Conductor Inspection and Test Plan

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Abstract

The EIC General Purpose Detector system, ePIC, is located at Interaction point 6 (IP6) and includes a 2T solenoid (MARCO) at its heart with an operational central field of 1.7T. The solenoid is 3.5 m in diameter and 3.8 m long, it will use a niobium-titanium conductor cooled at 4.5 K. The detector solenoid for the EIC is a large superconducting magnet. Most of the detector magnets are one-off magnets and require a unique conductor. The conductor required for the EIC detector solenoid is a copper-cladded Rutherford cable; 22 strands of 0.847 mm diameter NbTi superconductor will be used to make the Rutherford cable of 8.85 mm x 1.49 mm size. This Rutherford cable will then be soldered into a copper channel. The overall size of the copper cladded conductor is 11.4 mm x 4.6 mm. The conductor dimensions are shown in figure 1 below ***Error! Reference source not found.****. The insulation matrix shown is for reference only and is not part of the conductor specification. Along with the dimensions, other important parameters are the critical current (of the strands, cable and conductor), RRR of the final conductor, and twist pitch of the Rutherford cable. The overall conductor quality is very important for the success of the magnet.*

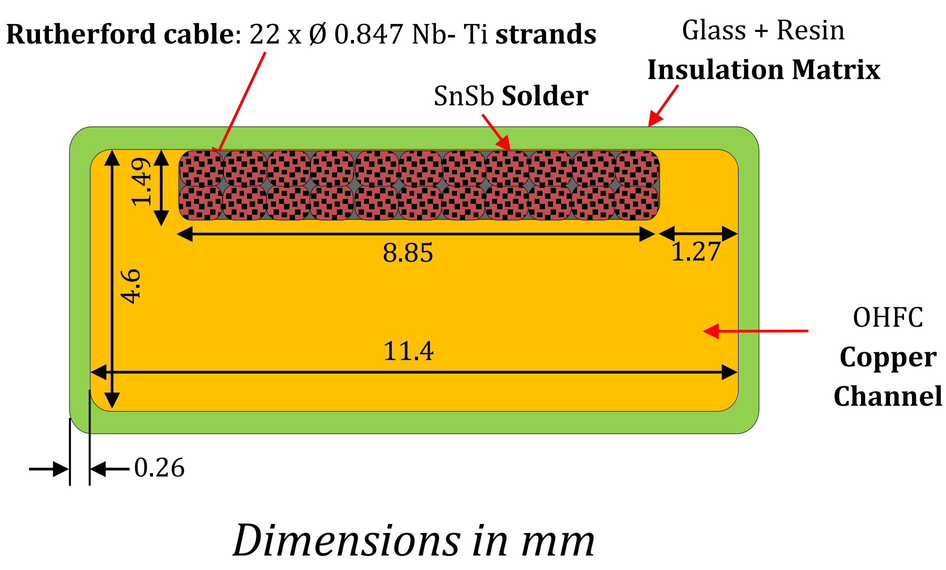

Figure 1. Conductor component definition and dimensions

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1. CONDUCTOR PROPERTIES

The conductor for the MARCO magnet is made up of four main components:

- NbTi Strand of 0.847 mm diameter
- A Rutherford type flat cable of ~22 NbTi/Cu strands
- A high conductivity copper stabilizer channel of overall dimension 11.4 mm x 4.6 mm
- Solder

The main characteristics of the superconducting conductor are summarized in **Error! Reference source not found.**. The subcontractor shall ensure that the chemical, metallurgical, electrical, mechanical, dimensional and surface characteristics of the conductor conform to the present specification. The conductor dimensions and tolerances are given in **Error! Reference source not found.**. The strand specification is given in table 2, the Rutherford cable specifications are given in table 3. The solder details and melting temperature of the solder will be provided by the vendor/subcontractor to JLab for approval before conductor fabrication.

Table 1. Conductor specifications

Parameter	**Nominal Value**	**Tolerance**
Critical Current at 3T and 4.22 K – Extrapolated from extracted Strand value (A)	>13800	
n - value (transition index) for the extracted strand out of conductor	>40	
0.2 % Yield stress (tensile on the whole conductor at 300 K) (MPa)	>165 MPa	
RRR conductor	>80	
Outer width (mm)	11.4	± 0.08
Outer thickness (mm)	4.6	± 0.06
Corner radius (mm)	0.2 to 0.5	
Cu:SC ratio	8.57	± 1.0
Profile tolerance and overall conductor dimensions (mm)	± 0.08	

Table 2. Strand specifications

Parameter	**Nominal Value**	**Tolerances**
Strand Diameter (mm)	0.847	± 0.003
Filament Diameter (µm)	<30	
Cu:SC Ratio	1.31	± 0.1
RRR (before cabling)	>110	
Twist Pitch (mm)	30	± 15%
Filament Twist Direction	Defined by the Vendor	
Critical current at 3T and 4.2 K before cabling (for one strand) (A)	>735	
"n" value at 3T and 4.2 K (Transition Index)	≥ 40	

Table 3. Specifications of the Rutherford Cable

Parameter	Nominal Value	Tolerances
Critical Current at 3T and 4.22 K – Extrapolated from extracted Strand value (A)	>15300	
Channel Width (mm)	8.85	± 0.23
Thickness (mm) or channel depth (mm)	1.49	± 0.03
Number of Strands	22	
Transposition Pitch (mm)	50	± 5
Cable Transposition Direction	Opposite to Strand twist Direction	
Acceptable Critical current Degradation on a strand (%)	< 5	
"n" value of extracted Strand at 3T and 4.2 K	> 40	

The following are the key properties that will be evaluated by these tests and inspections.

1.1. Electrical:

- The diameter of the strands
- The size of the cable, copper channel and conductor
- The critical current of the strands, cable and conductor at B = 3 T, 4 T and 5 T
- Residual Resistance Ratio (RRR) measurements
- Critical current (Ic) & RRR measurement after bending of sample on Ø40 mm rod

1.2. Mechanical Tests

- The mechanical stability of the conductor and the absence of cracks and fractures after bending
- Tensile Test for mechanical properties measurement
- Peeling Test: The cable soldering should be strong enough to avoid the cable being extracted on from the channel with a pulling force of 15 kg.

2. PROCESSES AND PROCEDURES

This section will describe the processes and procedures that are required to evaluate each of the properties described the preceding section. There should be a level 2 sub-section for each of the properties identified in section 1.

2.1. Strand Diameter

The strand diameter will be measured while manufacturing the strand. The strand diameter will be measured at several places in a single spool of strand, at least three measurements will be taken in the first and last meter length of the spool. The values will be recorded in the conductor traveler with the spool number.

2.1.1. In-Process Testing

The strand diameter will be measured while manufacturing.

2.1.2. Incoming Inspections or Acceptance Testing

The ends diameter will be measured again before cabling the strands.

2.1.3. Verification Testing

The strand diameter measurement will be verified either by the quality person from the vendor and/or technical representative of JLab.

2.1.4. Failures and Non-Conformances

If the strand diameter is out of specification range, that spool will not be used for cabling.

2.2. Cable, copper channel and conductor size

The Rutherford cable size is very important for the mechanical integrity of the conductor. The groove size in the copper channel should be sized properly so that the Rutherford cable fits in nicely. The overall conductor size is important for the coil build up.

2.2.1. In-Process Testing

All the size will be measured several times during the manufacturing process, once cable is soldered in the channel only conductor size can be measured.

2.2.2. Incoming Inspections or Acceptance Testing

The final conductor size will be measured during soldering process and before winding the magnet.

2.2.3. Verification Testing

The conductor dimensions will be measured by the conductor vendor and JLab technical representative.

2.2.4. Failures and Non-Conformances

If the conductor dimensions are out of specification range, that conductor will not be used for winding the magnet.

2.3. Critical current of Strand, cable and conductor

The critical current is an important parameter to maintain the safety margins in the magnet. The critical current will be measured for each strand taking samples from the ends of the spool. To measure the critical current of the cable and conductor three strands will be pulled out of cable and conductor and critical current of these pulled strands will be measured. The critical current will be measured at 3, 4 and 5 T field at 4.2K. The critical current of the strands will also be measured after sharp bending the strand on a 1 mm diameter rod.

2.3.1. In-Process Testing

Critical current will be measured after making each billet of stand, each cable spool and soldering each spool length of the conductor.

2.3.2. Incoming Inspections or Acceptance Testing

Critical current will be measured after completing each process of strand, cable and conductor manufacturing.

2.3.3. Verification Testing

The critical current will be measured by the vendor and the test report will be submitted to JLab for verification.

2.3.4. Failures and Non-Conformances

If the critical current at any stage is lower than the specified value, that strand/cable/conductor will not go for further manufacturing.

2.4. Residual Resistance Ratio (RRR)

The RRR will be measured for each strand taking samples from the ends of the spool. To measure the RRR of the cable and conductor three strands will be pulled out of cable and conductor and RRR of these pulled strands will be measured. The RRR of the strands will also be measured after sharp bending the strand on a 1 mm diameter rod.

2.4.1. In-Process Testing

RRR will be measured after making each billet of stand, each cable spool and soldering each spool length of the conductor.

2.4.2. Incoming Inspections or Acceptance Testing

RRR will be measured after completing each process of manufacturing strand, cable and conductor manufacturing.

2.4.3. Verification Testing

The RRR will be measured by the vendor and the test report will be submitted to JLab for verification.

2.4.4. Failures and Non-Conformances

If RRR at any stage does not meet the specification, that strand/cable/conductor will not go for further manufacturing.

2.5. Mechanical Bend Sample Tests on Strand, Cable and Conductor

To ensure that the strands are well suited for cabling, the subcontractor shall subject the strands, after coating, to a sharp bend test, by bending the strand sample in half over a rod 1 mm in diameter. The sharp bend test must be performed on three adjacent samples of each strand production length. Before etching, no deterioration of the bond between the superconducting filaments and the copper matrix and no sign of cracking at the outer diameter of the sharp bend must be visible under a magnification of at least x50. After etching, the bent samples must be inspected for broken filaments. The strand production length shall be rejected if one sample shows more than 1 % of broken filaments

To check the mechanical stability of the cable and the absence of cracks and fractures after bending in order to ensure that the cable is suitable for insertion into the copper channel a Cable sample of 200 mm long is bent over a 20 mm diameter rod while applying a 10 kg tensile load. The cables must keep their coherence after bending, proving their mechanical stability.

To check the mechanical stability of the conductor and the absence of cracks and fractures after bending in order to ensure that the cable is suitable for coil winding. A Conductor sample of 200 mm long is bent and wrapped over a 40 mm diameter rod for three turns while applying a 30 kg tensile load. The conductor must keep their coherence especially at the cable and channel soldering interface after bending, proving their mechanical stability. The conductor must be bent with the cable face on the external radius.

The bent cable will be examined under a microscope with a magnification of at least 50 to determine if any strands are cracked or fractured near the conductor surfaces. Subsequently, the bent area of the sample will be etched in nitric acid and examined for possible filament damage on cable strands. Conductor showing more than 1 % broken filaments will not be accepted. The bending test of the conductor must be performed on one sample for each first three length of Conductor.

2.5.1. In-Process Testing

Mechanical stability will be checked for strand/cable and conductor.

2.5.2. Incoming Inspections or Acceptance Testing

Mechanical stability check will be performed after completing each spool of strand, cable and conductor manufacturing.

2.5.3. Verification Testing

The conductor vendor will perform these tests and share the results with the JLab technical team for approval.

2.5.4. Failures and Non-Conformances

Any failure will lead to the rejection of that strand/cable/conductor.

2.6. Tensile and Peeling Test on Conductor

The mechanical properties of the conductor shall be determined on a sample extracted at the end of each continuous length, following the standard IEC 61788-6 “Superconductivity – Part 6: Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors”.

The cable soldering should be strong enough to avoid the cable being extracted on from the channel with a pulling force of 15 kg.

2.6.1. In-Process Testing

Tensile and peeling tests will be done for each spool of conductor.

2.6.2. Incoming Inspections or Acceptance Testing

Tensile and peeling check will be performed after completing each spool of conductor manufacturing.

2.6.3. Verification Testing

The conductor vendor will perform these tests and share the results with the JLab technical team for approval.

2.6.4. Failures and Non-Conformances

Any failure will lead to the rejection of that conductor spool.

3. EXPERIMENTAL/TEST SETUPS

This section will have an individual sub-section for each of the experiments/tests that will be performed. If the same experimental process will be used for multiple properties, it does not need to be repeated. Each experimental section should provide a detailed description of the method, resource requirements, conditions, and equipment.

3.1. Dimensional Checks

All the dimensional checks are simple and need only digital vernier. Vendor to provide a method for measuring soldered conductor dimensions while soldering is in process.

3.1.1. Resource Requirements

No special resources required for the dimensional checks.

3.1.2. Test Conditions

These tests to be done at controlled room temperature ~27 deg C.

3.1.3. Equipment

List all specialized equipment that will be required to conduct this test. For instance,

- Digital vernier

3.2. Critical current and RRR measurement

Special test equipment is required to measure the critical current at low temperature and in high magnetic field. Most of the superconducting vendors have their in-house test facility. There are some specialized facilities around the world for these types of measurements. The vendor will provide their test methodology to JLab for approval.

3.2.1. Resource Requirements

A trained test technician and a test engineer are required to perform these tests.

3.2.2. Test Conditions

These critical current tests will be performed at 4.2 K temperature and at applied field of 3, 4 and 5 T magnetic field.

3.2.3. Equipment

Special set up for measurement at low temperature and high field.

3.3. Mechanical Bend Sample Tests on Strand, Cable and Conductor

For testing the effect of bending on the starnd parameters, one need 1 mm diameter rod to bend the samples. For the bend test on cable and conductor a “bending principle device” similar to one shown in Figure 2 is required.

Figure 2. Bending Principle Device

3.3.1. Resource Requirements

A trained test technician and a test engineer are required to perform these tests.

3.3.2. Test Conditions

These tests to be done at controlled room temperature ~27 deg C.

3.3.3. Equipment

a bending principle device and load is required to perform these tests.

3.4. Tensile and Peeling Test

For the tesnsile strength, the test consists of straining a test piece by tensile force, generally to fracture, for the purpose of determining the mechanical properties. A tensile machine control system that provides a constant strain rate shall be used. The test machine shall conform to ISO 7500-1. The peeling test is simple and will be done by the vendor.

3.4.1. Resource Requirements

A trained test technician and a test engineer are required to perform these tests.

3.4.2. Test Conditions

These tests to be done at controlled room temperature ~27 deg C.

3.4.3. Equipment

A tensile machine for tensile test and appropriate load for the peeling test.

4. ENVIRONMENT, SAFETY & HEALTH CONSIDERATIONS

The procedures will be implemented in a way consistent with the environment, safety, and health policies of the relevant work areas. Within Jefferson Lab the process is described in the ES&H manual Chapter 3200, Work Planning and Control Program and at BNL within the SBMS: “Work Planning & Control for Experiments and Operations”.

5. RECORDS AND DOCUMENTATION

All the test reports provided by the vendor will be part of the documentation for magnet manufacturing. These will be saved/stored in JLab controlled folders for future reference.

5.1. Manufacturer/Producer Records

Conductor vendor will do all the tests and provide all the test results to JLab.

All controls and tests will be recorded in documents with a summary of the conductor performances and all the details of possible deviations from the specification characteristics. All material or object will have full traceability, in particular for the strands.

5.2. Deliverable Documentation and Records

The following deliverable documentation will be provided:

- Critical current data for each conductor spool
- RRR data for each conductor spool
- Tensile strength for each conductor spool

6. REFERENCES

EIC Systems Engineering Group. (2022). *Interface Management Plan.* Brookhaven, NY: Brookhaven National Laboratory.

EIC Systems Engineering Group. (2022). *Requirements Management Plan.* Brookhaven, NY: Brookhaven National Laboratory.

EIC Systems Engineering Group. (2022). *Systems Engineering Plan.* Brookhaven, NY: Brookhaven National Laboratory.