Large Hadron Collider
Magnet Division Specification

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- Prepared by: Signature on File
- Cognizant Engineer/Scientist: Signature on File
- Q. A. Approval: Signature on File
- ES&H Review: Signature on File

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1. Scope:

This specification establishes the requirements for the manufacture, inspection, test, identification and delivery of 30 strand Rutherford-type cable for use in LHC RF and Insertion dipole magnets. These cables are to be fabricated from surplus SSC strand of diameter 0.0255 in. supplied by BNL. These strands were manufactured by three separate vendors and have been accepted for cable manufacture following the inspection procedure LHC-MAG-M-1007.

The main emphasis of the specification is on adherence to a uniform production method for the conductor. Wires manufactured by the same vendor will be selected for use in cable. Wires produced by different vendors shall not be mixed.

The vendor will be responsible for checking cable mechanical measurements. BNL will measure electrically all cable samples following the procedures given in Appendix B.

2. Applicable Documents:

The following documents in effect on the date of invitation to quote form a part of this specification to the extent specified herein:

- RHIC-MAG-M-7142 — RHIC 8cm Dipole/Quadrupole Cable Test Methods
- BNL-QA-101 — Brookhaven National Laboratory Seller Quality Assurance Requirements
- BNL Dwg. 14000001 — Superconductor Keystoned Cable

3. Requirements:

3.1 Frequency of Sample Testing: The expected frequency of cable sample testing by the vendor and by BNL is summarized in Appendix A. The transmittal of the data and samples to BNL is given in paragraphs 4.2 and 5.4 for the cable.

3.2 Manufacturing Data: BNL does not require regular transmittal of manufacturing data related to wire and cable fabrication. This data will be audited regularly by BNL staff at the vendor facility. The vendor must maintain manufacturing data records for two (2) years after the date of acceptance of the cable by BNL.

3.3 Cable Performance Requirements: The superconductor cable must meet the performance requirements described in Tables I and II and explained in subsequent paragraphs. Checks of the cable dimensional and mechanical requirements are the responsibility of the vendor. An exception to this is periodic off-line checks of the cable keystone angle; see paragraph 3.3.4 Checks of the cable electrical requirements are the responsibility of BNL and will be made using the 24 ft.-long Pre-shipment Cable Test Specimen; see paragraph 5.4. The frequency of cable sample testing is given in Appendix A.

Table I. Cable Dimensional and Mechanical Requirements.

Requirement	Value	Defined in Para. No.
Number of Wires in Cable	30	--
Cable Mid-Thickness	0.04590 ± 0.00025 in.	3.3.1, 3.3.2
Cable Width	0.383 ± 0.001 in.	3.3.1, 3.3.3
Cable Keystone Angle	1.2 ± 0.1 degrees	3.3.1, 3.3.4
Cable Lay Direction	Left	3.3.5
Cable Lay Pitch	2.9 ± 0.2 in.	3.3.5
Maximum Cable Residual Twist	+ 120 degrees	3.3.7 and RHIC-MAG-M-7142
Cable Bend Test	No Damage	3.3.8 and RHIC-MAG-M-7142
Cable Filament Condition	No Damage	3.3.9 and RHIC-MAG-M-7142
Cable Surface Condition	Clean and free from chips, roughness, sharp edges or burrs; surface uniform to < 25% of a single wire diameter; no broken wires or crossovers. No oil residue.	3.3.10
Cable Lengths	Maximum length on a spool: 15,000 ft. Minimum length on a spool: 2,050 ft.	3.3.11

Table II. Cable Electrical Requirements.

Requirement	Value	Defined in Para. No.
Cable Minimum Critical Current at 5.0T	9000A	3.3.12, 3.3.13 Test Method 4141-4, App.B
Cable Maximum R(295)	0.00288 ohms/m	3.3.15 and Test Method 4141-4, App. B
Cable Minimum RRR	38	3.3.15 and Test Method 4141-4, App. B

3.3.1 Cable Dimensions: The primary measurements of the cable mid-thickness, width and keystone angle are to be made with a Cable Measuring Machine (CMM) calibrated to a BNL-approved, certified reference standard. The Measurements shall be given to BNL on PC-compatible 3-1/2 in. diameter floppy disc.

The Cable Measuring Machine is a computer controlled device which continuously measures these dimensions at variable, discrete positions under a stress of (5,000 ± 40) psi. The machine is calibrated against a certified reference standard at the beginning of a run. Normally it is placed in the production line following the cabling machine and monitors the dimensions of the cable so the tolerances given in Table I can be achieved. The tension on the cable when measurements are made by the CMM must be less than 60 lb. The machine can be produced commercially. Availability of this machine for this production is the responsibility of the vendor.

3.3.2 Cable Mid-Thickness: Mid-thickness measurements by the Cable Measuring Machine shall be checked periodically off-line using a ten-stack measuring fixture. The tooling and methods to make the ten-stack measurement are described in RHIC-MAG-M-7142. A ten-stack measuring fixture will be provided by BNL to the vendor. Ten-stack measurements are to be done to check for consistency of the CMM. Correlation of measurements with CMM data is expected to be within ±0.3 mils.

3.3.3 Cable Width: Width measurements provided by the Cable Measuring Machine shall be considered as the primary measurement. No off-line checks are necessary.

3.3.4 Cable Keystone Angle: Keystone angle measurements provided by the Cable Measuring Machine shall be checked periodically off-line with the cable under (40 ± 2) lb. tension and mounted in the Cable Keystone Measurement Fixture. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. Because of the uniqueness of this fixture, checks of this angle will be made by BNL using the Pre-shipment Cable Test Specimen provided by the vendor.

3.3.5 Cable Lay Direction and Pitch: All cable is to be fabricated as left lay so the wires follow the same rotation as a left-hand screw thread. When the cable lay is opposite to the wire twist direction, this will reduce the amount of residual twist in the cable which is a necessary characteristic for conductor to produce satisfactory coils. The cable lay pitch is to be measured parallel to the cable edge. Once a value of cable lay pitch is chosen, it shall not vary during production to the measurement accuracy of this parameter which will be less than 0.1 inch.

3.3.5 Wire Twist Pitch in Cable: Since some cabling machines can add or remove wire twist during cabling, it is necessary to define this parameter. For RHIC 30-strand cable the wire twist shall not be altered during cabling. Therefore, a cabling machine with simple planetary operation is required.

3.3.6 Cable Residual Twist: The cable shall not have excessive twist. A check is made on the twist by using the Cable Twist Measurement Fixture. The cable tension during measurement shall be (40 ± 2) lb. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. The tooling is the responsibility of the vendor. The direction of twist must be recorded with the following convention: positive (+) is clockwise when looking down onto a vertically hanging cable sample.

3.3.8 Cable Bend Test: The purpose of the test is to check the cable resistance to bend-induced cracks and fractures. A cable sample is to be bent over a (0.50 ± 0.01) in.-diameter pin while applying a (40 ± 2) lb. tensile load. Visual inspection under a magnification of 10x must show no visual damage to the wires. The bent cable sample shall be straightened and acid etched. It is again inspected to look for filament damage at the bend. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. The tooling is the responsibility of the vendor.

3.3.9 Cable Filament Condition: The condition of the Nb-Ti filaments in individual wires must not show excessive breakage as a result of the cabling process. After acid etching of an unbent (nominally straight) cable sample, it is inspected under a magnification of 10x. For example, clumps of broken filaments usually at the cable edge, or > 5% general breakage in any wire, is indication of excessive damage and would be cause for rejection of the cable by BNL.

3.3.10 Cable Surface Condition: As delivered to BNL, the cable surface must be thoroughly clean and free from metallic particles or residue. The cable shall not have any residue of lubricating oil on the surface. It is therefore recommended that Mobil 1 not be used. Vendor must disclose the lubricant that will be used in production of this cable. The cable must be free of roughness, sharp edges or burrs that could damage insulation material, and it must be compacted in a stable, uniform manner. In order to avoid "popped wires", it is required that the top surfaces of adjacent wires (forming the wide surface of the cable) lie in the same plane to within 25% of a single wire diameter. This condition should be met when the cable is laid flat with minimal (<2 lb.) tension applied. There shall be no broken wires or crossovers of wires in the cable.

3.3.11 Cable Lengths: The total amount of the actual cable order and the exact piece lengths will be given in the purchase order. Length of cable fabricated must be determined with tension <60 lb. The cable lengths given in Table I represent the longest and shortest lengths expected to be produced by the vendor and are as measured on the cabling machine at the location of the CMM. The amounts given do not include the Pre-shipment Cable Test Specimens described in paragraph 5.4 and Appendix A. All leaders used for cabling setup and which do not meet the cable requirements must be cut off and discarded.

- The maximum amount of cable on a spool will be 15,000 ft.
- Only fully conforming cable shall be shipped to BNL; all non-conformances must be removed by the vendor.
- Based on a production length of cable (< 15,000 ft.) and the purchase order, the vendor shall propose cutting the cable. These "Cut Diagrams" shall be identified with the spool number and submitted to BNL. No cutting of cable or separation will be required by the vendor.
- The length of the cable in a spool must be a multiple of 2,050 feet which is the unit length required to fabricate a single magnet coil.

3.3.12 Cable Critical Current Determination: The critical current values refer to a temperature of [(4.22 ± 0.1)K] and a critical current criterion of $\rho = 1\text{x}10^{-14}$ ohm · m across the entire cable cross section. The applied magnetic field is perpendicular to the wide surface of the cable. The tolerance on the magnetic field is less than ± 0.01T. A correction is made for self-field effects and the required field value is obtained at the narrow edge of the cable. The critical current test procedure to be used by BNL is given in Appendix B. Although it is not included as a technical requirement, the Quality Index (n) will be determined by BNL for every critical current measurement. This parameter is described in Appendix B. It is required that under the test conditions the quench current, I_Q, be greater than the critical current. I_Q is also to be reported.

3.3.13 Cable Minimum Critical Current at 5.0T: This parameter is specified to ensure that the cabling degradation is not excessive. Critical currents less than the minimum would be sufficient reason to stop production pending BNL review.

3.3.14 Cable Maximum R(295) and Minimum RRR: The resistance of the cable at room temperature [(295.0 ± 0.2)K] and the residual resistance ratio (RRR), given by the ratio R(295)/R(10), will be determined by BNL following the procedures given in Appendix B.

3.3.15 Cable Map: The vendor shall supply a "Cable Map" giving the serial numbers of the wires used in the cable manufacturing.

3.3.16 Cold Welds: The cable lengths in conformance with this specification shall have no cold welds.

3.3.16.1 If the vendor decides to follow a practice of placing cold welds in the wire spools during cabling and subsequently removing the corresponding sections of cable, there must be extremely careful quality control to assure that the appropriate regions of the cable are identified and removed. The vendor's Quality Assurance program must address the removal of cold welds from the cable.

4. Quality Assurance Provisions:

The vendor shall maintain a quality assurance program to insure that each item offered for acceptance or approval conforms to the requirements herein.

4.1 Requirements of BNL-QA-101

4.1.1 The vendor shall accomplish the following requirements of BNL-QA-101, Brookhaven National Laboratory Seller Quality Assurance Requirements:

3.1 including 3.1.2 or the Note following 3.1.3
4.1
4.2
4.3
4.4 including 4.4.1, 4.4.2, 4.4.3, 4.4.4
4.5
4.6
4.10 including 4.10.1, 4.10.2, 4.10.3, 4.10.4, 4.10.5
4.12 see para. 5.4 of LHC-MAG-M-1009
4.18 including 4.18.2 and 4.18.4
4.19
4.21
4.23
4.35 for the Cable Meas. Machine (CMM), etc.
4.37 for the Cable Meas. Machine (CMM), etc.

4.1.2 BNL does not grant the Seller material review authority to accept as-is items that do not conform to the requirements of this procurement, or to repair items to a still nonconforming condition.

4.1.3 In the event of conflict between this specification and BNL-QA-101, this specification shall take precedence. Conflict shall be brought to the attention of BNL personnel for resolution prior to commencement of manufacture.

4.2 Data Transmittal: The vendor shall complete and submit to BNL cable measurement data as given in Appendix C. Electronic data transmittal to BNL is required. An acceptable format will be developed by BNL and the vendor.

5. Preparation for Delivery:

5.1 Packaging: Spools of cable shall be packaged and secured to pallets to assure adequate protection against dirt, chips and handling damage.

5.2 Reels/Spools: The cable must be spooled on BNL-approved reels with a minimum hub diameter of 24 inches. The spools must be constructed to prevent damage to the cable during spooling and unspooling. The spools shall be boxed or strapped to a pallet and protected to prevent damage during shipment and handling. They must be stacked and shipped with the spool flanges maintained in a vertical orientation (axes horizontal) in order to prevent the cable from settling on the spool.

5.3 Winding Requirements: During fabrication or transport, the cable must be wound so there are no crossovers of the cable windings. Filler cord shall be used at the reel flanges as required so the cable will lie flat. For required winding direction, see Fig. 1.

5.4 Pre-shipment Cable Test Specimen Submittal: The vendor shall deliver to BNL 24 ft.-long samples of cable from one end of every continuous length of cable or a minimum of one sample every 15,000 ft. Each sample must be adjacent to one used by the vendor to verify the cable dimensional and mechanical requirements by off-line measurement. Sample identification shall include "Pre-shipment Cable Test Specimen" and the information required by paragraph number 5.6. These samples shall be individually marked with their serial numbers and identified as coming from either hub or lead end of cable spool, and shipped to BNL within seven working days of manufacture of the cable and ahead of the regular cable shipment. The cable samples must be accompanied by results of mechanical measurements made during the cabling operation and by the off-line tests made by the vendor. A Cable Map must accompany these results. The samples shall be shipped to BNL wound on a spool of minimum 12-inch hub diameter in a manner so they will not be damaged. These samples will be used by BNL to verify the mechanical and electrical requirements of the cable while production is in progress. It is important that they arrive at BNL rapidly so there is minimal continued production before verification of Cable Test Specimens.

5.5 Coordination of Cable Lengths: The vendor shall develop a standard system to be approved by BNL for coordination of cable length information so there is a clear understanding of "Pre-shipment Cable Test Specimen" location, CMM data and the "Cable Map".

5.6 Marking/Requirements: Spools and exterior packaging shall be identified with the following information in the order shown:

"Superconductor Cable for LHC RF & Insertion
Dipole magnets
Specification No. LHC-MAG-M-1009
BNL Dwg. No. 14000001
BNL P.O. No. ____________
Cable No. LHC-6 ___________
Length ___________ feet
Gross Weight _________ pounds
Net Weight ____________ pounds
Tare Weight ____________ pounds
Cable Machine No. ________________________
Cable Measuring Machine No. ______________
Date of Manufacture ______________________
Name of Manufacturer _____________________

Marking labels shall be applied so they are visible on each spool flange and on the top surface.

5.7 Cable Identification Numbers: The system for cable identification will be given by BNL to the vendor.

APPENDIX A
FREQUENCY OF SAMPLE TESTING

I. Cable Testing

A. Reference: Table I. Cable Dimensional and Mechanical Requirements. All measurements are to be completed by the vendor with the exception of Cable Keystone Angle with separate off-line tooling; see paragraph 3.3.4

Note: The Pre-shipment Cable Test Specimen which is delivered to BNL shall be adjacent to the location used by the vendor to verify the cable dimensional and mechanical requirements by off-line measurement.

Requirement	Test Frequency
Cable Mid-Thickness, Width and Keystone Angle	Continuous measurement with CMM, max. interval 100 ft. Check of mid-thickness with separate off-line tooling every continuous length or min. every 15,000 ft.
Cable Lay Direction and Pitch	Vendor QC
Wire Twist Pitch in Cable	Vendor QC
Cable Residual Twist	Every continuous length or min. every 15,000 ft.
Cable Bend Test	Every continuous length or min. every 15,000 ft.
Cable Filament Condition	Every continuous length or min. every 15,000 ft.
Cable Surface Condition	Vendor QC
Cable Lengths	Vendor QC

II. Cable Testing

B. Reference: Table IV. Cable Electrical Requirements. All measurements to be completed by BNL using the Pre-shipment Cable Test Specimen.

Requirement	Test Frequency
Cable Critical Current at 5.0T - to satisfy minimum and variation requirements; Cable Maximum R(295); Cable Minimum RRR	Every continuous length or min. every 15,000 ft.

Definitions for Cable Testing:

"Vendor QC" indicates that the Quality Control (QC) of the parameter is the responsibility of the vendor. The vendor must initiate a program to assure control of the parameter within the required tolerance.

APPENDIX B
SUPERCONDUCTOR WIRE AND CABLE TEST METHODS

Test Method 4141-4 Verification of Electrical Properties of Superconducting Cable

A. Cable Critical Current Determination

1. Introduction

The sections which follow describe the test method used at BNL to determine transport critical currents of cable short samples. The measurement of critical currents of order 10^4 A is more difficult than the corresponding measurement for a wire carrying several hundred amps for a number of reasons. Large power supplies are required and sensitive voltage measurements must be made in the presence of much noise. Forces on the samples are large and care is required to restrain mechanical motion. Finally, self-field effects are large and must be carefully corrected. This section describes the methods and procedures which have been developed at BNL over a number of years. These procedures have proven suitable for production testing.

2. Relation Between Wire and Cable Critical Currents

For a multifilamentary composite wire, the critical current I_{cw}, may be written as

$$I_{cw} = J_c (\pi d^2/4)/(1+x)$$

where J_c = critical current density in superconductor, A/mm^2

d = wire diameter, mm,

x = copper:superconductor volume ratio (or more generally copper:non-copper ratio)

The quantity J_c provides a figure for comparing wires of different diameter or of different copper/superconductor ratios. (The intrinsic current density of the Nb-Ti may be larger than J_c since the latter is reduced somewhat by variations in cross-section of the filaments.)

Present manufacturing art is such that we may expect to obtain, in multifilamentary composite wires of diameter 0.1 to 1 mm

$$J_c > 2600 \text{ A/mm}^2 \text{ (T = 4.2K, B = 5T)}$$

This value serves as the basis for a wire specification. [The notation used here for temperature is as follows: t-in degrees Celsius, T-in degrees Kelvin.] For a RHIC wire, for example,

$$d = 0.648 \text{ mm } (= 0.0255 \text{ in.})$$

$$x = 2.25$$

and we may expect

$$I_{cw} > 264 \text{ A} .$$

The critical current of a cable, I_c, is somewhat less than the sum of the individual wire values as there is invariably some degradation during the fabrication of the cable. This is expressed as follows:

$$D = 1 - (I_c/\Sigma\, I_{cw})$$

An allowance for degradation, in modern practice, is $D < 0.05$ (=5%). If we let $\Sigma\, I_{cw} = N$ @ 264 A where N = number of wires in a RHIC cable = 30, then

$$I_c > 0.95 \text{ @ } 30 \text{ @ } 264 \text{ A}$$

$$= 7524 \text{ A (at 4.2K, 5.0T)}$$

The critical current is a function of temperature, T, and magnetic field, B. It is generally necessary to convert (or "correct") short sample test results obtained at particular values of T and B, to values corresponding to a standard temperature and field. The steps in this conversion are as follows:

a) Obtain raw data for several applied fields: I_t, critical current at bath temperature,T, and applied field, B_a.

b) Convert I_t to I_c, the value corresponding to reference temperature T_{ref}.

c) Calculate the peak field, B: the sum of the applied field and the self field, due to the measurement current.

d) Plot I_c vs. B and calculate I_c at the reference field from a linear fit to the data.

The calculations used in the above steps are described in detail below. The I_c vs. B short sample curve may be combined with the load line of the magnet to obtain a prediction of its expected performance.

2. Definition of Critical Current

Accelerator magnet cables are designed to carry currents of 1-10 kA in fields of order 6T, at 4.2K. The voltage drop under these conditions is not zero; typically it is a few microvolts per meter. The variation of voltage with current can be measured in a range corresponding to about 0.5 μV/m to 50 μV/m. Smaller voltages are difficult to measure. At the high end, the V-I curve is unstable and an ineversible quench occurs. For currents less than the quench current, the V-I curve is reversible. The critical current is a property of the reversible portion of the V-I curve. It is defined as that current for which

$$V/I = 10^{-14}/(N\pi d^2/4)$$

where

V = voltage drop per m
I = current in amps
N = no. of wires in cable
d = wire diameter in m

For purposes of numerical illustration let d = 6.48×10^{-4} m (=0.0255 in.), N = 30, and I = 7000 A; then V = 7.1 μV/m. It is desirable, therefore, that test lengths of order 1 m be used when the measuring sensitivity is of order 0.1 μV.

The shape of the V-I curve is of the form

$$V = \text{constant} @ I^{n+1}$$

where $\rho = (V/I(N\pi d^2/4)$. The quantity n is routinely measured as described in Section 6 below. Large n-values are indicative of uniform filaments. The n-value is, therefore, a useful diagnostic for monolithic conductors and individual wires, although less so for cables. It is sometimes required that n exceed a specified value for some types of conductor.

The quench current is dependent on T and B in a somewhat similar way as the critical current. Unlike the critical current, however, it is also dependent on several external factors: insulation, ramp rate, mechanical security. These affect the characteristic feature of quench current behavior, viz., training. This is the increase in quench current upon successive applications of current until, except in pathological cases, a limiting or plateau value is reached. This value is referred to as I_q. Temperature and field corrections are not generally made for I_q. The number of training quenches is minimized in short sample testing by using bare cable samples and by strong mechanical clamping as discussed below.

I_q is generally greater than I_t and, as it provides a measure of the ultimate current carrying capability of the cable, it is routinely recorded. If I_q is less than I_t, the latter may be determined by extrapolation provided there is enough of the V-I curve to permit this. However, in this event I_t is of academic interest only as it cannot be attained in practice.

3. Magnet; Temperature Bath; Power Supplies

The sample probe is located in a dipole magnet which is 48 in. long and has a 3-inch diameter bore. The maximum field is 6T at a current of approximately 3 kA. The sample test length is 70 cm; over this length, the field homogenity is about 1/1000. The magnet is equipped with a superconducting persistent switch which is very useful for keeping the field constant in time and noise free.

The magnet is supported in a vertical dewar of 24 in. ID and length 9 ft. Current is supplied to the samples through 15000 A gas-cooled leads and to the magnet through 5000 A leads. A dewar overpressure of 2-3 psi provides the gas flow for these leads.

A 4 kA power supply is used to energize the dipole magnet. A 15 kA power supply is used to supply the sample current. Although peak-to-peak AC noise is not small (it is of order 1 mV), this does not affect the critical current determination because of the method of measurement described below.

4. <u>Sample Mounting</u>

The samples are mounted in a compression fixture which is illustrated in Fig. 4141-4 #1. The usual test arrangement involves four bare cable samples. As these are keystoned, (i.e., they are trapezoidal in cross-section), care is taken to alternate thick and thin edges so that pairs of conductors present parallel surfaces to the clamping faces. As indicated in Fig. 4141-4 #1 there are a series of separators: 0.030 in. thick G-10 strips which carry electrical instrumentation described below, and 0.010 in. thick Mylar strips which insulate adjacent samples of the upper and lower cable pairs.

Compression is applied by tightening 3/8 in. bolts. These run along each side at 1-1/2 in. intervals. A torque of 200 inch-pounds is used to tighten the bolts. This produces a clamping pressure of 10 " 1 kpsi at room temperature. The pressure has been found to increase slightly at low temperature. With this method training behavior is limited to a few quenches.

The sample compression fixture is supported together with the sample leads from a room temperature flange, which may be rotated. The standard configuration for quality control testing is the perpendicular one, i.e., the applied dipole field is perpendicular to the sample faces. In this configuration, a strong twist about a vertical axis is generated by a bifilar sample for currents above a few kiloamps in fields above several Tesla. Rotation of the sample fixture relative to the magnet is prevented by means of a locating key on the fixture and a slotted plate on the magnet.

Figure 4141-4 #2 shows schematically how the cables are connected to each other and to the gas cooled leads. The connections are made using ordinary soft solder over a 1-1/2 in. length. A typical joint resistance is about 10^{-9} ohm. The samples are excited in pairs, either A-B, or C-D.

5. Electrical Instrumentation

Primary instrumentation consists of the following:

- Five voltage taps and thin foil heater element for each sample. These are contained on the G-10 strips shown in Fig. 4141-4 #1. The voltage taps work by the pressure contact of a copper wire across the width of the sample; the leads run out through a fine groove in the G-10. The heater element is a strip of stainless steel foil, 0.0005 in. thick x 1/8 in. x 1/4 in., which is located in a shallow well formed in the G-10 strip.

- Hazemeyer or other manufacturer DCCT secondary current standard.

- Digital voltmeters, 6-1/2 digit, 0.1 μV sensitivity.

- Nicolet 12 bit, 4 channel digital oscilloscope.

- Two calibrated carbon resistor thermometers, located at each end of the magnet.

- Isolation preamplifiers, 1 μV noise level.

Secondary instrumentation consists of the following:

- Quench current protection circuits for the magnet, the gas-cooled leads, and the samples.

- DC power supplies for persistent switch, and sample heater element.

- Pulse power supply for sample heater element.

6. Measurement Procedure

The cable samples are energized in pairs, either A-B or C-D in Fig. 4141-4 #2, and the V-I curves are determined simultaneously for each member of the bifilar pair. In the event that one member has a low I_q its partner may be unmeasurable in the set-up. The latter must be tested at another time with a partner having a comparable I_q - another piece of the same cable, for example. In situations like the preceeding, a minimum of two and perhaps three of the cable samples can be measured. In quality control tests of production cables, the match between samples is close enough that I_c's can usually be determined for all four samples. In the rest of this section we shall describe the procedure for testing one cable only, it being understood that a pair of samples, or all four, are under simultaneous test.

The measurements are made with the helium bath level above the upper sample and well above the top of the dipole magnet. The magnet field is set to a desired value and locked in with the persistent switch. The standard arrangement is such that the field is oriented perpendicular to the cable face.

The relative direction of the current flow and of the magnet field is very important for reasons which will be discussed below. The polarity of the power supply connections is carefully checked, therefore. Before the V-I curve is measured the sample is trained. This is done by ramping the current until a quench occurs. For relatively high Cu/SC ratio cables, as in the RHIC design, one quench is usually sufficient to reach the plateau value of I_q.

The V-I curve of the sample is now determined. A point-by-point method is used: the current is ramped to a suitable value, stopped, and the voltage measured. This is repeated for progressively higher values of current until a quench occurs (usually while ramping between currents). The most important feature of this method is that a very high degree of filtering of noise voltage can be achieved by the following technique. The noise is mostly in the form of harmonics of the line frequency. By integrating the voltage signal for an integer number of cycles, this harmonic noise is filtered to a very low value. In practice, the integration is over 100 cycles, and AC peak-to-peak voltages of order 10^{-3} volts are reduced to an effective uncertainty in any DC reading of 10^{-7} volts. Another advantage of the point-by-point method is that inductive voltage drops are eliminated. A third feature is that the measurement is a DC measurement - there is no ramp rate effect in the I_t determination. I_q is determined while ramping by means of a peak-reading DVM. The ramp rate is about 200 A/sec (between points). I_q is determined by one sample of the pair being measured; this value is a lower limit of I_q for the other sample. By observing the quench on a digital oscilloscope one can determine in which sample the quench originates. It is usually the one with the lower I_t value.

A few points are taken in the first several kiloamps of current, where the DC voltage is below the limit of detectability. This establishes a zero level base-line. Once the voltage signal exceeds a few tenths of a microvolt, the interval between measurement currents is reduced. Between the onset of a detectable voltage drop and the quench, 10 or 15 points are taken, typically.

The digital voltmeters are under computer control, and the set of V-I data is now promptly analyzed by a technician, utilizing the same on-line program which was used to take the data. The V-I data are converted to log ρ - log I data and fitted by a straight line. This gives the 10^{-14} ohm - m current and the n-value (the slope of the log-log plot). The following data are the result of the measurement: B_a, T, I_t, I_q, n, where B_a is the applied field, and I_q is the quench current or a lower limit of it. This procedure is repeated for each of the four cables at several fields in the vicinity of the specification field.

The temperature sensors are monitored continuously. If the temperature varies more than " 0.010K during the taking of a V-I curve, the measurement is aborted. Efforts are then made to reduce the temperature variation. These include waiting for the helium bath to settle down, increasing the flow of gas through the current leads, and refilling the dewar. The last measure is generally unnecessary if the run is less than 3 hours. (The usual run duration is 2 hours.)

7. Temperature Calculation

The discussion in this section pertains to Nb-Ti conductors of composition and metallurgical treatment appropriate for accelerator magnet applications.

Calculations of the critical currents at temperatures other than that at which I_t is measured are made using a linear fit:

$$\frac{I_c}{I_t} = \frac{T_{ref} - T_c(B)}{T - T_c(B)}$$

where I_t is the measured critical current at T and I_c is the calculated critical corresponding to T_{ref}. $T_c(B)$ is an effective critical temperature, i.e., the temperature at which the linear portion of the I_c vs. T curve for Nb-Ti extrapolates to zero. The above equation is a good approximation in the temperature range of interest, viz., 2K to 4.6K. A good approximation for $T_c(B)$ in the field range of interest, viz., 3T to 8T, is given by the following expression:

$$T_c(B) = 9.2\left[1 - \frac{B}{14.5}\right]^{0.59}$$

where B is the field in Tesla. B is determined as described in the following section.

8. Magnetic Field Correction (See Reference 2)

The magnetic field is the sum of the applied field produced by the dipole magnet and the self-field produced by the measuring current. The latter produces a substantial correction. However, its effect is difficult to assess precisely because it is spacially non-uniform, and therefore to calculate exactly, and because it depends upon the geometrical details of the bifilar sample. Experience has shown that the following assumptions give results which are self-consistent for a wide variety of geometries and which give reliable predictions of magnet behavior.

a) The critical current of the sample is determined by the peak magnetic field. This depends, of course, on the orientation of the applied field and the direction of the sample current. This important point will be discussed further in the next section.

b) The sample current is distributed uniformly over, and normal to, the area of the trapezoid which encloses the cable cross-section.

c) The geometry is accurately reproducible; this is a matter of care in assembly, as discussed above.

With the dipole field perpendicular to the wide face of the sample, the peak field occurs at a point on the surface of the sample where the self-field and the applied field are very nearly parallel; that is, they are simply additive. For the standard test configuration, therefore, the self-field correction can be written:

$$B = B_{peak} = B_a + c@I$$

where B_a = dipole field and c = geometric constant. Below is given the value of c for RHIC cable, for B_a perpendicular to the sample, and for the standard BNL test geometry in which the bifilar samples are separated by 0.010 in.

Self-field constant, c, gauss/amp, for RHIC cable: 0.395.

9. Critical Current of the Thin Edge:

The thin edge of a keystone-shaped cable is of special interest for two reasons. First, it forms the inner surface of a dipole (or quadrupole) magnet coil, and the maximum value of the field occurs there. Second, this part of the cable experiences the most deformation during fabrication, and possibly the most degradation. The bifilar sample test arrangement with applied field perpendicular has the characteristic feature that the peak fields occur at diagonally opposite points, at the two thin edges (c.f. Fig. 4141-4 #3). Experience has shown that when the current is reversed, so that the peak field points are along the thicker edges, a higher critical current is measured (even though the calculated peak field is slightly higher in this case). This is due to the smaller degree of degradation along this edge. In practice, the quality control test determines the critical current for the thin edge; i.e. the field and current direction are oriented as in Fig. 4141-4 #3.

10. Data Averaging Using I-B Graph; Degradation

The critical currents are plotted on a graph of I vs. B and I_c is obtained from an interpolation to the specification field.

The degradation of the cable, as mentioned before,is $D = 1 - (I_c/\Sigma\ I_{cw})$. In practice, a few wires may be measured and $\Sigma\ I_{cw}$ estimated from this sample, but in cases where questions arise as to whether D meets a specification, it is necessary to determine I_{cw} for all the wires in the Cable Map.

We have ignored the fact that the critical current of a wire is also subject to a self-field effect. However, it has become general practice not to take account of this correction, notably in discussions of J_c in the literature. For cables it is not acceptable to ignore self-field corrections for the reasons given previously: sensitivity of measurements to sample configuration and comparison of data with magnet performance. As a result of this convention, the specified degradation is lower than the true degradation, which would take account of wire self-field effect and lead to a larger value of $\Sigma\ I_{cw}$.

B. Cable R(295) and RRR Determination

1. Scope

This method covers the measurement of electrical resistance of cables made from Nb-Ti multifilimentary composite wires. The composite matrix is copper. The resistance is determined at 295K and at a temperature just above the superconducting transition, about 10K. The resistance per unit length at these two temperatures is designated R(295) and R(10), respectively. The residual resistance ratio, RRR, is defined to be R(295)/R(10). R(295) is measured with an accuracy of 0.5%; R(10) is measured with an accuracy of 2%.

2. Purpose

The quantities R(295) and R(10) provide a measure of the amount of copper and its electronic purity. Cu/SC is calculated as discussed in Section 6.

The quantity RRR provides a measure of the state of anneal of the copper matrix. It may be used to check that a cable has been given a post-cabling heat treatment in order to facilitate coil winding, if this has been specified. Such cables have RRR values over 100, whereas unannealed cables have values around 70, typically, if the wire has a final anneal, and 35 if it has not been annealed during the final drawing stages.

3. Apparatus; Test Sample; Procedure

The measurements are made on the samples assembled for critical current measurements, as described in the preceding part of this Appendix.

The room temperature measurement is made using a DC current of 1 A, and voltage contacts 70 cm apart (see Fig. 4141-4 #2). A thermocouple device of 0.1^0C accuracy is used to determine the ambient temperature.

The low temperature measurement is a dynamic one, made by inducing a superconducting-normal state quench while the cable is carrying current. Referring to Fig. 4141-4 #2, a quench is triggered in Cable A, for example, by means of heater HA. The resulting waveform observed at nearby voltage taps, A2-A3 or A3-A4, consists of three parts: a superconducting state baseline voltage, a linear ramp voltage corresponding to the passage of the superconducting-normal interface between the voltage taps, and a slowly increasing signal characteristic of the normal state resistance. The latter increases in time due to normal state heating. However, at first the voltage is almost constant due to the residual resistance characteristic of the copper. Thus, there is a kink in the voltage waveform at the beginning and at the end of the linear ramp portion. The voltage difference between these two points equals the current times the residual resistance of the section of cable between the voltage taps. The resistance per centimeter is determined for two pairs of taps (A2-A3 and A3-A4 in the above illustration) and averaged. The taps are relatively close to the heater in order to minimize the effect of current fall-off which results from the increase of normal state resistance as the quench propagates.

Some rough values to illustrate the magnitude of the quantities involved are: I = 3000 A, V = 3 mV/4 cm, R = 0.25 μV/cm.

The usual specification is for zero magnetic field. The above measurement may be made in an external field, however, in order to determine the magnetoresistance effect.

4. Room temperature Resistance Correction

Normally occurring room temperature variations produce significant variations in the measured resistance. Designating this resistance as R_m and the ambient temperature as $t(^0C)$, the resistance at the reference temperature of 295K is calculated as follows:

$$R(295) = R_m/[1 + 0.0039\ (t - 22)]$$

The effect of the Nb-Ti is negligible for the purpose of this correction.

5. Reported Quantities

The manufacturer ID, wire diameter, nominal Cu/SC ratio, and number of wires are recorded for each test specimen. The following results are recorded:

R(295) (μ ohms/cm)
R(10) (μ ohms/cm)
RRR

Optional (if requested)

R(10) for B = 5T
RRR for B = 5T

6. Copper/Superconductor Ratio

6. Cu/SC Ratio Calculation

The copper: superconductor volume ratio (x) is calculated from R(295) and RRR by means of the formula

$$x = \frac{1 - R(295)\ A/\ \rho_s}{R(295)\ A/\ \rho_{Cu} - 1}$$

where R(295) = resistance of the cable at 295K in ohms/m

ρ_{Cu} = resistivity of the copper at 295K, in ohm • m

$$= \rho_I \frac{RRR}{RRR - 1}$$

ρ_i = resistivity of pure copper at 295K

= 1.695×10^{-8} ohm • m

ρ_s = resistivity of Nb-Ti at 295K

= 60×10^{-8} ohm • m

and A = wire cross section area in m^2 in the cable

= $N\pi d^2/4$ (d = wire diameter in m)

The spiral path of the wires necessitates applying a length correction to the measured value of R(295). For RHIC cables R(295) is replaced by 1.04 x R(295) in the formula of Section B-6, Test Method 4141-3.

The specification on R(295) is based on the cited calculations. It is an alternative to the etch and weigh Cu/SC specification and is operationally preferable. The range of acceptable values of R(295) is determined by the Cu/SC ratio and the mean wire diameter. The maximum resistance specification determines the minimum Cu/SC ratio with an accuracy which is determined by the wire dimensional tolerance.

The resistance determination of Cu/SC for cables is routinely done in the BNL short sample test procedure and serves as an accurate check on the wire data. Cable and wire Cu/SC values agree to better than 2% in well-behaved cases, i.e. those in which there have been no errors in the strands used for cabling. This determination is, therefore, an important quality control check.

APPENDIX C
CABLE MEASUREMENT DATA

Below are summarized data transmittal for measurement information from the vendor to BNL. It is only necessary for the vendor to supply the data as given in Appendix A. The vendor will coordinate with BNL the regular transmittal in electronic form on 3-1/2 inch floppy discs in any density. The file structures listed below can easily be imported into R: Base at BNL and are listed in order of preference.

1. ASCII delimited
2. ASCII fixed
3. Lotus 1-2-2 (.WKS)
4. Excel (.XLS)

Cable Off-Line Mechanical Data

Cable ID
Sample ID (Hub, Lead, ...)
Mid-thickness by 10-stack method (inches)
Cable lay direction (Left/Right)
Cable lay pitch (inches)
Wire twist direction in cable (Left/Right)
Wire twist pitch in cable (twists per inch)
Cable residual twist (± degrees)
Bend test (Pass/Fail with comment)
Filament condition (Pass/Fail with comment)
Surface condition (Pass/Fail with comment)
Comments

Cable Measuring Machine Data

Cable ID
Cabling date
Cable measuring machine number
Cabling machine number
Pressure - Minimum
Pressure - Maximum
Pressure - Average
Pressure - Standard deviation
Pressure - Data points
Keystone - Minimum
Keystone - Maximum

Keystone - Average
Keystone - Standard deviation
Keystone - Data points
Width - Minimum
Width - Maximum
Width – Average
Width - Standard deviation
Width - Data points
Thickness - Minimum
Thickness - Maximum
Thickness - Average
Thickness - Standard deviation
Thickness - Data points
Comments

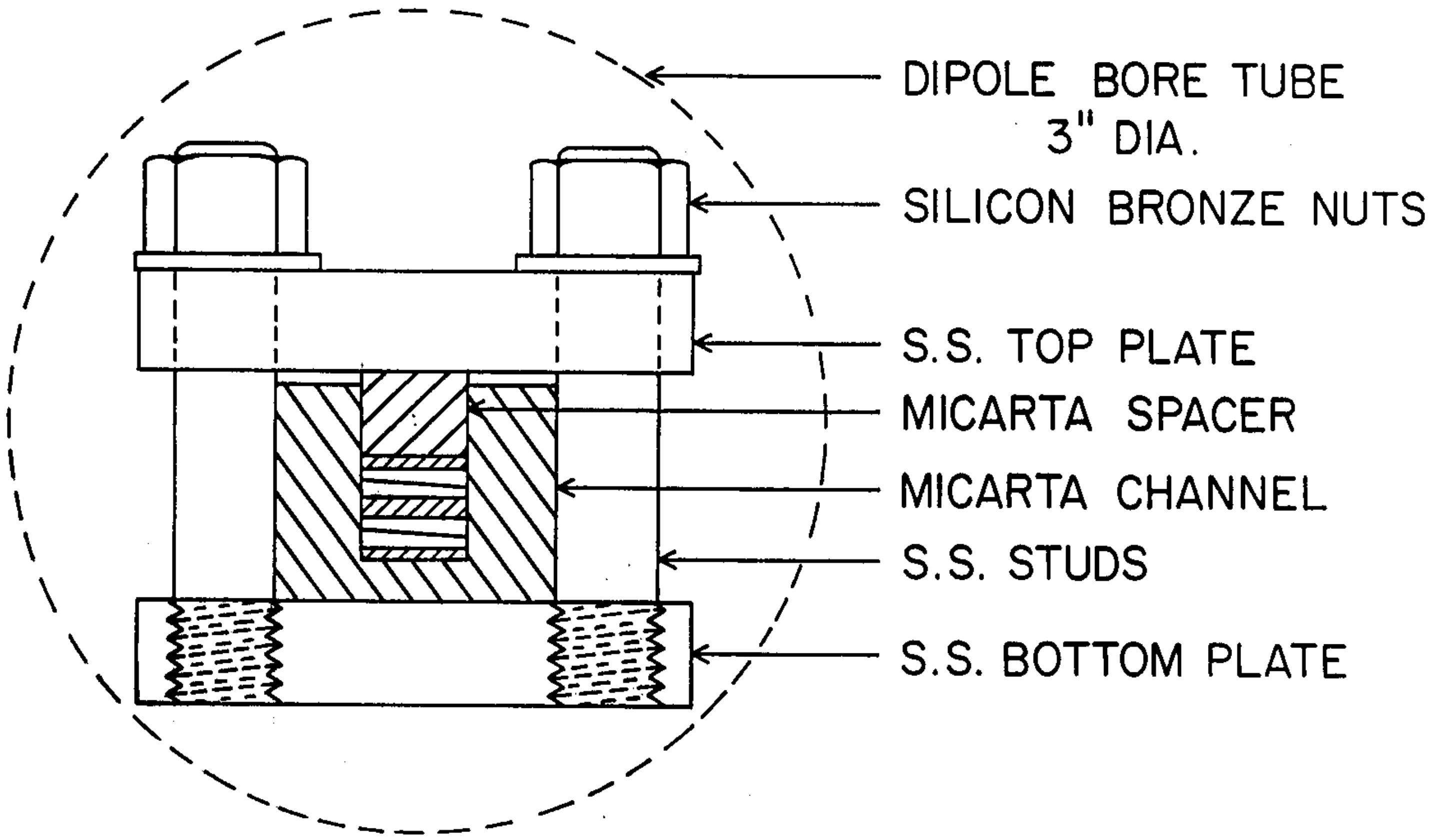

FIG. 4141-4 #1 Mechanical Assembly.

Two bifilar pairs of keystoned samples are assembled, as shown. The members of each pair are separated by Kapton, 0.010 in. thick. Instrumentation is located in G-10 strips placed below, between, and above the bifilar pairs; thicknesses of the G-10 strips are 0.030, 0.100, and 0.030 in., respectively. The stainless steel studs are located 1.5 in. apart along the 48 in. length of the fixture. The silicon bronze nuts are tightened to 200 in.-lbs. torque resulting in a mean pressure on the samples of approximately 10 kpsi.

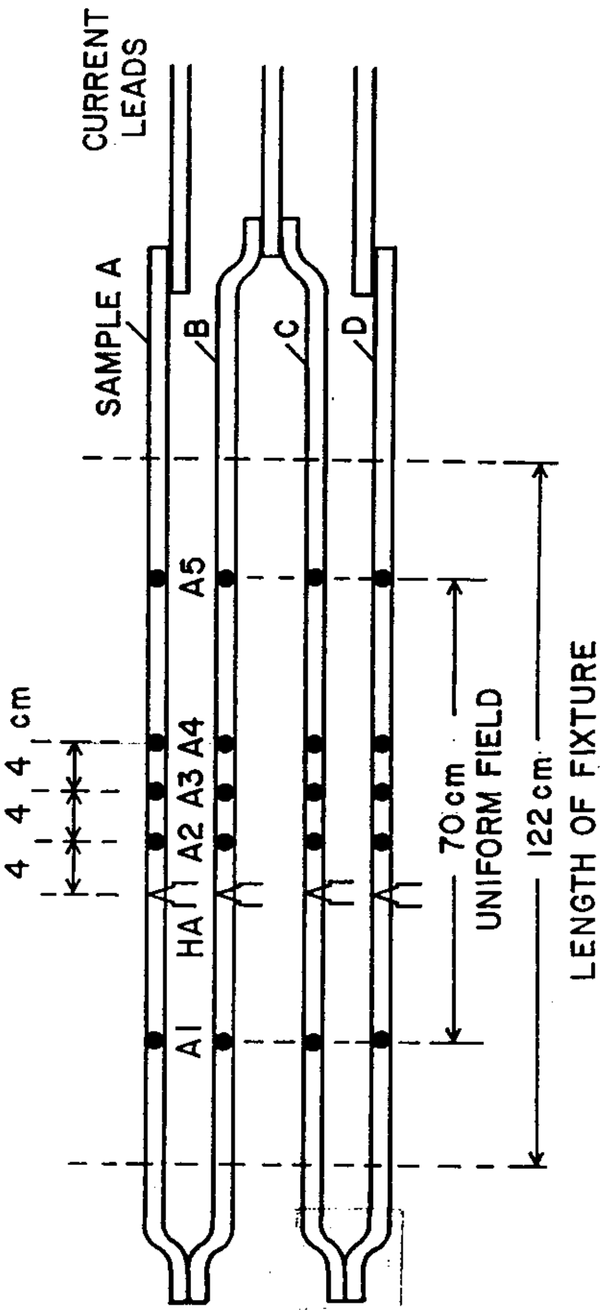

FIG. 4141-4 #2 Electrical Wiring Schematic.

Samples are tested in pairs: A-B and C-D. The critical current and room temperature resistance of sample A, for example, are determined using voltage taps A1 and A5. The low temperature resistance and quench propagation velocity are determined using the spot heater HA and voltage taps A2, A3, and A4.

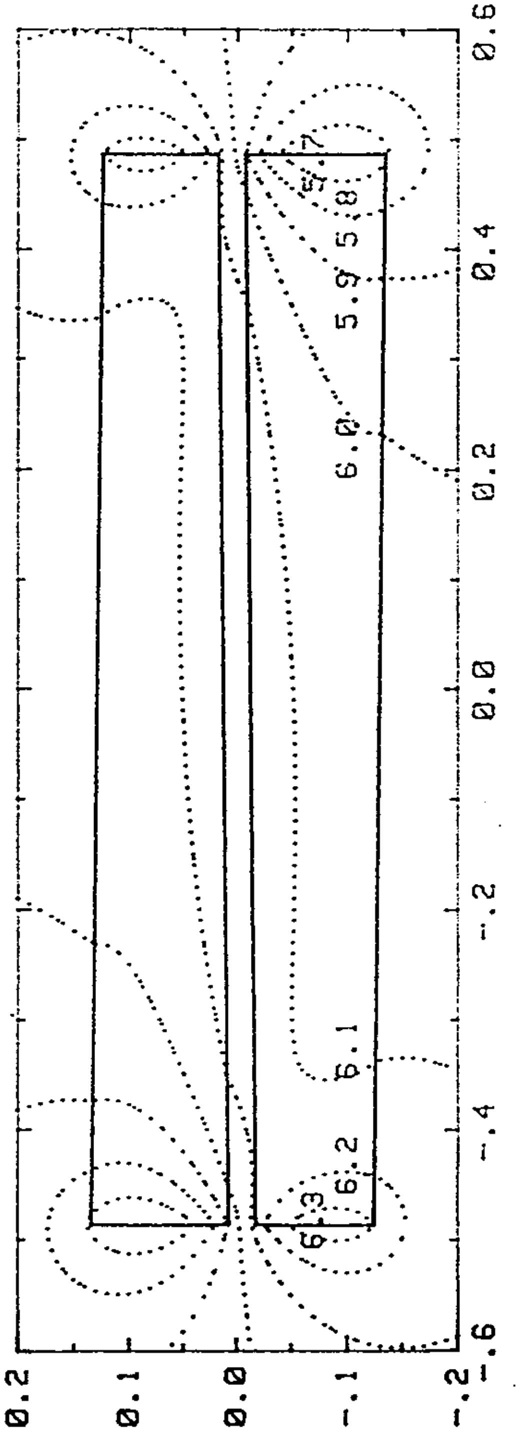

FIG. 4141-4 #3 Contours of Constant Field Magnitude.

Calculated contours for perpendicular applied field of 6 T and current of 10 kA. The peak field is 6.4 T and occurs along the thinner edge of each conductor (left side of lower and right side of upper conductor).