IEC 61788-26

Edition 1.0 2020-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Superconductivity –
Part 26: Critical current measurement – DC critical current of RE-Ba-Cu-O composite superconductors**

**Supraconductivité –
Partie 26: Mesurage du courant critique – Courant critique continu des composites supraconducteurs de RE-Ba-Cu-O**

IEC 61788-26:2020-06(en-fr)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

COMMISSION ELECTROTECHNIQUE INTERNATIONALE

ICS 17.220.20; 19.080; 29.050

ISBN 978-2-8322-8436-0

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The text of this standard is based on the following documents:

FDIS	Report on voting
90/455/FDIS	90/458/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61788 series, published under the general title *Superconductivity*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

In 1986, superconductivity in some perovskite type materials containing copper oxides at temperatures far above the critical temperatures of metallic superconductors was discovered. In 1987, it was discovered that Y-Ba-Cu-O (YBCO) has a critical temperature (T_c) of 93 K. After a quarter century, the RE-Ba-Cu-O (REBCO, RE = rare earth) superconductors became commercially available.

In 2013, VAMAS-TWA 16 started working on the critical current measurement methods in REBCO superconductors. In 2014, an international round robin test (RRT) on the critical current measurement method for REBCO superconductors was conducted that was led by VAMAS-TWA 16. 10 institutions/universities/industries from five countries participated. The pre-standardization work of VAMAS was taken as a base for this document, on the DC critical current test method of REBCO composite superconductors.

The test method covered in this document is intended to give an appropriate and accepted technical base to engineers working in the field of superconductivity technology.

SUPERCONDUCTIVITY –

Part 26: Critical current measurement – DC critical current of RE-Ba-Cu-O composite superconductors

1 Scope

This part of IEC 61788 specifies a test method for determining the DC critical current of short RE (rare earth)-Ba-Cu-O (REBCO) composite superconductor specimens that have a shape of straight flat tape. This document applies to test specimens shorter than 300 mm and having a rectangular cross section with an area of 0,03 mm^2 to 7,2 mm^2, which corresponds to tapes with width ranging from 1,0 mm to 12,0 mm and thickness from 0,03 mm to 0,6 mm.

This method is intended for use with superconductor specimens that have critical current less than 300 A and n-values larger than 5 under standard test conditions: the test specimen is immersed in liquid nitrogen bath at ambient pressure without external magnetic field during the testing. Deviations from this test method that are allowed for routine tests and other specific restrictions are given in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *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 and the following apply.

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3.1
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, and where the U-I data are acquired continuously or frequently

3.2
ramp-and-hold method
U-I data acquisition method where a current is swept in stages from zero to a current above I_c, where the current is held for an appropriate amount of time at each stage, and where the U-I data are acquired continuously or frequently

4 Principle

The critical current of a composite superconductor specimen shall be determined from a voltage–current (U-I) characteristic measured in a liquid nitrogen bath at ambient pressure. To get a U-I characteristic, a direct current is applied to the superconductor specimen and the voltage generated along the specimen is measured. The current is increased from zero and the U-I characteristic is recorded. The critical current shall be determined as the current at which a specific electric field strength criterion (electric field criterion) (E_c) is reached. For any selected E_c, there shall be a corresponding voltage criterion (U_c) for a specified voltage tap separation.

5 Apparatus

5.1 General

The apparatus required for the present test method includes the critical current measuring system. Additional information relating to the apparatus is given in Annex A.

5.2 Critical current measuring system

The apparatus to measure the U-I characteristic should consist of a specimen probe, an open bath and a U-I measurement system.

The specimen probe, which consists of a specimen and a measurement holder, is inserted in the open bath filled with liquid nitrogen. The U-I measurement system consists of a DC current source and necessary data acquisition system, preamplifiers, filters or voltmeters, or a combination thereof. Suitable measurement holder materials are recommended in A.3.1.

A computer assisted data acquisition system is recommended.

6 Specimen preparation and setup

6.1 Length

An example of a schematic view of measurement setup is shown in Figure 1.

The length (L) of specimen to be measured shall be defined as follows:

$$L = L_1 + 2 \times L_2 + 2 \times L_3 + L_4 \geq 5 \times W \qquad (1)$$

$$L_1, L_2, L_3 \geq W \qquad (2)$$

where

L_1 is the distance between the voltage taps;

L_2 is the length of the current contact;

L_3 is the shortest distance from a current contact to the neighbouring voltage tap;

L_4 is the width of a voltage tap.

W is the width of a specimen to be measured.

The larger the current-carrying capacity of the specimen, the larger shall be L_2. L_2 shall be increased for a specimen that has a stainless steel or other high-resistivity material backing or jacket. For a measurement that needs the higher voltage sensitivity, L_1 shall be increased. For some practical values for L_1 through L_4, see A.3.2.

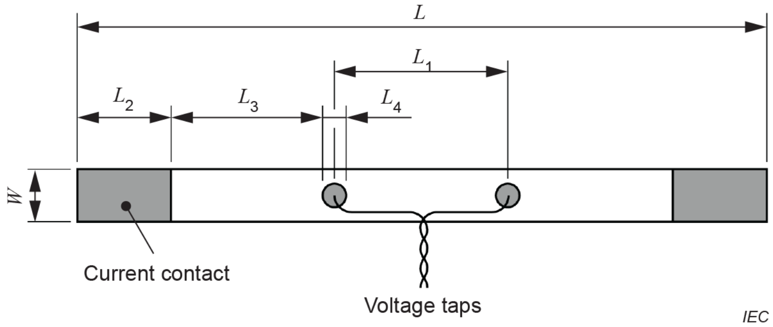

Figure 1 – Schematic view of measurement setup

6.2 Mounting of the specimen

The specimen shall be mounted to the flat surface of the holder. Both ends shall be fastened or soldered to the current contact blocks.

The voltage taps shall be placed in the central part with or without solder.

The current contacts and the voltage taps shall be on the superconducting layer side.

Voltage leads shall be twisted as close to the voltage taps as possible.

7 Critical current measurement

The critical current shall be measured while minimizing mechanical strain.

The specimen shall be inserted slowly into the liquid nitrogen bath. The volume of the liquid nitrogen bath shall be sufficiently larger than the specimen and the measurement holder. The depth of the bath shall be sufficiently higher than the height of the measurement holder. The specimen shall be cooled from room temperature to liquid nitrogen temperature until the specimen and the measurement holder are sufficiently cooled by liquid nitrogen that boils with microbubbles, i.e. steady state. It takes several tens of seconds.

When using the constant sweep rate method, the sweep rate shall be selected not to influence the voltage measurement.

When using the ramp-and-hold method, the current sweep rate between stages shall be lower than the equivalent of ramping from zero current to I_c in 3 s. Data acquisition at each stage shall be started as soon as the flow or creep voltage generated by the current ramp can be disregarded. The current drift during each current set point shall be less than 1 % of I_c.

Record the U-I characteristic with increasing current.

After measurement, the specimen shall be warmed up to room temperature.

Additional information relating to the measurement is given in Annex A.

8 Calculation of results

8.1 Critical current criteria

The critical current I_c shall be determined by using an electric field criterion E_c.

I_c shall be determined at E_c = 100 μV/m. I_c determined at E_c = 10 μV/m is optional.

The I_c shall be determined as the current corresponding to the point on the U-I curve where the voltage U_c is measured (see Figure 2 and Figure 3):

$$U_c = L_1 E_c \tag{3}$$

where

U_c is the voltage criterion in microvolts (μV);

L_1 is the voltage tap separation in metres (m);

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

U_c and I_c are the corresponding voltage and current values at the intersecting point of the straight lines with the U-I curve as shown in Figure 2.

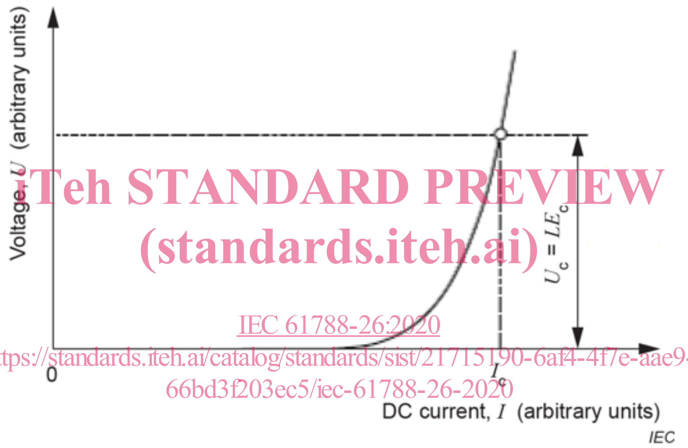

Figure 2 – Intrinsic *U-I* characteristic

If the measured U-I curve includes a resistive component, it is recommended to increase L_3 to minimize the current transfer component voltage.

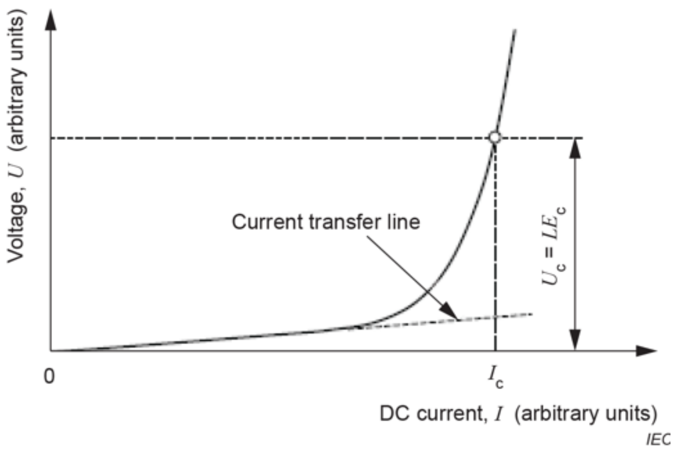

Figure 3 – *U-I* curve with a current transfer component

8.2 n-value (optional)

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. The corresponding electric field region is recommended to be from 10 µV/m to 100 µV/m.

The electric field region used to determine the n-value shall be reported.

Additional information relating to the calculation is given in Annex A.

9 Uncertainty of measurement

Unless otherwise specified, measurements shall be carried out in a liquid nitrogen bath whose temperature can range from 76,8 K to 77,7 K. A voltmeter having 7,5 digits resolution, providing 1 nV sensitivity on 10 mV setting shall be used to measure specimen voltage.

According to the international round robin test (see Annex B), the relative standard uncertainty is less than 3 %. The target measurement uncertainty shall be 6 % with a coverage factor of 2.

10 Test report

10.1 Identification of test specimen

The test specimen shall be identified by the following:

a) name of the manufacturer of the specimen;

b) classification and/or symbol;

c) lot number.

10.2 Reporting of I_c values

The following values shall be reported:

a) I_c values with their corresponding electric field criteria;

b) specimen temperature and/or ambient pressure.

The reporting of n-values is optional.

10.3 Reporting of I_c test conditions

The following test conditions shall be reported:

a) length of specimen (L);

b) width of specimen (W);

c) thickness of specimen;

d) distance between voltage taps (L_1);

e) shortest distance from a current contact to a voltage tap (L_3);

f) length of the current contacts (L_2);

g) sweep rate when using the constant sweep rate method;

h) ramp pitch, ramping time and holding time when using the ramp-and-hold method.

Annex A
(informative)

Additional information relating to measurement, apparatus, and calculation

A.1 General information

There are variables that have a significant effect on the measured value of critical current in REBCO superconductors. Some of them are addressed in Annex A for users' attention (see also Annex B).

Special features found in REBCO superconductors may be classified into two groups. The first group is specific to REBCO multilayer composite superconductors, including mechanical fragility of delamination, magnetic flux flow and creep, large anisotropy, screening current caused by magnetic field change, non-uniformity of superconducting properties, etc. The second group is due to length of the specimen used in this document. A critical current measurement on such a specimen may easily pick up different voltage signals due to inductive voltage, thermal noise, current redistribution, etc. Current transfer voltages may be present due to the short distance from a current contact to a voltage tap.

Superconductor specimens with critical currents above 500 A could be measured with this present method with an anticipated increase in uncertainty. A superconductor specimen longer than 300 mm could be measured with this present method. However, care needs to be taken for the measurement preparation.

This document assumes that measurements are made in a liquid nitrogen bath. The cryogen is used at a temperature near boiling point for the normal atmospheric pressure of the test site. This document could be extended to measurements conducted in the cryogen at temperatures other than near boiling point, i.e. depressurized or pressurized. The measurements in a gas or a vacuum are not covered by the scope of this document.

A.2 Measurement condition

The minimum total length of the tape specimen is five times the tape width (W) + the voltage tap width (L_4), which represents the sum of the following:

– the minimum voltage tap separation ($L_1 \geq W$);

– the length of current contacts ($L_2 \geq W$);

– the shortest distance between current and voltage contacts ($L_3 \geq W$).

It is expected that the specimen mounting and the specimen cooling procedures in this test method may be one of the most significant contributors to the overall uncertainty of the critical current measurement. The value of I_c is sensitive to strain. Cooling rates influence thermally induced strain due to different thermal time constants and coefficients of thermal expansion (CTEs) between the sample and mounting materials.

A.3 Apparatus

A.3.1 Measurement holder material

In this method, the specimen strain is controlled to a minimum (less than 0,1 %). A 0,1 % thermal contraction may result in no appreciable I_c deviation at 0 T and near 77,3 K. One significant source of strain is the mismatch in thermal contraction rates between the measurement holder and the specimen when cooled to liquid nitrogen temperature.

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

Recommended holder material is glass-fibre epoxy composite, with the specimen lying in the plane of the fabric warp.

Table A.1 – Thermal contraction data of superconductor and sample-holder materials [1]

Material	$\Delta L/L_{293K\text{-}77K}$ [%]	α_{293K} [10^{-6} K^{-1}]
YBCO polycrystal [2]	0,21	11,5
YBCO *a*,*b*-plane avg. [2]	0,14	8,5
Ni based alloy (UNS N10276) [3]	0,216	10,9
Silver [4]	0,370	18,5
Copper [5]	0,302	16,7
Glass-fibre epoxy composite, warp [6] [7]	0,21	12,5
Glass-fibre epoxy composite, normal [6] [7]	0,64	41

A.3.2 Measurement holder construction

An example of measurement holder is shown in Figure A.1. Typically, the current contacts are made from copper blocks, and the thickness of the contact should be determined so that there is no difference in the level between the holder and the contact surfaces. The contact blocks should be rigidly affixed to the holder. Solder is often used to make current contacts. However, the soldering skills depend on the individual. Thus, this document recommends not to use solder to make current contacts.

Typical L_1 through L_4 values which were used by the participants of the international round robin test [8] were as follows: L_1: 30 mm to 90 mm, L_2: 25 mm to 40 mm, L_3: 10 mm to 30 mm, and L_4: 1 mm to 10 mm.

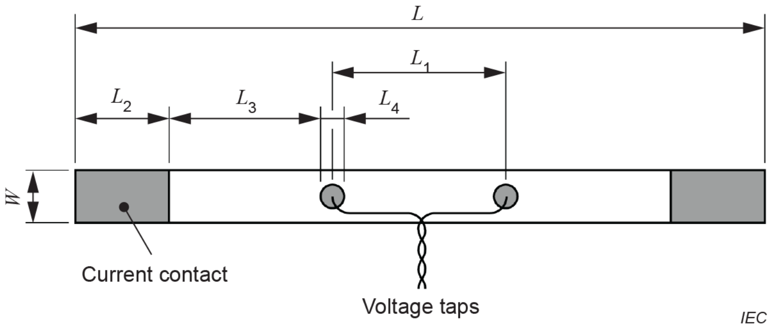

Figure A.1 – Illustration of a measurement configuration for a short specimen of a few hundred amperes class REBCO conductor