SSC-MAG-118

SSC-N-291

3-24-87

SPECIFICATION FOR NbTi SUPERCONDUCTOR WIRE FOR SSC DIPOLE MAGNETS

1. Technical Requirements

1.01 Conductor Type: The conductor shall be a composite of NbTi filaments in an oxygen-free copper matrix. The superconductor composition shall be Nb 46.5 ± 1.5 wt.% Ti, and shall be high homogeneity grade or equivalent.

1.02 Critical Current: The conductors shall have a critical current greater than the values listed in Table I. These values refer to a test temperature of 4.222 K and a critical current criterion of $\rho = 10^{-14}$ ohm • m, based on the total wire cross section area and with the applied magnetic field perpendicular to the wire axis. The currents given in Table I and the conditions defined above correspond to a current density in the superconductor of 2750 A/mm^2 at 5 T and 1100 A/mm^2 at 8 T.

1.03 Filament Size: The filament size shall be 6 microns. In order to insure that the filaments are electrically decoupled, the filament spacing shall be greater than 1.0µm in the billet design.

1.04 Copper-to-non-copper Ratio: The copper-to-superconductor area ratio is determined by first weighing a length of wire and then weighing the filaments after dissolving the copper matrix in the same wire. The ratio is defined by the equation and constants below; the required values and tolerances are given in Table I.

$$\frac{A_{Cu}}{A_{SC}} = \frac{\rho_{SC}}{\rho_{Cu}} \left(\frac{\text{Total Weight}}{\text{Superconductor Weight}} - 1 \right)$$

ρ_{SC} = Density of Superconductor = 6.02 gm/cm^3

ρ_{Cu} = Density of Copper = 8.95 gm/cm^3

1.05 Resistance at Room and Transition Temperatures: The resistance of the wire at room temperature (or normal state resistance is usually expressed as R at 295K or R_{295}. It is an important parameter for magnet construction and depends on the content and purity of the copper. The resistance of the wire at transition temperature, usually expressed as R at 10K or R_{10} can also provide a convenient independent check of the copper-to-superconductor ratio. The procedures for measuring R_{295} and R_{10} are described in Appendix A of this specification. The values for resistances and tolerances are given in Table I.

1.06 Copper Residual Resistivity Ratio: The RRR for wire at final size, equal to R_{295}/R_{10}, is defined by the values of R_{295} and R_{10} given in Table I. The target values for RRR as given there are greater than 83 for the inner layer wire and greater than 89 for the outer layer wire.

Table I. Requirements for Inner and Outer Layer Superconducting Wire

Requirement	Inner Layer	Outer Layer
Minimum Critical Current at 5 T	N.A.	323 A
Minimum Critical Current at 7 T	321 A	N.A.
Copper-to-Superconductor Ratio	(1.5 ± 0.1):1	(1.8 ± 0.1):1
Wire Diameter	0.0318 ± 0.0001 in.	0.0255 ± 0.0001 in.
Maximum R_{295} (micro-ohms/cm)	503	800
Maximum R_{10} (micro-ohms/cm)	6.1	9.0

1.07 Twist Pitch: There are two options for twist pitch depending upon which cabling method will be followed.

Option A requires the wire to be twisted to produce a twist pitch of 2.0 ± 0.1 twists/inch at the final wire size. All wire shall be twisted clockwise so that the filaments follow the same rotation as a right-hand screw thread. Requirements on twisting shall apply over the full length of delivered wire (no leaders with variable twist are allowed).

Option B requires that the wire be delivered in the untwisted condition.

1.08 Final Anneal: The wire may be ordered in the annealed or unannealed condition. If the wire is ordered in the unannealed condition, samples for testing purposes shall be annealed for 3 hrs. at 230°C in order to verify that the R_{10} and RRR values are satisfied.

1.09 Surface Condition: The wire surface shall be free of all surface defects, slivers, folds, laminations, dirt, or inclusions. No NbTi filaments shall be visible.

1.10 Minimum Lengths: At least 90% of each order shall be delivered in lengths greater than 10,000 ft. The remaining 10% may be made up of lengths between 1000 ft. and 10,000 ft. If more than 10% of the ordered quantity falls below 10,000 ft. in length, the additional short lengths may be accepted, but at a reduced price which reflects the added costs associated with testing and cabling short lengths. Minimum length shall be determined after all lead and end defects have been removed by cropping. These defects include areas of distorted cross section due to wire point by swag- ing, and foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion.

1.11 Mechanical Properties: The wire shall survive a sharp bend test without any visible sign of cracking at the outer diameter of the sharp bend.

2. Seller's Quality Assurance, Inspection, and Tests

2.1 Seller Responsibility: The seller shall establish a quality assurance program that assures manufacture of a product that complies with this specification. The seller shall provide the purchaser with seller's sampling plan and inspection schedule and a description of the means whereby he will maintain control over his own and his subcontractor's manufacturing processes, inspection and testing, handling and storage. Included shall be means for identification of conforming material, serialized identification by lot of finished product, and procedures for the segregation of nonconforming material. The seller's record-keeping system shall be such that traceability exists for all QC records and material used in the conductor from the time raw materials are received by the seller until the final conductor is completed. In particular, detailed records shall be maintained for billet extrusion conditions (time and temperature of pre-heat, extrusion temperature and speed, post extrusion cooling if any, etc.) and wire annealing conditions.

2.2 Test Witnessing: The purchaser reserves the right to witness manufacturing steps, tests, and inspections established under the seller's quality assurance program, and all other testing performed at the seller's plant and his subcontractor's plants to demonstrate compliance with this specification. Any information of a proprietary nature must be identified in the seller's bid response. The seller will not be required to disclose this proprietary information, but will be required to show that adequate records and quality controls are maintained in these proprietary steps.

2.3 Sample Testing: The seller shall measure the critical current for samples from each continuous length of wire at B = 5 T and 8 T, and T = 4.222 K. If a temperature of 4.222 is not possible, measurements may be made at another temperature and a conversion constant must be supplied. The conversion constant must be approved by Buyer. A 5-foot sample of wire adjacent to each length used by the Seller for critical current measurements shall be sent to the Buyer. These samples shall be identified by billet number, spool number, original continuous wire length, and purchase order number. Samples will be checked by the Buyer to insure that they conform to all aspects of the specification, both mechanical and electrical.

ASTM B-714-82 and Item 1.2 of this specification will form the basic method and criteria for measurement of the critical current of these samples. The techniques described in Appendix A of this specification are consistent with the ASTM procedures for determining the short sample critical current and will be employed by the Buyer to verify the measurements. In addition, Appendix A describes the practical test methods to be used for determining the normal state resistance and copper-to-superconductor ratio of the wire.

The seller shall measure the bend strength of a sample from each continuous length of wire. This test shall be performed according to the procedure in Appendix B.

2.4 Certification: The seller must provide a written statement with each wire shipment certifying that it meets all of the buyer's specifications.

3.0 Spooling and Shipping: Wire shall be level-wound. Spools shall be labeled with wire length, weight, billet number and purchase order number. Spools shall be packaged so that neither spools nor wire are damaged in shipment.

APPENDIX A. VERIFICATION OF ELECTRICAL PROPERTIES OF SUPERCONDUCTING WIRE

A. Short Sample Test Method for Critical Current Determination of Twisted Multifilamentary Wire.

1. General Outline; Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is carried out in specified external fields, 5 T or 8 T typical, applied normal to the wire axis, and in a temperature bath of liquid helium at 4.222 K. For currents less than the quench current the V-I curve is reversible.

The critical current is defined as that at which the resistance per unit length, R, is:

$$R = 10^{-10} / (\pi D^2/4) \text{ ohms/m}$$

where D is the wire diameter in centimeters. The effective resistivity of the wire is 10^{-14} ohm • m.

2. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical former so that it fits in a solenoid magnet (see Section 4 below). Either bifilar or monofilar mounting arrangement may be used, if the procedures outlined below are followed. A non-inductive (bifilar) form will provide adequate length, reduce inductive voltage signals, and provide for ease of connection; see Fig. 1. Shorter, monofilar mounts may be used if adequately sensitive signal detectors are available; voltage taps are arranged as in Fig. 2 in this case. Means must be provided for constraint of mechanical motion without interfering with coolant contact: use of a G-10 former with grooved location of wire and careful tensioning during mounting. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

3. Procedure (See Fig. 3)

The sample length (between voltage taps) should be $\geq$ 25 cm. This corresponds, typically, to a voltage drop of several microvolts. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The amplifier signal should be recorded on an X-Y recorder (or if desired in a digital memory device). The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of ± 5%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is < 1%. Electronic circuitry for quench protection is preferable. Frequently, a quality index, n, is estimated using the equation $V = \text{constant} \times I^n$.

4. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to ± 0.5%. The direction between field and wire axis must be 90° ± 6° everywhere. This range of angles corresponds to a variation in I_c of 0.5%.

5. Temperature Bath Correction

The specification temperature is 4.222 K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath) with a precision of ± 0.010 K (10mK). Deviations of 25 mK or less from 4.222 K correspond to an error in I_c of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

$$\frac{I_c}{I_m} = \frac{T_c - T}{T_c - T_m}$$

where T_c is the transition temperature at the specified magnetic field. (Tc = 7.2 K at 5T and 5.7 at 8T.) I_m is the current measured at temperature T_m, and $I_c$is the critical current at the specification temperature, T(= 4.222 K).

B. Test Method for Normal State Resistance of NbTi Superconducting Wire

1. General Outline; Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of NbTi multifilamentary composite wire which is used to make high current superconducting cables. The composite matrix is copper. The resistance per unit length is determined at room temperature (295 K) and just above the transition temperature ($T_c \sim 9.5$ K). These quantities are designated R_{295} and R_{10}, respectively, and are measured with an accuracy of 0.5%. The ratio R_{295}/R_{10} is defined to be the residual resistance ratio, RRR.

R_{295} is determined chiefly by the copper matrix. For a given wire diameter it provides a measure of the volume copper-to-superconductor ratio (Cu/SC) of the wire.

R_{10} is determined chiefly by the residual resistance of the copper matrix. The ratio RRR provides a measure of the electronic purity of the copper matrix.

2. Apparatus Description

A four wire method is used to determine the resistance. The wire sample is mounted on a probe which is also used for superconducting critical current measurements. It has leads which are suitable for carrying the required current from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a digital voltmeter of 0.5 μV resolution. It is helpful during the low temperature measurement to use an X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time (see Section 4 below).

Current in the range 0.1 to 1.0 A is provided by a well regulated and filtered DC power supply. It is measured by a shunt of 0.5% accuracy.

In the room temperature measurement a thermocouple device of 0.1° C accuracy is used to determine the ambient temperature.

3. Sample Mounting

The test specimen is wound on a grooved form. The ends are soldered to the copper terminations of the current leads over a minimum length of 1". Voltage taps are soldered to the specimen at a distance of at least 1" from the current joint. Voltage taps are soldered to the specimen at a separation distance of at least 1" from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% this length should be 50 cm or more. The voltage leads should follow the sample in a non-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. A typical value is 0.5 A. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is raised so that the lowest point of the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. As the sample warms, the voltmeter reading will go suddenly from zero to a finite value corresponding to its normal state resistance. The latter is substantially independent of temperature from the transition temperature, T_c, to 15 K, so that the voltage remains constant long enough to be read and is recorded. With a reasonably designed probe and former it may take 1 or 2 seconds for the specimen to go normal. The resistance will remain in the residual resistance region several times longer than this. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible.

5. Room Temperature Correction

Normally occurring room temperature variations may produce significant variations in the measured resistance. Designating this resistance as R_m and the ambient temperature as T_m(°C), the resistance at the reference temperature of 295 K is calculated as follows:

$$R_{295} = R_m/[1 + .0039\ (T_m - 22)]$$

The effect of the NbTi is neglected for the purpose of this correction.

6. Copper/Superconductor Ratio

The copper-to-superconductor (Cu/SC) ratio is related to R_{295}. Therefore, an independent check can be made of this ratio measured by a weighing technique and by measuring R_{295}. The range of acceptable values of R_{295} is determined by the Cu/SC ratio and the wire diameter.

SPRINGBACK TEST FIXTURE