BRITISH STANDARD

BS EN
61788-2:2007

Superconductivity —

Part 2: Critical current measurement — DC critical current of Nb_3Sn composite superconductors

The European Standard EN 61788-2:2007 has the status of a British Standard

ICS 17.220; 29.050

National foreword

This British Standard was published by BSI. It is the UK implementation of EN 61788-2:2007. It is identical with IEC 61788-2:2006. It supersedes BS EN 61788-2:1999 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee L/-/90, Superconductivity.

A list of organizations represented on L/-/90 can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

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Superconductivity
Part 2: Critical current measurement - DC critical current of Nb_3Sn composite superconductors
(IEC 61788-2:2006)

Supraconductivité
Partie 2: Mesure du courant critique - Courant critique continu des supraconducteurs composites Nb_3Sn
(CEI 61788-2:2006)

Supraleitfähigkeit
Teil 2: Messen des kritischen Stromes - Kritischer Strom (Gleichstrom) von Nb_3Sn-Verbundsupraleitern
(IEC 61788-2:2006)

This European Standard was approved by CENELEC on 2006-12-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

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CENELEC

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Foreword

The text of document 90/195/FDIS, future edition 2 of IEC 61788-2, prepared by IEC TC 90, Superconductivity, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61788-2 on 2006-12-01.

This European Standard supersedes EN 61788-2:1999.

Modifications made to EN 61788-2:1999 are mostly wording that essentially includes no technical changes and an addition of a new annex (normative Annex D) in which the specifications in the one-mandrel method are described.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2007-09-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2009-12-01

Annex ZA has been added by CENELEC.

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Endorsement notice

The text of the International Standard IEC 61788-2:2006 was approved by CENELEC as a European Standard without any modification.

CONTENTS

INTRODUCTION

The critical currents of composite superconductors are used to establish design limits for applications of superconducting wires. The operating conditions of superconductors in these applications determine much of their behaviour and tests made with the method given in the present standard may be used to provide part of the information needed to determine the suitability of a specific superconductor.

Results obtained from this method may also be used for detecting changes in the superconducting properties of a composite superconductor due to processing variables, handling, ageing or other applications or environmental conditions. This method is useful for quality control, acceptance or research testing if the precautions given in this standard are observed.

The critical current of composite superconductors depends on many variables. These variables need to be considered in both the testing and the application of these materials. Test conditions such as magnetic field, temperature and relative orientation of the specimen, current and magnetic field are determined by the particular application. The test configuration may be determined by the particular conductor through certain tolerances. The specific critical current criterion may be determined by the particular application. It may be appropriate to measure a number of test specimens if there are irregularities in testing.

The test method covered in this standard is based on that for the determination of the critical current of Cu/Nb-Ti composite superconductors (IEC 61788-1[2] [1)] and the VAMAS (Versailles project on advanced materials and standards) prestandardization work on the critical current of Nb_3Sn composite superconductors. The critical current of Nb_3Sn superconductors is known to be highly sensitive to mechanical strain compared to Cu/Nb-Ti superconductors. Hence, some modifications are made on the test procedures which may affect the strain state of a test specimen. See Annex B for the background to these modifications.

1) Figures in square brackets refer to the Bibliography.

SUPERCONDUCTIVITY –

Part 2: Critical current measurement – DC critical current of Nb_3Sn composite superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the d.c. critical current of Nb_3Sn composite superconductors which are fabricated by either the bronze process or the internal tin diffusion process and have a copper/non-copper ratio larger than 0,2.

This method is intended for use with superconductors which have critical currents of less than 1 000 A and *n*-values larger than 12 under standard test conditions and at magnetic fields of less than or equal to 0,7 times the upper critical magnetic field. The test specimen is immersed in a liquid helium bath at a known temperature during testing. The Nb_3Sn composite test conductor has a monolithic structure with a total round-cross-sectional area that is less than 2 mm^2. The specimen geometry used in this test method is an inductively coiled specimen. Deviations from this test method which are allowed for routine tests and other specific restrictions are given in this standard.

Nb_3Sn conductors with critical currents above 1 000 A or total cross-sectional areas greater than 2 mm^2 can be measured with the present method with an anticipated reduction in precision and a more significant self-field effect (see Annex C). Other, more specialized, specimen test geometries may be more appropriate for larger conductor testing which have been omitted from this present standard for simplicity and to retain precision.

The test method given in this standard should in principle apply to Nb_3Sn composite wires fabricated by any other process. This method is also expected to apply to other superconducting composite wires after some appropriate modifications.

2 Normative references

The following referenced document is indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-815:2000, *International Electrotechnical Vocabulary (IEV) – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815, some of which are repeated here for convenience, and the following apply:

3.1
critical current
I_c
maximum direct current that can be regarded as flowing without resistance

NOTE I_c is a function of magnetic field strength and temperature.

[IEV 815-03-01]

3.2
critical current criterion
I_c criterion
criterion to determine the critical current, I_c, based on the electric field strength, E, or the resistivity, ρ

NOTE E = 10 μV/m or E = 100 μV/m is often used as the electric field strength criterion, and $\rho = 10^{-13}$ Ω·m or $\rho = 10^{-14}$ Ω ·m is often used as the resistivity criterion.

[IEV 815-03-02]

3.3
***n*-value (of a superconductor)**
exponent obtained in a specific range of electric field strength or resistivity when the voltage (U) – current (I) curve is approximated by the equation $U \propto I^n$

[IEV 815-03-10]

3.4
quench
uncontrollable and irreversible transition of a superconductor or a superconducting device from the superconducting state to the normal state

NOTE A term usually applied to superconducting magnets.

[IEV 815-03-11]

3.5
Lorentz force (on fluxons)
force applied to fluxons by a current

NOTE 1 The force per unit volume is given by J x B, where J is the current density, and B is the magnetic flux density.

[IEV 815-03-16]

NOTE 2 "Coulomb-Lorentz force" is defined in IEV 121-11-20 [1].

3.6
stress effect
strain effect
change in superconducting properties upon application of mechanical, thermal or electro-magnetic stress to the superconductor

[IEV 815-03-14]

3.7
bending strain
ε_b
strain in percent arising from pure bending defined as $\varepsilon_b = 100r/R$, where r is a half of the specimen thickness and R is the bending radius

[IEV 815-08-03]

3.8
current transfer (of composite superconductor)
phenomenon that a d.c. current transfers spatially from filament to filament in a composite superconductor, resulting in a voltage generation along the conductor

NOTE In the I_c measurement, this phenomenon appears typically near the current contacts where the injected current flows along the conductor from periphery to inside until uniform distribution among filaments is accomplished.

3.9
constant sweep rate method
U-I data acquisition method where a current is swept at a constant rate from zero to a current above I_c while frequently and periodically acquiring *U-I* data

3.10
ramp-and-hold method
U-I data acquisition method where a current is ramped to a number of appropriately distributed points along the *U-I* curve and held constant at each one of these points while acquiring a number of voltages and current readings

4 Principle

The critical current of a composite superconductor is determined from a voltage (U) – current (I) characteristic measured at a certain value of a static applied magnetic field strength (magnetic field) at a specified temperature in a liquid helium bath at a constant pressure. To get a *U-I* characteristic, a direct current is applied to the superconductor specimen and the voltage generated along a section of the specimen is measured. The current is increased from zero and the *U-I* characteristic generated is recorded. The critical current is determined as the current at which a specific electric field strength (electric field) criterion (E_c) or resistivity criterion (ρ_c) is reached. For either E_c or ρ_c, there is a corresponding voltage criterion (U_c) for a specified voltage tap separation.

5 Requirements

The specimen shall be wound on a cylindrical reaction mandrel with a helical groove and after reaction, transferred to a measurement mandrel of the same diameter on which the helical angle is preserved. An alternate one-mandrel method is given in Annex D.

The specimen shall be longer than 430 mm.

The specimen shall be affixed to the measurement mandrel by tightening the specimen and/or bonding with a low temperature adhesive.

In this test method, the applied magnetic field shall be parallel to the measurement mandrel axis.

The target precision of this method is a coefficient of variation (standard deviation divided by the average of the critical current determinations), that is less than 3 % for the measurement at 12 T and near 4,2 K.

The use of a common current transfer correction is excluded from this test method. Furthermore, if a current transfer signature is pronounced in the measurement, then the measurement shall be considered invalid.

It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices, and determine the applicability of regulatory limitations prior to use. Specific precautionary statements are given below.

Hazards exist in this type of measurement. Very large direct currents with very low voltages do not necessarily provide a direct personal hazard, but accidental shorting of the leads with another conductor, such as tools or transfer lines, can release significant amounts of energy and cause arcs or burns. It is imperative to isolate and protect current leads from shorting. Also, the stored energy in the superconducting magnets commonly used for the background magnetic field can cause similar large current and/or voltage pulses, or deposit large amounts of thermal energy in the cryogenic systems causing rapid boil-off or even explosive conditions. Under rapid boil-off conditions, cryogens can create oxygen-deficient conditions in the immediate area and additional ventilation may be necessary. The use of cryogenic liquids is essential to cool the superconductors to allow transition into the superconducting state. Direct contact of skin with cold liquid transfer lines, storage dewars or apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. It is imperative that safety precautions for handling cryogenic liquids be observed.

6 Apparatus

For the one-mandrel method, continue with Clause D.2.

6.1 Reaction mandrel material

The reaction mandrel shall be made from a heat-resistant material that may or may not have a treated surface. Suitable reaction mandrel materials are recommended in A.3.1. Any one of these may be used.

6.2 Reaction mandrel construction

The overall geometry of the reaction mandrel should be matched closely to that of the measurement mandrel to which the individual specimen is to be transferred.

The reaction mandrel shall have a diameter large enough that the specimen bending strain, which is introduced into the specimen during winding, is less than 5 %.

The mandrel shall have a helical groove in which the specimen shall be wound. The pitch angle of the groove shall be less than 7°. The depth of the groove shall be at least half the wire diameter.

6.3 Measurement mandrel material

The measurement mandrel shall be made from an insulating material, or from a conductive non-ferromagnetic material that is either covered or not covered with an insulating layer.

The critical current may inevitably depend on the measurement mandrel material due to the strain induced by the differential thermal contraction between the specimen and the measurement mandrel.

The total strain induced in the specimen at the measuring temperature shall be minimized to be within ±0,03 %. If there is an excess strain due to the differential thermal contraction of the specimen and the mandrel, the critical current shall be noted to be determined under an excess strain state by identification of the mandrel material.

Suitable measurement mandrel materials are recommended in A.3.3. Any one of these may be used.

When a conductive material is used without an insulating layer, the leakage current through the mandrel shall be less than 0,2 % of the total current when the specimen current is at critical current I_c (see 9.5).

6.4 Measurement mandrel construction

The mandrel shall have a helical groove in which the specimen shall be wound.

The diameter of the measurement mandrel, the pitch angle of the helical groove and its depth and shape shall be close to those of the reaction mandrel.

The angle between the specimen axis (portion between the voltage taps) and the magnetic field shall be (90 ± 7)°. This angle shall be determined with an accuracy of ±2°.

The current contact shall be rigidly fastened to the measurement mandrel to avoid stress concentration in the region of transition between the mandrel and the current contact.

6.5 Measurement set up

The apparatus to measure the *U-I* characteristic of a superconductor specimen consists of a specimen probe, a test cryostat, a magnet system and a *U-I* measurement system.

The specimen probe, which consists of a specimen, a measurement mandrel, a specimen support structure, voltage taps, current leads etc. is inserted in the test cryostat filled with liquid helium. In most cases, the cryostat contains a superconducting solenoid magnet and its support structure to apply a magnetic field to the specimen. The *U-I* measurement system consists of a d.c. current source, a recorder and necessary preamplifiers, filters or voltmeters, or a combination thereof. A computer-assisted data acquisition system may be also used.

7 Specimen preparation

For the one-mandrel method, continue with Clause D.4.

7.1 Specimen mounting for reaction heat treatment

There shall be no joints or splices in the test specimen.

When using resistivity criteria for the critical current determination, the total cross-sectional area *S* of the specimen shall be determined to a precision of 5 %.

The specimen shall not be wound in a manner that would introduce additional twists into the specimen.

The specimen shall be located in the groove on the reaction mandrel under almost zero tension (less than 0,1 % tensile strain) so that location continues to be preserved and the contact pressure reduced to a minimum to discourage diffusion bonding.

The specimen wire shall be retained on the reaction mandrel by bending ends through small holes, one at each end of the mandrel, or be retained by some equivalent method.

The specimen shall be cleaned to avoid effects of contamination.

7.2 Reaction heat treatment

Reaction heat treatment shall be carried out according to the manufacturer's specification, which includes error limits which shall not be exceeded. Temperature variations within the furnace shall be controlled so as not to exceed those limits.

7.3 Specimen mounting for measurement

After the reaction heat treatment, the ends of the specimen shall be trimmed to suit the measurement mandrel.

The specimen shall be unscrewed from the reaction mandrel by lightly restraining it and rotating the mandrel within it.

The specimen shall be immediately screwed onto the measurement mandrel in the same manner as it was removed from the reaction mandrel. When mounting on the measurement mandrel, the specimen shall be laid into the groove and one end shall be soldered to the current contact ring. Starting from the fixed end, the specimen shall be stroked along its entire length, thus firmly seating the specimen in the groove. The free end shall then be soldered to the other contact ring.

The minimum length of the soldered part of the current contact shall be greater than the smaller of 40 mm and 30 wire diameters. No more than three turns of the specimen shall be soldered to each current contact.

The shortest distance from a current contact to a voltage tap shall be greater than 100 mm.

The voltage taps shall be soldered to the specimen. Minimize the mutual inductance between the applied current and the area formed by the specimen and the voltage taps by counterwinding the untwisted section of the voltage taps back along the specimen, as shown in Figure A.1.

The distance along the specimen between the voltage taps, *L*, shall be measured to an accuracy of 5 %. This voltage tap separation shall be greater than 150 mm.

7.4 Specimen bonding

Specimen tension and/or a low temperature adhesive (such as silicone vacuum grease or epoxy) shall be used to bond the specimen to the measurement mandrel to reduce specimen motion. If specimen tension is used to bond the specimen, then this shall be accomplished during the specimen mounting for the measurement process (see 7.3).

When an adhesive is used, a minimum amount of adhesive shall be applied in the groove containing the specimen, and the excess shall be removed from the outer surface of the specimen after the specimen has been mounted.

The adequacy of specimen bonding shall be demonstrated by a successful completion of the specified critical current repeatability.

Solder shall not be used to bond the specimen to the mandrel.

8 Measurement procedure

The specimen shall be immersed in liquid helium for the data acquisition phase. The specimen may be cooled slowly in helium vapour and then inserted into the liquid helium bath, or inserted slowly into the liquid helium bath, or first slowly immersed in liquid nitrogen and then liquid helium. The specimen shall be cooled from room temperature to liquid helium (or liquid nitrogen) temperature over a time period of at least 5 min.

The cryostat shall provide the necessary environment for measuring I_c and the specimen shall be measured while immersed in liquid helium. The liquid helium bath shall be operated so that the bath temperature is near the normal boiling point for the typical atmospheric pressure of the test site.

The temperature of the liquid helium bath shall be measured during each determination of I_c.

The specimen current shall be kept low enough so that the specimen does not enter the normal state unless a quench protection circuit or resistive shunt is used to protect the specimen from damage.

When using the constant sweep rate method, the time for the ramp from zero current to I_c shall be more than 10 s. When using the ramp-and-hold method, the current sweep rate between current set points shall be lower than the equivalent of ramping from zero current to I_c in 3 s. The current drift during each current set point shall be less than 1 % of I_c.

The d.c. magnetic field shall be applied in the direction of the mandrel axis. The relation between the magnetic field and the magnet current shall be measured beforehand. The magnet current shall be measured before each determination of I_c.

The direction of the current and the applied magnetic field shall result in an inward Lorentz force over the length of the specimen at least between the voltage taps.

Record the *U-I* characteristic of the test specimen under test conditions and monotonically increasing current.

A valid *U-I* characteristic shall give a repeatable I_c to a precision of 1 % and the characteristic shall be stable with time for voltages at or below the critical current criterion.

The baseline voltage of the *U-I* characteristic shall be taken as the recorded voltage at zero current for the ramp-and-hold method, or the average voltage at approximately 0,1 I_c for the constant sweep rate method.

9 Precision and accuracy of the test method

9.1 Critical current

The current source shall provide a d.c. current having a maximum periodic and random deviation of less than ±2 % at I_c, within the bandwidth 10 Hz to 10 MHz.

A four-terminal standard resistor, with an accuracy of at least 0,5 %, shall be used to determine the specimen current.

The record of *U-I* characteristic shall allow the determination of *U* to a precision of 10 %, the corresponding current to an accuracy of 1 % and with a precision of 1 %.

9.2 Temperature

The specimen temperature is assumed to be the same as the temperature of the liquid. The liquid temperature shall be reported to an accuracy of ±0,02 K, measured by means of a pressure sensor or an appropriate temperature sensor.

The difference between the specimen temperature and the bath temperature shall be minimized.

For converting the observed pressure in the cryostat into a temperature value, the phase diagram of helium shall be used. The pressure measurement shall be accurate enough to obtain the required accuracy of the temperature measurement. For liquid helium depths greater than 1 m, a head correction may be necessary.

9.3 Magnetic field

A magnetic system shall provide the magnetic field to an accuracy better than the larger of ±1 % and ±0,02 T and a precision better than the larger of ±0,5 % and ±0,02 T over the length of the specimen between the voltage taps.

The magnetic field shall have a uniformity better than the larger of 0,5 % and 0,02 T over the length of the specimen between the voltage taps.

The maximum periodic and random deviation of the magnetic field shall be less than the larger of ±1 % and ±0,02 T.

9.4 Specimen support structure

The support structure shall provide adequate support for the specimen and the orientation of the specimen with respect to the magnetic field. The specimen support is adequate if it allows additional determinations of critical current with a precision of 1 %.

9.5 Specimen protection

If a resistive shunt or a quench protection circuit is used in parallel with the specimen, then the current through the shunt or the circuit shall be less than 0,2 % of the total current at I_c.

10 Calculation of results

10.1 Critical current criteria

The critical current, I_c, shall be determined by using an electric field criterion, E_c, or a resistivity criterion, ρ_c, where the total cross-sectional area S of the composite superconductor is preferred for the estimation of the resistivity (see Figures 1 and 2).

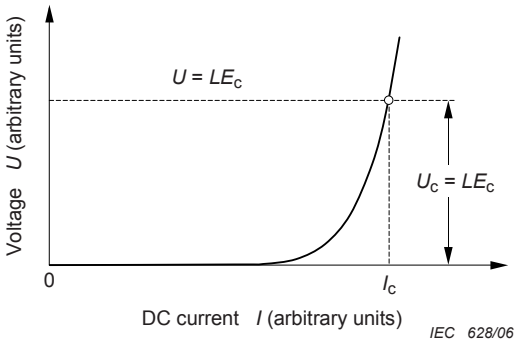


Figure 1a) – Application of the electric field criteria

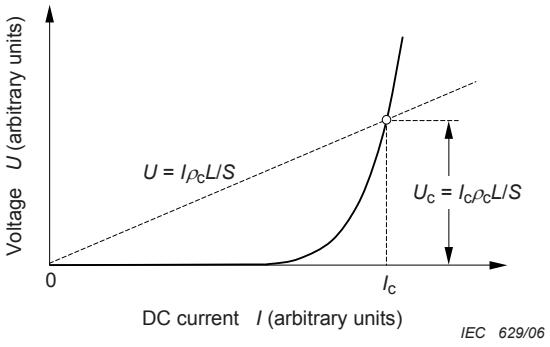


Figure 1b) – Application of the resistivity criteria

NOTE The application of the (Figure 1a) electric field and (Figure 1b) resistivity criteria to determine the critical current is shown above.

Figure 1 – Intrinsic *U-I* characteristic

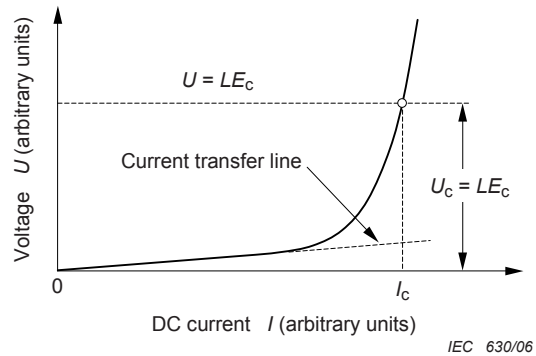


Figure 2a) – Application of the electric field criteria

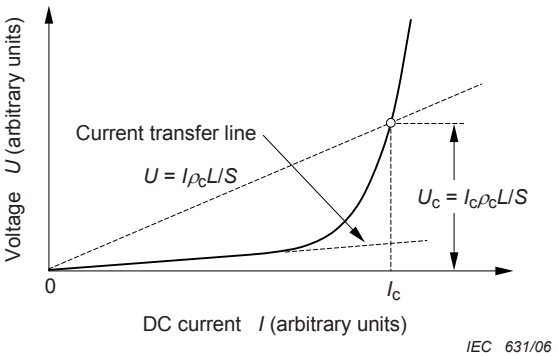


Figure 2b) – Application of the resistivity criteria

NOTE The application of the (Figure 2a) electric field and (Figure 2b) resistivity criteria to determine the critical current on a *U-I* characteristic with a current transfer component exhibited as a linear region at low current is shown above.

Figure 2 – *U-I* characteristic with a current transfer component

In the case of electric field criterion, two values of I_c shall be determined at criteria of 10 μV/m and 100 μV/m. In the other case, two values of I_c shall be determined at resistivity criteria of 10^{-14} Ωm and 10^{-13} Ωm.

When it is difficult to measure the I_c properly at a criterion of 100 μV/m, an E_c criterion less than 100 μV/m shall be substituted. Otherwise, the measurements using the resistivity criterion are recommended.

The I_c shall be determined as the current corresponding to the point on the *U-I* curve where the voltage is U_c measured relative to the baseline voltage (see Figures 1a) and 2a)):

$$U_c = L\, E_c \tag{1}$$

where

U_c is the voltage criterion, in microvolts (μV);

L is the voltage tap separation, in metres (m);

E_c is the electric field criterion, in microvolts/metre (μV/m).

Or, when using a resistivity criterion:

$$U_c = I_c\, \rho_c\, L/S \tag{2}$$

where U_c, I_c and ρ_c are the corresponding voltage, current and resistivity, in microvolts, amperes and micro-ohms × metres, respectively, to the intersecting point of a straight line with the *U-I* curve as shown in Figures 1b) and 2b), L is the voltage tap separation, in metres, and S is the total cross-sectional area, in square metres.

A straight line shall be drawn from the baseline voltage to the average voltage near 0,7 I_c (see Figures 1 and 2). A finite positive slope of this line may be due to current transfer. A valid determination of I_c requires that the slope of the line be less than 0,3 U_c/I_c, where U_c and I_c are determined at a criterion of 10 μV/m or 10^{-14} Ωm.

10.2 *n*-value (optional calculation, refer to A.7.2)

The *n*-value shall be calculated as the slope of the plot of log *U* versus log *I* in the region where the I_c is determined, or shall be calculated using two I_c values as determined in 10.1 at two different criteria.

The range of the criteria used to determine *n* shall be reported.

11 Test report

11.1 Identification of test specimen

The test specimen shall be identified, if possible, by the following:

a) name of the manufacturer of the specimen;

b) classification and/or symbol;

c) lot number;

d) raw materials and their chemical composition;

e) shape and area of the cross-section of the wire, number of filaments, diameter of filaments, volume fractions of filaments, copper/non-copper ratio, barriers, copper stabilizer and other components in the wire, twist pitch and twist direction;

f) manufacturing process technique (bronze, internal tin diffusion process, etc).

11.2 Report of I_c values

The I_c values, along with their corresponding criteria, shall be reported.

11.3 Report of test conditions

The following test conditions shall be reported:

a) test magnetic field, uniformity of field and accuracy of field;
b) test temperature and accuracy of temperature;
c) number of turns of the tested coil;
d) length between voltage taps and total specimen length;
e) the shortest distance from a current contact to a voltage tap;
f) the shortest distance between current contacts;
g) soldered length of the current contacts;
h) the specimen bonding method, including identification of the bonding material;
i) reaction mandrel and measurement mandrel materials;
j) reaction mandrel and measurement mandrel diameters;
k) depth, shape, pitch, and angle of grooves;
l) reaction heat treatment conditions.

Annex A
(informative)

Additional information relating to Clauses 1 to 10

A.1 General

There is a large number of variables that have a significant effect on the measured value of critical current which needs to be brought to the attention of the user. Some of these are addressed in this informative annex (see also Annex B).

The method described in this standard is not applicable to wires with a copper/non-copper ratio (i.e. a volume ratio of Cu stabilizer to all other components of wire, including Nb_3Sn filaments and diffusion barriers) that is smaller than 0,2 because the observed voltage-current (*U-I*) characteristics may not be stable at low magnetic fields.

Because this standard was originally written in the mid-1990's to be inclusive of a wide range of wire parameters, the new high-performance Nb_3Sn wires, which were developed in the early 2000's, fall within this scope. However, it was not anticipated that wires would be designed with the particular combination of wire parameters (low Cu to non-Cu ratio, high non-Cu current density, high effective filament diameter, and large wire diameters) that all tend to increase I_c and decrease stability. This topic has been discussed in detail by the responsible working group and the general consensus is that this standard is still valid for its Scope and a key requirement is the repeatable I_c and stable *U-I* characteristic listed in Clause 8. The user that is testing these high-performance Nb_3Sn wires needs to monitor and control the current-contact resistance and specimen damage near the transition from current contact to measurement mandrel in order to meet this repeatability and stability requirement.

This standard requires that the specimen be tested while immersed in liquid helium that is near the boiling point of liquid helium at the normal atmospheric pressure of the test site. Testing in liquid helium at temperatures other than near this normal boiling point or testing in a gas or a vacuum is not covered by the scope of this standard.

The reason for the restrictions in this test method is to obtain the necessary precision in the final definitive phase of long conductor qualification.

A.2 Requirements

In this test method, both a reaction and a measurement mandrel are prepared. The specimen wound on a reaction mandrel is reaction-heat-treated at a temperature in the region of 700 °C to form Nb_3Sn. After reaction, it is transferred to a measurement mandrel. To avoid deformation of the specimen, each mandrel should be of the same diameter and have the same helical groove on it.

Typically, the upper limit of the test magnetic field (0,7 times the upper critical magnetic field) is 17 T at a temperature near 4,2 K.

The minimum total length of the specimen is 430 mm, which represents the sum of the following:

– the soldered length of current contacts (2 × 40 mm);

– the distance between current and voltage contacts (2 × 100 mm);

– the minimum voltage tap separation (150 mm).

The target precision of the method described in this standard is defined by the results of an interlaboratory comparison. Results from previous interlaboratory comparisons (the first and second VAMAS intercomparisons and a Japanese domestic intercomparison) were used in this test method to formulate the tolerances of the many variables that affect the precision of critical current measurements. The target precision, for an interlaboratory comparison, is a coefficient of variation (standard deviation divided by the average of critical current determination) that is less than 3 % for the measurement at 12 T and near 4,2 K.

The coefficient of variation provides additional information on the expected distribution of results from a large number of determinations. However, if there are significant systematic errors, the measurements of two laboratories may differ by two or more times the coefficient of variation.

The expected and accepted precision of critical current measurements at 4,2 K and magnetic fields larger than 12 T will have a higher coefficient of variation due to the increased sensitivity of I_c to magnetic field, temperature, strain and required voltage sensitivity. It will reach a coefficient of variation of 5 % at the magnetic field of 0,7 times the upper critical field (around 17 T at 4,2 K).

It is expected that the accuracy of the magnetic field in this test method may be one of the most significant contributors to the overall imprecision of the critical current measurement. However, a more restrictive tolerance may not be achievable due to the difficulty in calibrating this parameter.

In the case of routine tests where it is impractical to adhere to these specific restrictions, this standard can be used as a set of general guidelines with an anticipated reduction in precision.

For routine tests, a wider range of parameters is accepted but, in definitive intercomparisons and performance verification, restrictions are needed to balance ease of use and resulting target precision.

Measurements on mandrel materials which put the Nb_3Sn sample in a certain strain state, other than near zero external strain (the intrinsic strain state), are expected to produce consistent critical current results. However, these results will deviate from the results in near zero external strain state. For example, Ti-6Al-4V (titanium alloy containing 6 mass% Al and 4 mass% V) measurement mandrels generally produce critical currents in a slightly tensional state because the thermal contraction of Ti-6Al-4V mandrel is less than that of the specimen. However, the results have been confirmed to be very consistent in international interlaboratory comparisons. Stainless steel mandrels have also produced very consistent results in VAMAS [3] and interlaboratory comparisons [4].

However, stainless steel mandrels require skilful techniques for mandrel design of the wall thickness, tight winding of specimen, and specimen bonding since the thermal contraction of stainless steel is closely matched, or even slightly greater than that of the specimen. Thus, the selection of such mandrel materials is considered an acceptable practice.

Measurements on short, straight specimens are considered acceptable practice for routine measurements if the cross-sectional area of the specimen is small in comparison with its length. However, for simplicity, this specimen geometry is omitted.

Measurements on non-inductively wound (bifilar) specimens in combination with epoxy specimen bonding are expected to give a precision similar to the target precision of this method. However, for simplicity, this specimen geometry is omitted. For a bifilar specimen geometry, the Lorentz force is away from the measurement mandrel for part of the specimen length, and grease is not strong enough to keep the specimen from moving in this case.

Measurements on a non-ferromagnetic stainless steel mandrel combined with the use of solder to bond the specimen to the mandrel is considered acceptable practice for routine measurements. It will be difficult to estimate the amount of current shunted through the mandrel in this case, especially if a superconducting solder is used and the measurements are made in low magnetic fields.

Rectangular cross-sectional conductors could be measured using the present method. In this case, mandrels without grooves may be preferable for both reaction heat treatment and measurement if the specimen is transferred to the measurement mandrel after reaction. If the specimen does not require transfer, mandrels with a rectangular groove instead of a V-shaped groove may be appropriate. In either case, it is recommended to use epoxy to secure the specimen to the measurement mandrel.

The test method for determining the I_c values of superconducting composite wires excluded from the present test method may be addressed in future standards.

A.3 Apparatus

A.3.1 Reaction mandrel material

The following materials are recommended for reaction mandrel material. There is no restriction on using other materials as long as they resist diffusion bonding with the specimen during the reaction heat treatment. It is, however, desirable that the thermal expansion coefficient of the material is close to that of specimen wire.

– Ceramics and graphite:
  - graphite;
  - alumina;
  - zirconia.
– Alloy with surface treatment:
  - ceramic (or carbon) coated stainless steel;
  - heavily surface oxidized stainless steel;
  - ceramic (or carbon) coated Ti-6Al-4V or Ti-5Al-2,5Sn (titanium alloy containing 5 mass% Al and 2,5 mass% Sn).

A.3.2 Reaction mandrel construction

For example, a 5 % bending strain for a 1 mm diameter specimen corresponds to a reaction mandrel diameter of 20 mm.

The groove on the reaction mandrel is preferably V-shaped. Mandrels with a rectangular groove or without groove can be used with caution. When reaction mandrels are used without grooves, the specimen should be co-wound with a spacer to form a uniform pitch that will fit closely with the pitch of the measurement mandrel.

A 7° pitch angle corresponds to a pitch of 9 mm for a 24 mm mandrel diameter.

A.3.3 Measurement mandrel material

In this method, the specimen strain is controlled to be minimum (less than 0,03 %). A 0,03 % thermal contraction may result in I_c deviation of around 2 % at 12 T and near 4,2 K. One significant source of strain is the mismatch in thermal contraction rates between the measurement mandrel and the specimen when cooled to liquid helium temperature. Although depending on volume fractions of the components in the cross-section, a typical thermal contraction of a Nb_3Sn composite superconductor is 0,25 % to 0,30 % from room temperature to 4,2 K.

If the thermal contraction of the measurement mandrel is less than that of the specimen, the specimen will be under tension when cooled. The tension will be reduced by the residual clearance between the specimen and the mandrel. In this case, it is noted that the winding looseness can be partially recovered during cooling. On the other hand, if the thermal contraction of the measurement mandrel is more than that of the specimen, the specimen clearance will increase in addition to the residual clearance of the winding. Therefore, the thermal contraction of the measurement mandrel material should be chosen to minimize the external strain of the specimen and to eliminate the residual clearance of the specimen following cooldown.

Based on the typical thermal contractions shown in Table A.1, the following materials are suggested for the measurement mandrel material. For alternate mandrel materials, a carefully prepared qualification study should precede the routine tests.

– Recommended measurement mandrel material:
  - fibreglass epoxy composite, with the specimen lying in the plane of the fabric;
  - fibreglass epoxy composite tube fabricated from a plate stock so that the planes of the fabric are perpendicular to the axis of the tube;
  - thin walled rolled fibreglass epoxy composite tube.
– Alternate measurement mandrel material:
  - non-ferromagnetic stainless steel, such as SUS 316L, with or without an insulating layer;
  - Ti-6Al-4V with or without an insulating layer, with the limitation that this material is superconductive at 4,2 K with magnetic fields below 2 T;
  - Ti-5Al-2,5Sn with or without an insulating layer, with the limitation that this material is superconductive at temperatures below 3,7 K with magnetic fields below 2 T.
– Other measurement mandrel material:
  - non-ferromagnetic copper alloy covered with an insulating layer;
  - ceramic dispersed epoxy;
  - alumina ceramic.

More specifically, a NEMA (US national electrical manufacturers association) standard fibreglass epoxy, G10 tube cut from a plate stock, is recommended. The second VAMAS measurements were carried out on this type of mandrel, since a G10 tube appropriately machined from a plate stock has a thermal contraction that does not vary significantly with its geometry and is close to that of a Nb_3Sn specimen wire.

Stainless steel mandrels may require careful mandrel design considering wall thickness and skillful techniques for specimen tightening and bonding.

Mandrels of Ti-6Al-4V usually produce critical currents in a slight tensional state. In the case of rather large residual clearance of winding, materials such as Ti alloys having smaller thermal contraction than that of the specimen may be used to minimize the residual clearance following cool down.

If the reaction mandrel and the measurement mandrel can be of the same material, then the same mandrel can be used for both reaction and measurement. In this case, it is not necessary to transfer the specimen from a reaction mandrel to a measurement mandrel after reaction. However, steps should be taken to ensure that the specimen is not bonded to the mandrel after reaction heat treatment. This operation requires the extreme care mentioned in A.4.3. The material and construction of the mandrel and detail of specimen preparation in this one-mandrel method are specified in Annex D.

The leakage current through a conductive mandrel without an insulating layer can be estimated by making measurements under test conditions with and without a specimen on the mandrel. The measurement of voltage drop from current contact to current contact without a specimen and under test conditions can be used to estimate the resistance of the leakage path including contact resistance. Then, measurement of voltage drop from current contact to current contact with a specimen and under test conditions can be used to estimate the leakage current.

It is possible to have a significant leakage current through a conductive mandrel when measuring conductors that are thermally unstable [5]. A section of the conductor outside the regular voltage taps can switch to the normal state, causing significant leakage current, a lowering of the actual net current through the specimen, and highly misleading results. This can easily be detected by monitoring and recording the voltage on a pair of diagnostic taps that measure the voltage between the current contacts to the specimen.

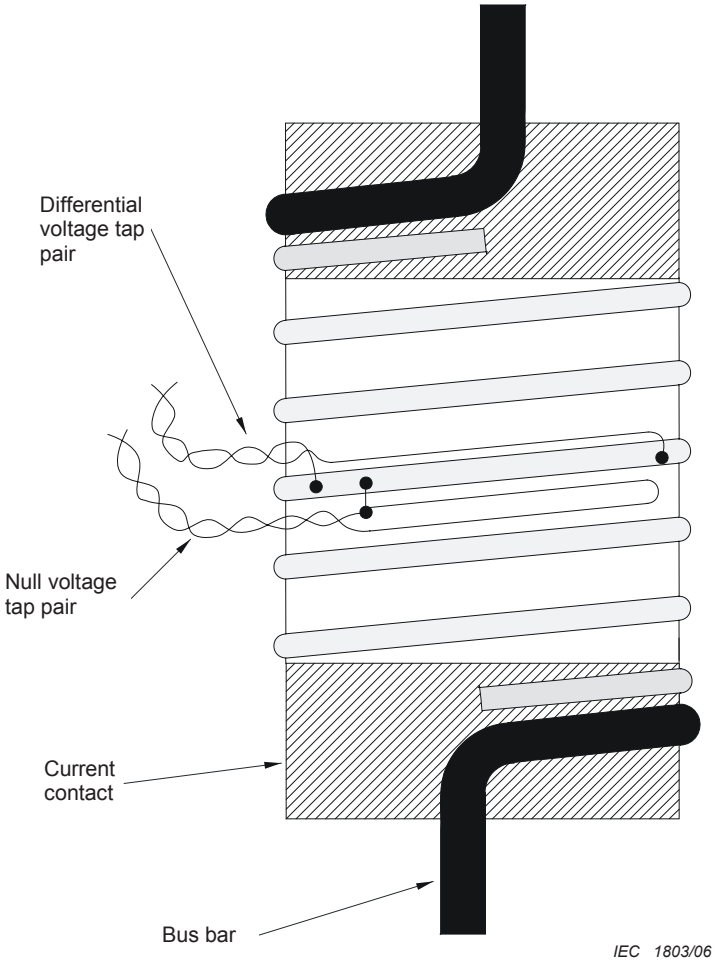
A.3.4 Measurement mandrel construction

The difference in diameter between the reaction and measurement mandrels should be less than 0,5 %. A 0,5 % difference in diameter introduces a sample strain of at most 0,01%. Also see third paragraph of A.4.3.

If a thin walled rolled fibreglass epoxy composite tube is chosen, the wall thickness of the tube should be less than 25 % of tube radius to satisfy the criteria mentioned in 6.3.

The groove on the measurement mandrel should be V-shaped. Mandrels with a rectangular groove or without groove may be used, together with a specimen bonding technique using a low temperature adhesive or epoxy (see A.4.4).

Typically, the current contacts are made from cylindrical copper rings as shown in Figure A.1; the outer diameter of the ring should be close to the inner diameter of the coiled specimen to minimize bending strain.



NOTE The null voltage tap pair is used for detection of ground loop or common mode voltage problems. The differential voltage tap pair (shown here over a short length for clarity) is left undisturbed, while a separate pair is attached to the specimen as shown, with one lead of the pair shorted to the other one which is still connected to the specimen. The null voltage tap pair is configured with a small loop of wire to simulate the mutual inductance of the differential voltage tap pair. The voltage measured on the null voltage tap pair should not be a function of specimen current, although it may be a function of current sweep rate. If it is a function of current, this indicates the level of the problem.

Figure A.1 – Instrumentation of specimen with a null voltage tap pair

Typically, a higher current capacity superconductive lead is used to carry current to and from the current contact to reduce the heat load near the ends of the specimen.

Superconductive leads may be wrapped partly around the copper rings to reduce the effective contact resistance. If the critical current of the superconductive lead is much larger than that of the specimen under test conditions, then the lead should not cover more than 90 % of the circumference of the copper ring.

A.4 Specimen preparation

A.4.1 Specimen mounting for reaction heat treatment

The cross-sectional area of the conductor is measured before it is mounted and this area is used in the determination of I_c when a resistivity criterion is used. A precision of 5 % is sufficient for the determination of I_c; however, a precision of 1 % is needed when a critical current density J_c determination is desired.

Coating materials, such as the chrome plate on the specimen, should be treated appropriately and carefully before and after the final heat treatment.

The coil is wound with the same curvature as the natural curvature set from spooling.

An alternative method for fixing the specimen to the mandrel may be to use screws, instead of holes, one at each end of the mandrel.

The ends of an internal tin processed wire specimen may be sealed following the recommendation of the manufacturer to prevent loss of tin when the conductor temperature is raised above the melting point of tin at the start of the reaction heat treatment. The ends shall be extended to a point outside the heated region of the furnace. Otherwise, they can be weld-sealed by a specially trained operator.

Typically, a specimen is cleaned by wiping with an organic solvent such as ethanol and acetone.

A.4.2 Reaction heat treatment

In the absence of the manufacturer's specification, temperature variations with time and location in the specimen area of furnace are recommended to be both within ±5 °C.

It is recommended to perform the specimen reaction in either a vacuum atmosphere below approximately 10^{-3} Pa (10^{-5} Torr), or a high-purity inert gas atmosphere at approximately 10^{5} Pa (760 Torr), unless otherwise specified.

A.4.3 Specimen mounting for measurement

Extreme care shall be taken in transferring the specimen from the helical groove of the reaction mandrel to the helical groove of the measurement mandrel so as not to damage the specimen due to bending strain.

When diffusion bonding occurs between the specimen and the reaction mandrel, the chance of damaging the specimen during the specimen transfer is greatly increased. Therefore, before attempting to transfer the specimen from the reaction mandrel, it should be checked for diffusion bonding to the mandrel. If there is a significant amount of bonding that might result in specimen damage, the specimen should be discarded.

The specimen can be unscrewed from the reaction mandrel by lightly restraining it and rotating the mandrel within it. This causes the diameter of the winding to expand away from the mandrel, thus reducing any friction. It is extremely important that the strain introduced during this operation is kept below about 0,1 %. This means that if ΔD is the increase in the winding diameter, D, and d is the wire diameter

$$\Delta D < 0{,}001\ (D^2/d) \qquad \text{(A.1)}$$

For example, if d = 1 mm and D = 40 mm, ΔD must be less than about 1,6 mm. A careful, skilled operator can perform this operation by hand. Having removed the specimen, it is immediately screwed onto the measurement mandrel in the same way.

The act of transferring the specimen from the reaction mandrel to the measurement mandrel can be performed simultaneously to reduce possible specimen damage. This can be accomplished by clamping the two mandrels together end-to-end with the two helical grooves in phase with each other.

Multiple turns soldered to the current contact can cause a slowly decaying magnetic field. This magnetic field is produced by the current induced by a change in the background magnetic field set point.

A.4.4 Specimen bonding

Specimen motion can result in a premature quench (irreversible thermal runaway), voltage noise and ultimately a reduction in the repeatability of critical current.

A tight winding can provide adequate specimen support depending on the differential thermal contraction between the specimen and the measurement mandrel. However, it is recommended to use a low temperature adhesive such as silicone vacuum grease or epoxy to secure the specimen to the mandrel.

Although a low temperature adhesive can help reduce the likelihood of a quench, too much adhesive can cause a quench by inhibiting the heat flow from the specimen to the helium bath.

A rough and clean surface on the measurement mandrel and a clean surface on the specimen is needed for strong specimen bonding.

It is impractical to specify a single specimen bonding technique for all conductors and measurement mandrel materials.

The use of solder to bond the specimen to the measurement mandrel between the current contacts is not allowed for reasons of difficulty in estimating leakage current, artificially increasing stability and amplified differential thermal contraction.

A.5 Measurement procedure

The specimen support structure is needed to hold the specimen in the centre of the background magnet in a liquid helium cryostat and to support current and voltage leads between room and liquid helium temperatures.

To reduce thermoelectric voltages on the specimen voltage leads, copper voltage leads are used, which are continuous from the liquid helium bath to room temperature and provide an isothermal environment for all room temperature joints or connections. It should be noted that the joints or connections immersed in liquid helium are isothermal.

The specimen cooling rate may affect the measured critical current. The grease bonding material, if used, has virtually no mechanical strength until it is cooled below its freezing temperature. Consequently, the strength of the bond between the specimen and its mandrel changes during the cooling process, when differential thermal contraction between the specimen and the mandrel is also occurring. This may result in different mechanical states for specimen cooled at different rates.

A quench protection circuit, or a resistive shunt can be used if it is necessary to protect the specimen from damage caused by the specimen current in the event that the specimen enters the normal state.

In the constant sweep rate method, the time limitation of 10 s for the ramp from zero current to I_c is due to considerations of inductive voltage and specimen heating. The inductive voltages at the upper end of the allowed ramp rates may not be constant with current depending on ramp rate, voltage sensitivity, quench history of the specimen, and when the background field was last changed [6]. These variable inductive voltages can appear to be current transfer voltages and can limit the validity of the measurement in 9.1. This effect may be reduced in subsequent measurements by first cycling the current up to I_c and back to zero after any change in the applied magnetic field or after the specimen has quenched.

In the ramp-and-hold method, compared to the constant sweep rate method, a faster ramp rate is allowed between each current set point in this case. However, a short settling time is needed after each fast current ramp.

Settling times as long as 3 s may be necessary depending on ramp rate, voltage sensitivity, quench history of the specimen, and when the background field was last changed. This effect may be reduced in subsequent measurements by first cycling the current up to I_c and back to zero after any change in the applied magnetic field or after the specimen has quenched.

If the system noise is significant compared to the prescribed value of voltage, it is desirable to increase the time for the ramp from zero to I_c to be more than 150 s in order to allow more time for data averaging. In this case, care should be taken to increase the heat capacity and/or cooling surface of the current contacts enough to suppress the influence of heat generation due to the longer time required for the measurement. It should be noted that the ramp-and-hold method allows for averaging data which can be appropriately distributed along the *U-I* characteristic.

With time, ramping the specimen current can induce a positive or negative voltage on the voltage taps. This source of interfering voltage during the ramp can be identified by its proportional dependence on ramp rate. If this voltage is significant compared to U_c, then decrease the ramp rate, decrease the area of the loop formed by the voltage taps and the specimen between them, or else use the ramp-and-hold method.

Notice that stick-slip or continuous specimen motion can occur during the ramp due to the increasing Lorentz force with time. If this source of interfering voltage is significant compared to U_c, then check the direction of the Lorentz force, improve the specimen bonding and support, or use the ramp-and-hold method.

If the *U-I* characteristic is not valid, the repeatability may be improved by improving the quench protection of the specimen. Changes can also be made to improve the specimen bonding and support or thermal stability (which might have longer current contacts and less adhesive on the outer surface of the specimen).

The baseline voltage may include thermoelectric, off-set, ground loop and common mode voltages. It is assumed that these voltages remain relatively constant for the time it takes to record each *U-I* characteristic. Small changes in thermoelectric and off-set voltages can be approximately removed by measuring the baseline voltage before and after the *U-I* curve measurement and assuming a linear change with time. If the change in the baseline voltage is significant compared to U_c, then corrective action to the experimental configuration should be taken.

Variation in ground loop and common mode voltages can be irregular functions of specimen current and thus, if they are large, action should be taken to reduce them. This is difficult to distinguish from a current transfer limit. A test for common mode problems can be performed by measuring a null voltage tap pair (see Figure A.1) as a function of specimen current. A non-zero voltage measured on this pair should not be a function of specimen current, although it may be a function of current sweep rate. If it is a function of current, this will indicate the level of the problem.

A.6 Precision and accuracy of the test method

The size and complex dependence of the self-field effect on current, coil diameter, pitch, etc. may result in a detectable systematic error, but is not expected to be significant compared to the target precision for an interlaboratory comparison on nearly identical specimens. However, a rough estimation of the self-field effect on I_c can be made, if necessary, using the information contained in the test report. See Annex C for a further discussion of the self-field effect.

A quench protection circuit that resets the specimen current to zero when the specimen voltage exceeds a trip point may be necessary to allow additional determinations of critical current.

An optional method for assessing the precision of a laboratory's critical current measurement system is to obtain and measure the standard reference material.

NOTE The Cu/Nb-Ti standard reference material SRM-1457 is available from

National Institute of Standards and Technology
Standard Reference Materials Program
100 Bureau Drive, Stop 2322
Gaithersburg, MD 20899-2322
U.S.A.

Telephone: +1-(301) 975-6776
Fax: +1-(301) 948-3730
srminfo@nist.gov

http://www.nist.gov/srm

This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this material.

There are additional technical difficulties in the critical current measurements on Nb_3Sn wires due to the high sensitivity to mechanical strain, as compared to that of Nb-Ti wires. It is recommended to evaluate the overall precision and accuracy of an individual laboratory method by interlaboratory test.

A.7 Calculation of results

A.7.1 Critical current criteria

For some applications, the non-Cu cross-sectional area is used in the resistivity criterion. For the externally-stabilized wires, this area is usually determined by a measurement of the Cu to non-Cu ratio using the weighing, etching and weighing method. Otherwise, it can be determined by using a graphical analyzing method.

When the criteria of 10^{-14} Ωm is adopted, the distance between voltage taps may need to be greater than 500 mm to increase the signal-to-noise ratio.

A larger separation between current and voltage connections may be necessary if a significant current transfer component exists relative to the criteria.

A.7.2 *n*-value (optional calculation)

The superconductor *U-I* characteristic can usually be approximated by the empirical power-law equation:

$$U = U_0(I/I_0)^n \tag{A.2}$$

where

U is the specimen voltage, in microvolts (μV);

U_0 is a reference voltage, in microvolts (μV);

I is the specimen current, in amperes (A);

I_0 is a reference current, in amperes (A).

The *n*-value (no units) reflects the general shape of the *U-I* curve.

A plot of log *U* versus log *I* is not always linear, even in the current range near the critical current criterion E_c = 10 μV/m, thus the range of the criteria used to determine *n* needs to be reported. Typically, this range is 10 μV/m to 100 μV/m or 10^{-14} Ωm to 10^{-13} Ωm.

The scatter in the determined values of *n* may have a coefficient of variation as large as 20 %; therefore, the procedure for determining the *n*-value is optional in the present method.

Other effects that may contribute to the variability of the *n*-value are the following:

– voltage noise;
– current ripple;
– specimen cooling (amount of adhesive used);
– magnetic field ripple and uniformity;
– the self-field of the specimen current;
– a thermal gradient on the specimen.

Table A.1 – Thermal contraction data of Nb_3Sn superconductor and selected materials
(see NOTE)

Thermal contraction %								
Material	**Temperature** K							
	273	**200**	**150**	**100**	**50**	**20**	**10**	**4**
Nb_3Sn [a]	0	–0,055	–0,08	–0,115	–0,135	–0,15	–0,15	
Nb_3Sn [b]	0	–0,05	–0,08	–0,11	–0,13	–0,15	–0,15	
Nb_3Sn composite wire [a]	0	–0,12	–0,17	–0,23	–0,26	–0,27	–0,27	
OFHC copper annealed [c]	0	–0,118	–0,18	–0,252	–0,288	–0,295	–0,295	
G10, warp [d]	0	–0,09	–0,13	–0,175	–0,205	–0,215	–0,220	–0,225
G10, normal [d]	0	–0,28	–0,428	–0,54	–0,62	–0,64	–0,65	–0,655
Stainless steel AISI SUS316 [c]	0	–0,111	–0,173	–0,23	–0,262	–0,265	–0,265	–0,265
Stainless steel AISI SUS304 [c]	0	–0,11	–0,172	–0,23	–0,261	–0,264	–0,264	–0,264
Ti-6Al-4V alloy [c]	0	–0,062	–0,10	–0,132	–0,15	–0,152		
Ti-5Al-2,5Sn alloy [c]	0	–0,061	–0,096	–0,128	–0,147	–0,152	–0,152	–0,153
Cu-5Sn alloy [c]	0	–0,118	–0,182	–0,252	–0,291	–0,297	–0,297	–0,297
Cu-13,5Sn alloy [a]	0	–0,12	–0,22	–0,28	–0,32	–0,33	–0,33	

NOTE The values are referred to zero at 273 K.

[a] A.G. Rupp, *Filamentary A15 Superconductors*, edited by M. Suenaga and A.F. Clark, Plenum Press, NY (1980) 155.

[b] J.W. Ekin, *et al*. Technical report, NBSIR 86-3044, NBS (1986).

[c] *Handbook on Materials for Superconducting Machinery*, NBS (1974, 1976).

[d] A.F. Clark, *et al*. IEEE Trans. on Magnetics, MAG-17 (1981) 2316.

Annex B
(informative)

Strain effect of Nb_3Sn conductors

Nb_3Sn superconductors are extremely brittle and their electrical properties can be irreversibly changed with relatively small mechanical strains. It is well-known that the critical current I_c of Nb_3Sn composite superconductors is sensitive to mechanical strain. In Figure B.1 a typical uniaxial strain dependence of I_c for a Nb_3Sn composite is shown. In addition to uniaxial strain, the I_c of Nb_3Sn composites is also sensitive to bending, twisting and transverse strains.

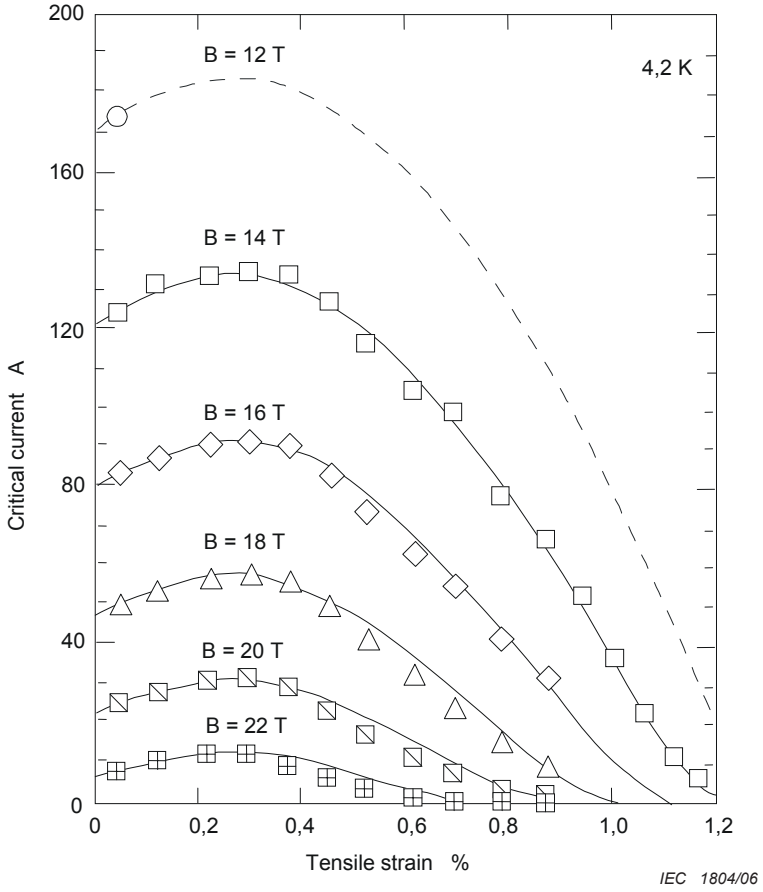
A typical Nb_3Sn multifilamentary composite superconductor contains Nb_3Sn filaments embedded in a bronze matrix surrounded by a diffusion barrier and Cu stabilizer. The filaments have different thermal contraction properties compared to the other composite components. Thus, pre-strain develops as the composite superconductor is heat treated and cooled.

The pre-strain or "intrinsic strain" of an Nb_3Sn composite superconductor in its "natural" condition at 4,2 K depends on the amount and distribution of the non-superconductive components, notably Cu and barrier material, present in a cross-section. In this context, "natural" means that no external strain is introduced into the test conductor. Critical current measurements made with the conductor in its "natural" condition provide a useful measure of the conductor's intrinsic performance.

It is desirable to minimize the differential contraction between the measurement mandrel and the conductor (and thus minimize the extrinsic strain) to obtain I_c data that are close to that of the conductor in its "natural" condition. Since Nb_3Sn superconductors are highly strain sensitive, varying results are still obtained depending on the contraction of the mandrel and the way the conductor is mounted.

In practice, conductors are used in different types of windings where the level of support varies considerably and where magnetic force related stresses may or may not be present. For example, the conditions within a dipole magnet are significantly different compared to a solenoidal magnet. Thus a magnet designer must have access to data on the strain dependence of I_c in order to accurately predict the performance of a specific magnet.

The I_c of a conductor under operating conditions inside a winding and the performance of the magnet can be estimated using the following: data obtained from a conductor on the type of measurement mandrel used in this method, an estimate of the pre-strain in the conductor, and data on the strain dependence of I_c. The pre-strain can be determined by either measurement or calculation using the geometry and properties of the components of the composite conductor. The strain dependence has to be determined in a test facility capable of providing I_c versus strain measurements.



NOTE Critical current reaches a maximum at an externally applied strain nearly corresponding to the pre-strain in Nb_3Sn filaments, and decreases rapidly with increasing strain. The percentage effect becomes more severe at high fields. In contrast, the critical current of an Nb-Ti composite is much less sensitive to mechanical strain; typically the critical current degradation is only 4 % at 7 T and 4,2 K for a strain of 1 %. The actual strain dependence of a conductor may vary depending on the rate of stoichiometry and ordering of the Nb_3Sn compound and the configuration of the composite.

Figure B.1 – Uniaxial (tensile) strain dependence of critical current for a typical Nb_3Sn composite wire shown with various magnetic fields [7]

Annex C
(informative)

Self-field effect

Because of the high current flowing through a coiled specimen, the specimen will generate its own magnetic field, giving rise to the self-field effect on the measured critical current. This self-field is generated in addition to the applied magnetic field, so the total field experienced by the specimen is greater than the applied magnetic field for a portion of the cross-sectional area of the conductor. Some laboratories make an approximate correction for this additional self-field.

In an interlaboratory comparison of critical current measurements, a self-field correction would unnecessarily compromise the I_c data, since each laboratory's specimen would experience nearly the same self-field effect. There would only be a difference in the self-field effect due to the diameter and pitch of the measurement mandrel (which is controlled in an interlaboratory comparison) and in the homogeneity of the applied magnetic field. Because the specimens are nearly identical in an interlaboratory comparison, there is little need to make an approximate correction for the self-field effect. Critical current data that are "corrected" for the self-field effect by some laboratories participating in the interlaboratory comparison, and not by others, yield incomparable results. Thus, it may be better to omit critical current self-field corrections in interlaboratory comparisons.

This does not diminish the need and utility of a self-field correction to compare critical current densities (J_c) of different diameter wires. When making comparisons of the critical current densities of different diameter wires, the self-fields experienced by the conductors are different, and should be corrected. The current densities after the self-field correction would yield more comparable data. An approximate correction is based on the magnetic field of a long straight wire:

$$B_{SF} = \mu_0 I/(2\pi r) \quad \text{(C.1)}$$

where

B_{SF} is the approximate self-field, in teslas (T);

μ_0 is the magnetic permeability of a vacuum, $4\pi \times 10^{-7}$ H/m;

I is the current in amperes (A);

r is the radius of the wire, in metres (m).

This equation can also be written as follows:

$$B_{SF} = (4 \times 10^{-4})I/d \quad \text{(C.2)}$$

where

B_{SF} is the approximate self-field, in teslas (T);

I is the current, in amperes (A);

d is the wire diameter, in millimetres (mm).

This approximate correction has been shown to partially resolve differences between transport J_c measurements and calculations using d.c. magnetization measurements, and to correct J_c measurements on wires with different diameters in J_c optimization studies. It has also been used to correlate wire and cable critical current measurements with magnetic performance. This method of correction was selected for presentation here because of its simplicity, wide range of application and demonstrated effectiveness. The approximation given by equation (C.1) does not include considerations such as the copper-superconductor ratio, the resistivity of the matrix, the twist-pitch of the filament, filament distribution, current redistribution among the filaments or the diameter and helical pitch of the measurement mandrel.

This approximate correction is generally considered to be accurate enough for its intended purpose as long as the measurement parameters do not enhance the self-field effect. However, this correction is not accurate enough for an interlaboratory comparison. Any correction that includes some of the parameters that may be different among laboratories in an interlaboratory comparison would be extremely complex and still might not be as accurate as necessary. Since this approximate self-field correction does not incorporate effects due to the measurement mandrel diameter and helical pitch, steps should be taken to reduce the contribution of these parameters on critical current measurements that will be used in critical current density comparisons. This implies that larger diameter (>30 mm) measurement mandrels with a pitch angle closer to 7° should be used for high current specimens (>300 A) or for measurements in low magnetic fields (<3 T) where the critical current is more dependent on magnetic field. More definitive guidelines would require additional research on these effects. Self-field effects are difficult to study because the transport critical current cannot be measured without some self-field, and the effect of bending strain on critical current is also convoluted with the self-field effect in many experiments.

An expedient method of reducing the influence of the self-field during an interlaboratory comparison is to standardize the diameter and pitch of the measurement mandrel. The reality of this approach is that the choice of parameters tends toward the smallest diameter which may be appropriate for the interlaboratory comparison, but impractical for routine current-density measurements. A single standard measurement mandrel appropriate for the range of conductors in this standard would be impractical because the mandrel diameter appropriate for the largest conductor would not fit into the access bore of magnets used by many laboratories.

Another method that is sometimes used to normalize part of the self-field effect is to average critical currents for currents flowing in both directions. This may reduce the effect of the diameter of the specimen measurement mandrel and the winding pitch. However, this correction method does not apply to the present measurement standard because the measurement standard does not allow for reversal of current direction.

Annex D
(normative)

One-mandrel method

D.1 Introduction

The material and construction of the mandrel and detail of specimen preparation in the one-mandrel method are specified in this annex.

D.2 Mandrel material

The mandrel shall be made from an insulating material, or from a conductive non-ferromagnetic material that is either covered or not covered with an insulating layer, satisfying the following requirements:

a) material that resists diffusion bonding with the specimen during the reaction heat treatment;

b) material of which thermal expansion coefficient between room and reaction temperatures is close to that of specimen wire;

c) material with which the total strain induced in the specimen at the measuring temperature is within ±0,03 % when cooling from room temperature.

The following materials are recommended. There is no restriction on using other materials as long as they satisfy the above requirements.

– ceramic (or carbon) coated non-magnetic stainless steel;

– heavily surface oxidized non-magnetic stainless steel;

– ceramic (or carbon) coated Ti-6Al-4V or Ti-5Al-2,5Sn.

Typical non-ferromagnetic stainless steels are SUS 304L and SUS 316L. It is noted that Ti-6Al-4V and Ti-5Al-2,5Sn are superconductive with magnetic field below 2 T at 4,2K and 3,7 K, respectively.

D.3 Mandrel construction

The mandrel shall have a diameter large enough that the specimen bending strain, which is introduced into the specimen during winding, is less than 5 %.

The wall thickness of the mandrel shall be thin enough to avoid the leakage of transport current through the mandrel. The leakage current through the mandrel shall be less than 0,2 % of the total current when the specimen current is at critical current I_c (see 9.5).

The mandrel has or does not have a helical groove in which the specimen shall be wound. The pitch angle of the groove shall be less than 7°. The depth of the groove shall be at least half the wire diameter. The groove on the mandrel is preferably V-shaped.

Mandrels with a rectangular groove or without groove can be used with caution. When the mandrel is used without a groove, the specimen shall be co-wound with a spacer to form a uniform pitch.

The current contacts shall be rigidly fastened to the mandrel to avoid stress concentration in the region of transition between the mandrel and the current contact.

Typically, the current contacts are made from cylindrical copper rings as shown in Figure A.1; the outer diameter of the ring shall be close to the inner diameter of the coiled specimen to minimize bending strain.

Now, follow 6.5 then return to the steps below.

D.4 Specimen preparation

D.4.1 Specimen mounting on the mandrel

There shall be no joints or splices in the test specimen.

When using resistivity criteria for the critical current determination, the total cross-sectional area *S* of the specimen shall be determined to a precision of 5 %.

The specimen wire shall be retained on the mandrel at an edge of current terminal by bending the specimen end through a small hole, or be retained by some equivalent method.

The specimen shall then be wound along the groove or the leading way on the mandrel under almost zero tension (less than 0,1 % tensile strain) so that the contact pressure reduced to a minimum to discourage diffusion bonding.

The specimen shall not be wound in a manner that would introduce additional twists into the specimen.

After having been wound on the mandrel, the specimen wire shall be retained at the other current terminal by bending the other specimen end through a small hole, or be retained by some equivalent method.

The specimen shall be cleaned to avoid effects of contamination.

D.4.2 Reaction heat treatment

Reaction heat treatment shall be carried out according to the manufacturer's specification, which includes error limits which shall not be exceeded. Temperature variations within the specimen area of furnace shall be controlled so as not to exceed those limits.

D.4.3 Instrumentation

After the reaction heat treatment, it shall be confirmed by cutting the specimen at a retained end and slightly rotating the end that there is no diffusion bonding between the specimen and the mandrel.

The retained end of the specimen shall be soldered to the current contact ring. Starting from the fixed end, the specimen shall be stroked along its entire length, thus firmly seating the specimen in the groove or the leading way. The free end shall then be soldered to the other contact ring.

The minimum length of the soldered part of the current contact shall be greater than the smaller of 40 mm and 30 wire diameters. No more than three turns of the specimen shall be soldered to each current contact.

The shortest distance from a current contact to a voltage tap shall be greater than 100 mm.

The voltage taps shall be soldered to the specimen. Minimize the mutual inductance between the applied current and the area formed by the specimen and the voltage taps by counter-winding the untwisted section of the voltage taps back along the specimen, as shown in Figure A.1.

The distance along the specimen between the voltage taps, *L*, shall be measured to an accuracy of 5 %. This voltage tap separation shall be greater than 150 mm.

Return to 7.4 and complete the procedure.

Bibliography

[1] IEC 60050-121, *International Electrotechnical Vocabulary (IEV) – Part 121: Electromagnetism*

[2] IEC 61788-1, *Superconductivity – Part 1: Critical current measurement – DC critical current of Cu/Nb-Ti composite superconductors*

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Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-815	2000	International Electrotechnical Vocabulary (IEV) Part 815: Superconductivity	-	-

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