply to this specification. The document version in effect on the date of invitation to quote shall be the version in force for the purposes of defining and complying with this specification.

2.1. US-HiLumi.doc.36 *MQXFA Functional Requirements Specification*

2.2. US-HiLumi.doc.37 *Advanced Acquisition Plan for Quadrupole Magnet Conductor*

2.3. US-HiLumi.doc.41 *Material Naming Scheme*

2.4. US-HiLumi.doc.42 *Quadrupole Magnet Conductor QC and QA Plan*

2.5. International Standard IEC 61788-2: *DC critical current of Nb_3Sn composite superconductors*

2.6. International Standard IEC 61788-11: *Residual resistance ratio of Nb_3Sn composite superconductors*

2.7. International Standard IEC 61788-12: *Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires*

2.8. ASTM B170: *Standard Specification for Oxygen-Free Electrolytic Copper—Refinery Shapes*

2.9. ASTM B392: *Standard Specification for Niobium and Niobium Alloy Bar, Rod, and Wire*

2.10. ASTM B393: *Standard Specification for Niobium and Niobium Alloy Strip, Sheet, and Plate*

2.11. ASTM B884: *Standard Specification for Niobium-Titanium Alloy Billets, Bar, and Rod for Superconducting Applications*

2.12. ASTM F86: *Standard Specification for Oxygen-Free Copper in Wrought Forms for Electron Devices*

3 NOMENCLATURE

This table defines acronyms listed in this document:

Term	Definition
ASTM	American Society for Testing and Materials, a standards organization
CERN	European Center for Nuclear Research
DOE	The United States Department of Energy
FRA	Fermi Research Alliance
HEP	The Office of High-Energy Physics
HL-LHC	The High Luminosity upgrade of the LHC
I_c	Critical current
IEC	International Electrotechnical Commission, a standards organization
LARP	LHC Accelerator R&D Program
LBNL	Lawrence Berkeley National Laboratory
LHC	Large Hadron Collider
MQXF	Main ring quadrupole magnets being produced by US-HiLumi. Magnets have designs designated ‘A’ through ‘D’, hence ‘MQXFA’, etc.
Non-Cu	The portion of the conductor cross section contained within diffusion barriers, including the barriers themselves. This portion contains the superconducting Nb_3Sn after reaction.
RRR	Residual resistance ratio, the ratio of resistance measured at room temperature to that measured just above the superconducting transition in zero magnetic field
US-HiLumi	The DOE-HEP project to support HL-LHC

4 TERMINOLOGY

Terminology from US-HiLumi.doc.41 *Material Naming Scheme* applies. *In addition*, the following terms apply to throughout this document:

4.1 ***Sub-element:*** A self-contained unit that contains copper, tin, niobium, and possibly other elements that is intended to produce the Nb_3Sn phase after a reaction.

4.2 ***Lot:*** All material having the same parent ingot or billet and having been annealed in the same furnace charge and processed on the same manufacturing line during the same production period.

4.3 ***Non-copper***: The portion of the conductor cross-section that is composed of sub-elements not made from pure copper.

4.4 ***Diameter*:** The diameter d is given by the arithmetic average of multiple simultaneous measurements of diameter for n axes perpendicular to the wire axis, $d = n^{-1}\sum_{i=1}^{n} d_i$. For a 2-axis measuring device reporting measurements a and b along orthogonal directions transverse to the wire axis, $d = (a + b) / 2$.

4.5 ***Ovality**:* The ovality o is given by $o = |a - b|$, where a and b are the maximum and minimum dimensions measured along orthogonal directions transverse to the wire axis. A perfectly round wire thus has an ovality of 0.

4.6 ***Unit Length*:** The length of each strand in a cable used to wind magnets. Since all magnets are the same size, all cables are the same length, and the Unit Length is a constant value.

4.7 ***Yield***: The yield of a billet shall be defined as the ratio of the total mass of pieces from the billet that meet all delivery requirements to the starting billet mass. Remnants that do not meet length requirements but could otherwise be delivered shall be included in the mass of pieces above.

5 PHYSICAL REQUIREMENTS AND PHYSICAL PROPERTY TESTING

5.1 Strand Diameter:

5.1.1 The strand diameter shall be determined by a calibrated multi-axis laser micrometer, with simultaneous measurement axes perpendicular to the strand axis. The requirement above is graphically presented in figure 1, for target diameter d_0 = 0.850 mm and tolerance δ = 0.003 mm.

5.1.2 The measurements shall be carried out at room temperature.

5.1.3 For each axis i,,measurements d_i shall be simultaneously recorded at least once per meter.

5.1.4 The average $\overline{d_i}$and standard deviation Δd_i for all points acquired over the length of the piece shall be reported for each axis i.

5.1.5 <u>For each axis</u> i, average values $\overline{d_i}$ must satisfy 0.847 mm $\le \overline{d_i} \le$ 0.853 mm.

5.1.6 The strand diameter d (see 4.4) and the ovality o (see 4.5) shall be determined from the average values $\overline{d_i}$ and the resulting determinations shall be reported.

Supplier should note that, while it is possible to determine a strand diameter that meets the target diameter and tolerance by taking an arithmetic average that includes values $\overline{d_i}$ which do not comply with 5.1.5, acceptance of the strand will be determined by both 5.1.5 and 5.1.6.

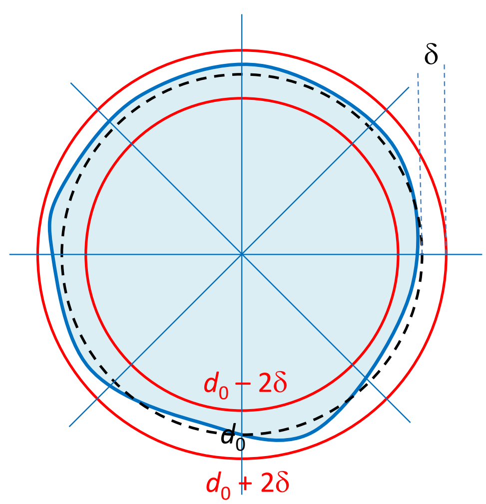

Figure 1. Graphical representation of multi-axis diameter measurements. The strand cross-section at a particular location is represented in blue.

Supplier shall also note that the maximum ovality value is 0.006 mm.

5.2 Superconductor after reaction:

5.2.1 The superconductor shall be formed by reaction at high temperature, after cabling and magnet winding have been completed.

5.2.2 The superconductor shall be primarily Nb_3Sn.

5.2.3 The superconducting phase shall be alloyed with up to 2% Ti by atomic fraction in order to enhance the high field performance.

5.3 Conductor materials and construction prior to reaction:

5.3.1 The superconductor shall be formed within sub-elements that contain copper, niobium, tin, and other requirements to form the alloyed superconductor as in 5.2.3.

5.3.2 The sub-elements (see 4.1) shall be independent and self-contained and surrounded by individual diffusion barriers. Strand designs that use a single diffusion barrier around a collection of sub-elements, or intend sharing of reactants between sub-elements, are not acceptable.

5.3.3 The sub-element count shall be greater than or equal to 108.

Supplier shall notice that this count defines an average sub-element diameter in micrometers, determined by the expression $850\,[N\,(1 + R)]^{-0.5}$, where N is the number of sub-elements and R is the measured copper to non-copper ratio per 5.4. The average defined by a count of 108, a diameter per 5.1.1, and R per 5.4.1 is thus 55 µm.

5.3.4 Supplier shall have liberty to designate material grade and other conditions of sub-element raw materials, such as grain size, hardness, annealing temper, and so on to suit the manufacturing process.

Use of Grade 1 niobium, per ASTM B392: *Standard Specification for Niobium and Niobium Alloy Bar, Rod, and Wire* or ASTM B393: *Standard Specification for Niobium and Niobium Alloy Strip, Sheet, and Plate*2.10 is strongly recommended.

5.3.5 The sub-elements shall be surrounded by copper stabilizer. The stabilizer shall be oxygen free high conductivity grade (also known as electrolytic grade) copper per ASTM B170: *Standard Specification for Oxygen-Free Electrolytic Copper—Refinery Shapes*. Copper tubes, stacking elements, shims, and any other pieces intended for stability shall also be able to meet ASTM F86: *Standard Specification for Oxygen-Free Copper in Wrought Forms for Electron Devices*, class 2 or better, after component fabrication and prior to billet assembly.

5.3.6 A central area of at least 4% of the strand cross section shall be copper stabilizer. Manufacturer shall note that 4% is equivalent to 7 of 169 elements as an example of a stacking pattern with hexagonal symmetry.

5.3.7 Supplier shall provide photo-micrographs of the cross-section of final size wire sufficient to distinguish all assembly details.

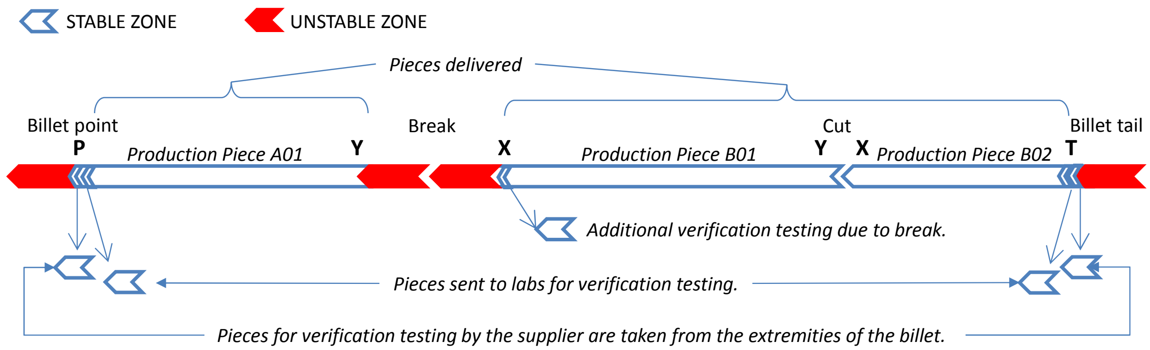

Figure 2. Schematic describing the location of verification samples for each billet and additional verification samples associated with wire breaks..

5.4 Copper Fraction and Copper to Non-Copper Volume Ratio:

5.4.1 The copper volume fraction of the conductor shall not be less than 52.4 % over any portion of wire.

5.4.2 The copper to non-copper ratio R shall satisfy $1.1 \leq R \leq 1.3$.

5.4.3 International Standard IEC 61788-12: *Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires*, or Appendix B of that standard, shall be used to determine the copper to non-copper volume ratio.

5.5 Stand Twist:

5.5.1 All strands shall be twisted such that all sub-elements follow the required rotation.

5.5.2 The strand shall be twisted before the final sizing die.

5.5.3 The twist pitch p shall satisfy 16.0 mm $\leq p \leq$ 19.0 mm.

5.5.4 The twist shall be a right-handed screw with respect to the wire axis.

5.5.5 The presence, pitch, and direction of the strand twisting shall be verified by light acid etching and microscopy observation. Photographs of these observations shall be included in verification data.

5.6 Length of strand pieces:

5.6.1 Delivered pieces of strand must exceed 500 m in length, excluding any lengths used for verification 5.6.2.

Supplier shall understand that very long strand piece lengths are highly desirable, not only to reduce waste and excess, but also because this is a sign of high quality and homogeneity, both of the strand and of its manufacturing process.

5.6.2 Strand pieces for verification purposes shall be nominally 20 m length and equally divided for supplier and purchaser verification testing (i.e. 10 m + 10 m).

Verification purposes include quality control property measurements for certification by the supplier, and verification by the purchaser.

5.6.3 Any verification length must be adjacent to one end of a delivered piece of production conductor or another verification length. Verification lengths delivered to the purchaser shall, moreover, be adjacent to verification lengths selected by the supplier, i.e. they should be cut from the same end of a long conductor piece. This is described in figure 2.

5.6.4 Supplier shall not make unnecessary cuts to continuous pieces. Remnants after accounting for whole unit lengths shall be left on the spool.

5.6.5 Supplier shall report the manufacturing yield for each billet per 4.7. When reporting yield, supplier shall furthermore report a compilation of all final-size pieces derived from the billet, listing length, diameter, and either the mass of the piece or a conversion of mass per unit length for each piece.

5.7 Surface Condition:

5.7.1 Each strand piece length shall be checked continuously on its overall length by an eddy-current method to detect inclusions, voids, cracks, and other surface defects.

5.7.2 The strand surface at the final diameter shall be free of any surface defects, slivers, folds, laminations, or inclusions, and shall not have any component other than the copper stabilizer material visible.

6 ELECTRICAL AND MAGNETIC REQUIREMENTS AND ELECTROMAGNETIC TESTING

6.1 Critical Current:

6.1.1 The strand critical current I_c shall exceed 632 amperes at 12 T field and 4.2 K temperature.

6.1.2 The strand critical current shall also exceed 331 amperes at 15 T field and 4.2 K temperature.

6.1.3 The strand critical current shall be reported for 13 and 14 T field and 4.2 K temperature.

6.1.4 The strand critical current shall exceed 600 A at 12 T, 4.2 K, and also shall exceed 314 A at 15 T, 4.2 K, after rolling to 0.7225 mm thickness (i.e. 15% reduction).

6.1.5 The I_c shall be measured according to International Standard IEC 61788-2: *DC critical current of* Nb_3Sn *composite superconductors* for fully reacted strands at the final diameter.

6.1.6 The I_c shall be defined for an electric field criterion of 10 μV/m.

6.1.7 The I_c shall be reported without any self-field correction.

6.1.8 The voltage tap separation for determining I_c shall be at least 40 mm.

6.1.9 The I_c test at 15 T, 6.1.2, shall include the measurement of *n* as defined in International Standard IEC 61788-2: *DC critical current of* Nb_3Sn *composite superconductors*International Standard IEC 61788-2: *DC critical current of* Nb_3Sn *composite superconductors*. The value of *n* shall equal or exceed 30. The electric field range used to determine *n* shall be at least one decade in magnitude and shall include the I_c criterion.

6.1.10 Supplier shall note that the international standard requires reporting of uncertainty, which includes variations of liquid helium bath temperature from nominal 4.22 K, magnetic field uncertainty, and calibrations.

6.2 Residual Resistance Ratio, RRR:

6.2.1 The value of *RRR* shall exceed 150 for final size strand after full reaction.

Manufacturer shall note the reaction conditions for all samples must comply with 8.1.7.

6.2.2 In addition, the value of *RRR* shall exceed 100 for a final size strand rolled to a thickness of 0.7225 mm, i.e. 15% reduction, also after full reaction.

6.2.3 International Standard IEC 61788-11: *Residual resistance ratio of* Nb_3Sn *composite superconductors* shall be used to determine the RRR value.

Supplier shall note that RRR is defined as the ratio of resistance at 293 K (room temperature) to that defined by the intersection of the superconducting transition region and the onset of the normal conducting region upon warming the sample from the superconducting state. Measurements at 20 K will not be accepted for the low-temperature resistance.

Manufacturer shall note that the international standard accommodates convenient ambient measurements at 20 ± 10 °C via a correction formula. Manufacturer also shall note that thermometry need not be used for the cryogenic measurement if the international standard is followed properly.

6.3 Magnetization

~~6.3.1 The strand magnetization at 3 T field shall not exceed 256 kA m^{-1}, using measurements in transverse magnetic field at nominal 4.2 K, where the entire width of the fully penetrated magnetization loop is used to determine the magnetization. Copper shall not be removed from the strand for this measurement. Supplier shall note that this magnetization expressed as a flux density is 320 mT.~~

~~Supplier shall notice that a strand that produces the specified performance exactly will yield a magnetization of approximately 197 kA m^{-1} at 3 T and 4.2 K. Thus, there is 25% headroom for the supplier to exceed the critical current specification and still comply with the magnetization requirement.~~ (Requirement removed in revision.)

6.3.2 A strand that exhibits flux jumps in perpendicular magnetic fields above 2.7 T at 4.2 K is not acceptable.

6.3.3 A vibrating sample magnetometer, extraction magnetometer, or SQUID magnetometer shall be used for the magnetization measurement. Supplier shall notice that many instruments report magnetic moment in emu (electromagnetic units) instead of A m^2. Supplier shall take careful note of any conversions used; the conversion from emu to A m^2 is to divide emu by 1,000. Thus, a 5 mm length of final-size strand, which has volume 2.837 mm^3, should not produce a magnetic moment higher than 7.26×10^{-4} A m^2 = 0.726 emu.

7 MECHANICAL REQUIREMENTS AND MECHANICAL TESTING

7.1 Sharp bend test

A strand at final diameter in the un-reacted state shall withstand a bend that folds the wire back upon itself lengthwise without cracking or rupture. Upon etching the copper from the bent region, no broken sub-elements shall be visible.

7.2 Strand Spring-Back:

7.2.1 Final diameter strand shall not spring back more than 720 arc degrees.

7.2.2 A 10-turn, 10 mm diameter helix shall be wound with 20 N tension and the ends shall be marked. Upon removal of tension, the helix will unwind. The angular rotation of the marked ends during unwinding of this spring is defined as the spring-back.

8 HEAT TREATMENT REQUIREMENTS

8.1 Schedule

8.1.1 The manufacturer shall recommend a heat treatment (HT) schedule based on internal verification tests. The schedule shall be chosen to ensure performance of delivered pieces meets or exceeds the required specifications after reaction, as well as meet the other constraints below. Once approved by purchaser, the HT schedule shall not change for all materials delivered except by written notification from the purchaser.

8.1.2 The total duration of the heat treatment, from the time when temperature starts its first increase to the time at which the furnace is turned off and allowed to cool from high temperature, shall not exceed 240 hours.

8.1.3 The heat treatment time during the high temperature reaction segment, during which time the Nb_3Sn is formed, shall not be less than 40 hours.

8.1.4 The heat treatment shall not incorporate temperature increase at a rate faster than 50 °C per hour. Supplier shall take note that finished magnets have large mass, which prohibits rapid thermal cycles. Temperature ramp rates shall not affect the final performance.

8.1.5 The maximum temperature shall be as low as possible, yet sufficient to guarantee performance.

8.1.6 The recommended heat treatment environment shall be flowing Ar at atmospheric pressure or vacuum.

8.1.7 Any HT performed by the manufacturer for purposes of verification testing must be identical to the HT recommended for delivered product. This includes exposure to the heat treatment environment for all samples; special shielding or other provisions will invalidate the verification tests.

8.2 Uncertainty

Manufacturer's HT equipment shall comply within the following uncertainty:

8.2.1 All thermocouples used for recording the sample temperature must be calibrated to within ±1°C at the maximum HT temperature

8.2.2 Actual thermocouple readings at sample positions shall be within of 2 °C of each other.

8.2.3 The average of all thermocouples must be within ±5°C of the target temperatures for any dwell stage.

8.2.4 The dwell time, from the point in time when the average temperature reaches within ±5°C of the temperature dwell target, until the point in time that the temperature falls outside ±5°C of the dwell target, must be within ±2 h of the target dwell time.

9 OTHER TESTING AND REPORTING REQUIREMENTS

Supplier shall submit a quality plan that includes testing to verify compliance with this specification. The following items are required elements of the plan.

9.1 Raw materials

Supplier shall verify the following properties for each lot received: copper RRR, niobium RRR, niobium mechanical properties, niobium microstructure, and chemical assay for all components.

9.2 Minimum sampling rate for conductor physical and electromagnetic property tests

A schematic of the *minimum* sampling rate for each wire billet is shown in Figure 1. In general, strand pieces for verification testing shall be taken from production pieces at the extremities of the billet (the "P" and "T" locations, sometimes called "front end" and "back end").

9.3 Minimum testing rate for properties

The required testing rate at the start of production is specified in the following sections. Purchaser may designate a different rate of testing at later times, depending on the progress of production. A production process with good statistical controls is highly desirable, because this should facilitate a reduction of testing frequency at later stages.

9.3.1 Conductor physical property testing

Parameter or characteristic	Testing rate
Strand diameter	Each piece, see 5.1.5, 5.1.6
Ovality	Each piece, see 5.1.5, 5.1.6
Twist Direction and Pitch	Each piece
Length	Each piece
Strand Spring Back	6 per billet (3 point, 3 tail)
Sharp bend test	6 per billet (3 point, 3 tail)
Cu : Non-Cu volume Ratio (*R*)	2 per billet
Photomicrographs	1 per billet

9.3.2 Electromagnetic property testing of round wires

Parameter or characteristic	Testing rate
Critical current	2 per billet (see also 9.4 below) 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)
Residual Resistance Ratio RRR	2 per billet (see also 9.4 below)
~~Magnetization* at 3 T, 4.2 K~~	(No longer required)

9.3.3 Electromagnetic property testing of rolled wires

Supplier shall conduct tests for verification pieces rolled to 0.7225 mm thickness (i.e. 15% reduction). Supplier shall place the flat surface of the rolled sample against the test mandrel when conducting electromagnetic property testing.

Parameter or characteristic	Testing rate
Critical current	1 per billet
n-value	(with tests above)
Residual Resistance Ratio RRR	1 per billet

9.4 Additional testing for billets with more than 2 pieces

Supplier shall provide the additional verification tests below for internal pieces of billets that have 3 or more pieces for delivery.

Parameter or characteristic	Testing rate
Critical current	If I_c (15 T, 4.2 K) ≥ 350 A and RRR ≥ 260 for both tests under 9.3.2, then one additional test should be performed on the piece immediately after the first break or cut location. Otherwise, all pieces for delivery should receive tests.
n-value	(with tests above)
Residual Resistance Ratio RRR	If I_c (15 T, 4.2 K) ≥ 350 A and RRR ≥ 260 for both tests under 9.3.2, then one additional test should be performed on the piece immediately after the first break or cut location. Otherwise, all pieces for delivery should receive tests.

10 IDENTIFICATION REQUIREMENTS

All delivered conductor pieces shall comply with US-HiLumi.doc.41 *Material Naming Scheme*.. In addition, all pieces kept at the supplier for validation shall be labeled according to the same scheme to facilitate cross-referencing.

Supplier shall notice that the scheme for a piece contains the billet number and an identifier of the piece(s) that result from wire drawing. If the billet number does not conform to the naming scheme, supplier and purchaser shall determine a number to comply with the 14-character scheme, which is used by US-HiLumi participants and CERN.

Supplier shall notice that samples used for verification of properties receive additional identification under the naming scheme.

11 DOCUMENTATION AND DELIVERY REQUIREMENTS

Supplier shall note that this specification is part of a larger acquisition plan, which compels all suppliers to provide certain information as part of their offer. The information includes a management plan, a quality assurance plan, a manufacturing plan, and evidence of qualification. The details of the acquisition plan are not discussed here.

Supplier shall disclose the design of the conductor in a Disclosure Statement.

All test results shall be supplied in a format mutually agreed by supplier and FRA. Raw data, certificates of materials, processing records, and similar information related to the production of strand shall be made available after a reasonable period upon request by FRA.

11.1 Documents required for Request for Delivery Approval

Supplier shall *not* deliver any product without authorization or approval from the purchaser. Supplier shall schedule deliveries based on billet number or production lot number.

Prior to the shipment of a product for delivery, the supplier shall notify the purchaser in writing of intent to ship. The notification shall include the following information:

- The billet yield report;
- Certificate of conformity to specification for each billet;
- Raw materials certifications;
- Test results and test reports, using the standards or test methods specified herein.

In addition, the supplier shall be prepared to transmit the raw data from tests, micrographs or microscopy analyses, or other raw information related to the purchaser's database. Purchaser may request this data in conjunction with the strand delivery, or as a follow-up, as deemed appropriate.

11.2 Authorization to Deliver

The purchaser will compare the supplier's information with information obtained from validation testing. Any discrepancies will be resolved to the satisfaction of the purchaser on a case-by-case basis. Purchaser may choose to waive some or all product validation tests associated with a particular billet.

Purchaser shall issue a written authorization to deliver as an indication of product acceptance.

11.3 Shipping Instructions for Long Pieces

11.3.1 Long strand pieces shall be shipped on spools. Each spool shall contain only one piece of strand. No preference is given to the spool axis.

11.3.2 The spools shall be labeled with:

- Date of shipment,
- The Purchase Order Number,
- The Billet number and the Production Lot identifier (if any);
- The 14-character virgin strand identifier (see US-HiLumi.doc.41 *Material Naming Scheme*);
- The length of the piece;

- The spool net and tare weights;
- The bar code generated by the information above;
- The direction of wire drawing relative to the end.

Supplier shall affix this information directly to the outside of the spool.

11.3.3 Packaging

The outside end shall be secured to the spool, such as by wrapping with a plastic shrink wrap.

If the spool is packaged in a cardboard box, an additional copy of the spool label should be affixed to the outside of the box. The strand shall be shipped in the un-reacted condition, preferably in sturdy wooden boxes. Cardboard boxes can be shipped securely on a wooden pallet provided that the dimensions of the pallet prevent shipping damage.

11.4 Shipping Instructions for Verification Pieces

Pieces supplied to the purchaser for validation shall be packaged in sealed plastic bags. Only one piece per bag shall be permitted.

The bag shall be labeled with the virgin strand identifier, with the appropriate suffix that identifies a validation piece. See US-HiLumi.doc.41 *Material Naming Scheme*

Pieces shall be shipped in the un-reacted state.

Multiple bags can be shipped together.

All shipment shall use protective cartons or boxes.

ANNEX – SUMMARY OF PERFORMANCE REQUIREMENTS

Parameter or characteristic	Value	Unit
Superconductor composition	Ti-alloyed Nb_3Sn	
Strand Diameter	0.850 ± 0.003	mm
Critical current at 4.2 K and 12 T	> 632	A
Critical current at 4.2 K and 15 T	> 331	A
n-value at 15 T	> 30	
Count of sub-elements (Equivalent sub-element diameter)	≥ 108 (≤ 55)	 (µm)
Mean Cu:Non-Cu volume Ratio Variation around mean (Mean copper fraction)	≥ 1.2 ± 0.1 (54.5%)	
Residual Resistance Ratio *RRR* for reacted final-size strand	≥ 150	
Twist Pitch	19.0 ± 3.0	mm
Twist Direction	Right-hand screw	
Strand Spring Back	< 720	arc degrees
Minimum piece length	500	m
High temperature HT duration	≥ 40	Hours
Total heat treatment duration from start of ramp to power off and furnace cool	≤ 240	Hours
Heat treatment heating ramp rate	≤ 50	°C per hour
Rolled strand (0.7225 mm thk.) critical current at 4.2 K and 12 T	> 600	A
Rolled strand (0.7225 mm thk.) critical current at 4.2 K and 15 T	> 314	A
Rolled strand (0.7225 mm thk.) *RRR* after reaction	> 100	