IEC 61788-22-1

Edition 1.0 2017-07

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Superconductivity –
Part 22-1: Superconducting electronic devices – Generic specification for sensors and detectors

Supraconductivité –
Partie 22-1: Dispositifs électroniques supraconducteurs – Spécification générique pour les capteurs et détecteurs

IEC 61788-22-1:2017-07 (en-fr)

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SUPERCONDUCTIVITY –

Part 22-1: Superconducting electronic devices – Generic specification for sensors and detectors

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This bilingual version (2019-08) corresponds to the monolingual English version, published in 2017-07.

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

FDIS	Report on voting
90/388/FDIS	90/391/RVD

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

The French version of this standard has not been voted upon.

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This document 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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
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- amended.

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INTRODUCTION

Superconductivity offers various possibilities for the realization of sensing and detection of a variety of measurands. Several sensors and detectors have been developed, exploiting features like superconducting energy gaps, sharp normal-superconducting transition, nonlinear I–V characteristics, superconducting coherent states, and quantization of magnetic flux. All these properties can be influenced by the interaction with electromagnetic fields, photons, ions, etc. Superconducting sensors and detectors have extremely high performance for energy resolution, time response, and low noise, most of which cannot be realized by any other phenomena.

The word "sensor" is normally used for measuring stationary or slowly changing electromagnetic fields, physical quantities such as current and temperature. On the other hand, the word "detector" is normally used for single quanta such as photons from infrared to γ-rays and individual particles. However, the boundary between "sensor" and "detector" is ambiguous. In this document, therefore, both "sensor" and "detector" are used. Additionally, a detector using a sensor is possible, for example, X-ray detector using transition edge sensor (TES) that measures temperature rise due to the deposition of measurand energy. In this document, for example, the terminology "transition edge sensor X-ray detector" is used for X-ray detection using TES.

Superconducting sensors and detectors have been applied to a variety of fields including medical diagnosis, telecommunications, mineral exploration, astronomical instruments, quantum information processing, and analytical instruments. For users, IEC standardization is necessary because there is confusing terminology, there are no graphical symbols for diagrams, and no test methods.

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SUPERCONDUCTIVITY –

Part 22-1: Superconducting electronic devices – Generic specification for sensors and detectors

1 Scope

This part of IEC 61788-22-1 describes general items concerning the specifications for superconducting sensors and detectors, which are the basis for specifications given in other parts of IEC 61788 for various types of sensors and detectors. The sensors and detectors described are basically made of superconducting materials and depend on superconducting phenomena or related phenomena. The objects to be measured (measurands) include magnetic fields, electromagnetic waves, photons of various energies, electrons, ions, α-particles, and others.

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 60027 (all parts), *Letter symbols to be used in electrical technology*

IEC 60050-815, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

IEC 60417, *Graphical symbols for use on equipment* (available at: http://www.graphical-symbols.info)

IEC 60617, *Graphical symbols for diagrams* (available at: http://std.iec.ch/iec60617)

ISO 1000, *SI units and recommendations for the use of their multiples and of certain other units*

ISO 7000, *Graphical symbols for use on equipment – Registered symbols* (available at: http://www.graphical-symbols.info)

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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- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

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3.1
additional positive feedback
APF
method enhancing voltage-flux transformation ratio by using resistance and coupling coil to SQUID ring

3.2
critical current modulation parameter
β_L
parameter defined by $2LI_c/\Phi_0$, where L is the SQUID washer inductance, I_c is the critical current of a Josephson junction, for DC SQUIDs, and a parameter defined by $2\pi LI_c/\Phi_0$ for RF SQUIDs

Note 1 to entry: The term "shielding parameter" can also be used.

3.3
Stewart-McCumber parameter
β_C
parameter defined by $2\pi I_c R_n^2 C/\Phi_0$, where R_n is the normal state resistance of a Josephson junction, and C is the capacitance of a Josephson junction

3.4
bridge junction
junction formed from two superconductors connected by a superconducting bridge of small section

Note 1 to entry: The term "microbridge" can also be used.

3.5
critical current
I_c
maximum direct current that can be regarded as flowing through a Josephson junction without resistance

3.6
critical current density
J_c
critical current divided by the cross-section of the conductor or the junction area of the Josephson junction

3.7
feedback coil
coil that is inductively coupled to a SQUID operated in the flux locked loop (FLL) mode

3.8
flux locked loop
FLL
method that improves linearity and dynamic range of a SQUID by using negative feedback to keep the constant flux number in the SQUID ring

3.9
gradiometer
configuration of superconducting loops coupled to a SQUID magnetometer, or of multiple SQUID magnetometers that are arranged so as to be insensitive to homogenous magnetic fields or to be sensitive to magnetic field gradients

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3.10
metallic magnetic calorimetric detector
type of superconducting device that the temperature increase of a metallic absorber is measured by sensing the magnetization change of the absorber because of measurand energy deposition

3.11
microwave kinetic inductance detector
type of superconducting device that uses the microwave surface impedance change of a superconducting strip because of measurand energy deposition

3.12
normal state resistance
resistance of a superconductor or a Josephson junction at a normal state

Note 1 to entry: In a superconductor or a TES, it is the resistance at a temperature just above the superconducting transition.

Note 2 to entry: In a Josephson junction, it is the tunnelling resistance at a bias voltage well above $2\Delta/e$.

3.13
planar gradiometer
kind of configuration of the flux pickup loop that measures a magnetic field gradient in the plane of the flux pickup loop coupled to a SQUID

3.14
quasiparticle
excitation combining properties of an electron and a hole that is created by breaking a Cooper pair in a superconductor

3.15
superconducting hot electron bolometric mixer
type of superconducting device that uses heterodyne mixing with the resistive transition from the superconducting state to the normal state in a superconducting microbridge because of measurand energy deposition

3.16
superconducting quantum interference device sensor
SQUID sensor
type of superconducting device that uses quantum interference occurring in a closed electrical circuit containing one or more Josephson junctions

Note 1 to entry: Every measurand, for example magnetic fields or electric currents, that is transformed into a change of magnetic flux threading the superconducting structure can be sensed by a SQUID.

3.17
SQUID array
SQA
device consisting of series and/or parallel arrays of multiple SQUIDs

3.18
nano-SQUID
device whose largest loop dimension is less than 500 nm

3.19
SQUID ring
multiply superconducting structure that contains one or more Josephson junctions

Note 1 to entry: The term "SQUID loop" can also be used.

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3.20
SQUID amplifier
current–voltage converter using a single SQUID, SQUID array or other SQUID-based current sensor circuits

3.21
subgap region
lower branch of the hysteretic I–V characteristic of a tunnel junction where the voltage is less than 2Δ

3.22
subgap current
quasiparticle tunnelling current in the subgap region of a tunnel junction

Note 1 to entry: In Josephson tunnel junctions, the whole subgap region is observable when the DC Josephson effect is suppressed by applying a magnetic field parallel to the plane of the junction area.

3.23
superconducting strip detector
type of superconducting device that uses the local resistive change in a long superconducting strip because of measurand energy deposition

Note 1 to entry: The name for a photon detector, superconducting nanowire photon detector, is not recommended for most cases, since the dimensions of superconductors are often in discord with the current definition of "nanowire" in ISO/TS 80004-2:2015, in which "nanowire" or "nanofibre" is defined as nano-objects with two external dimensions in the nanoscale that are approximately 1 nm to 100 nm, and the third dimensions significantly larger. The dimensions of the superconducting strip type meet the definition of "nanoribbon" or "nanotape" in most cases.

Note 2 to entry: The terms "nanoribbon" and "nanotape" have one external dimension in the nanoscale and the other two external dimensions significantly larger (typically by more than 3 times). In addition, the two larger dimensions significantly differ from each other. "Nanostrip" is preferable to "nanoribbon" and "nanotape" for superconducting sensors and detectors.

Note 3 to entry: An example of the superconducting nanowires is the strip with the dimensions of 10 nm × 30 nm × 10 µm. The difference between the thickness and width is approximately less than 3 times. That superconductor can be called "superconducting nanowire photon detector".

3.24
superconducting tunnel junction detector
type of superconducting device that uses the change of electron tunnelling between two superconductors or a superconductor and a normal conductor separated by tunnelling barrier because of measurand energy deposition

3.25
temperature sensitivity
superconducting transition edge steepness that is defined by $\mathrm{d}\ln R/\mathrm{d}\ln T$ where R is the resistance and T is the temperature of TES

3.26
transition edge sensor detector
type of superconducting device that uses the resistive change within a sharp normal-to-superconducting transition as a temperature sensor because of measurand energy deposition

4 Symbols

Units, graphical and letter symbols shall be taken from the following standards:

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- IEC 60027 (all parts);
- IEC 60417;
- IEC 60617;
- ISO 1000;
- ISO 7000.

Graphical symbols for use on equipment and diagrams, such as superconducting region, normal connection, superconducting connection, normal-superconducting boundary, Josephson junction, are defined in Annex C, and IEC 60417 and IEC 60617. Graphical symbols specific to other sensors or detectors are defined in other parts of IEC 61788.

5 Terminology and classification

5.1 Terminology

Table 1 lists the measurands which are defined as categories, objects, or physical quantities that induce enegy deposition and are to be sensed or detected by superconducting sensors and detectors. The measurands, arranged in alphabetical order, are: atoms and molecules, elementary particles, physical quantities, and radiations. Each entry in Table 1 not only represents the measurand itself, but also its temporal or spatial distribution.

Any other terminology peculiar to one of the devices covered by this document shall be taken from the relevant IEC or ISO standards.

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Table 1 – Measurands

Category	Object	Physical quantity
Atoms and molecules	Atoms	Count, energy, flux, time
	Organic molecules	Count, energy, flux, time
	Nonorganic molecules	Count, energy, flux, time
	Other (specify)	
Elementary particles	Dark matters	Count, energy, flux, time
	Electrons	Count, energy, flux, time
	Neutrinos	Count, energy, flux, time
	Neutrons	Count, energy, flux, time
	Photons	Count, energy, flux, time
	Protons	Count, energy, flux, time
	Positrons	Count, energy, flux, time
	Other (specify)	
Physical quantities	Capacitance	Amplitude
	Current	Amplitude
	Inductance	Amplitude
	Magnetic field	Strength, distribution
	Magnetic flux	Density, distribution
	Magnetic susceptibility	Amplitude
	Polarization	Amplitude
	Resistance	Amplitude
	Voltage	Amplitude
	Other (specify)	
Radiations	Alpha-particles	Count, energy, flux
	Beta-particles	Count, energy, flux
	Electromagnetic waves	Amplitude
	Gamma-rays	Count, energy, flux
	Optical radiation	Count, energy, flux
	X-rays	Count, energy, flux
	Other (specify)	

The objects for measurands fall into two classes: fields and physical quantities, and particles, as listed in Table 2. Based on these classes, detection mechanisms are classified into coherent detection for fields and physical quantities, and direct detection for particles.

Table 2 – Classification of measurands

Classification	Measurand category
Field and physical quantities	Physical quantities
	Radiations (electromagnetic waves)
Particles	Atoms and molecules
	Elementary particles
	Radiations (individual electromagnetic radiation quanta)

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Table 3 lists the various types of sensors and detectors (alphabetical order). The sensors and detectors convert measurands to electronic signals. The word "sensor" tends to be used for devices that measure fields and physical quantities, while the word "detector" tends to be used for devices that measure single particles. When naming sensors or detectors, the following word order should be used for nomenclature: device structure or function; measurand; and a word of detector, magnetometer, mixer, sensor, or other words. Examples of full names and corresponding acronyms are also listed.

Table 3 – Nomenclature of superconducting sensors and detectors: type, full names, and acronym examples

Type	Full names and acronym example
Metallic Magnetic Calorimetric (**MMC**) type	Metallic Magnetic Calorimetric α-ray Detector (**MMC** α-ray detector or **MMCAD**)
	Metallic Magnetic Calorimetric γ-ray Detector (**MMC** γ-ray detector or **MMCGD**)
	Metallic Magnetic Calorimetric X-ray Detector (**MMC** X-ray detector or **MMCXD**)
Microwave Kinetic Inductance (**MKI**) type	Microwave Kinetic Inductance Photon Detector (**MKI** photon detector or **MKIPD**)
	Microwave Kinetic Inductance X-ray Detector (**MKI** X-ray detector or **MKIXD**)
Superconducting Hot Electron Bolometric (**SHEB**) type	Superconducting Hot Electron Bolometric Photon Detector (**SHED** photon detector or **SHEBPD**)
	Superconducting Hot Electron Bolometric Terahertz Mixer (**SHEB** terahertz mixer or **SHEBTM**)
Superconducting Quantum Interference Device (**SQUID**) type	Superconducting Quantum Interference Device Amplifier (**SQUID** amplifier or **SQUIDA**)
	Superconducting Quantum Interference Device Current Sensor (**SQUID** current sensor or **SQUIDCS**)
	Superconducting Quantum Interference Device Gradiometer (**SQUID** gradiometer or **SQUIDG**)
	Superconducting Quantum Interference Device Magnetometer (**SQUID** magnetometer or **SQUIDM**)
	Superconducting Quantum Interference Filter Magnetometer (**SQIF** magnetometer of **SQIFM**)
	Superconducting Quantum Interference Device Array Magnetometer (**SQUID** array magnetometer or **SQUIDAM**)
Superconducting Strip (**SS**) type	Superconducting Strip Electron Detector (**SS** electron detector or **SSED**)
	Superconducting Strip Ion Detector (**SS** ion detector or **SSID**)
	Superconducting Strip Particle Detector (**SS** particle detector or **SSPD**)
	Superconducting Strip Photon Detector (**SS** photon detector or **SSPD**)

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Type	Full names and acronym example
	Superconducting NanoStrip Photon Detector (**SNS** photon detector of **SNSPD**)
Superconducting Tunnel Junction (**STJ**) type	Superconducting Tunnel Junction Ion Detector (**STJ** ion detector or **STJID**)
	Superconducting Tunnel Junction Terahertz Mixer (**STJ** terahertz mixer or **STJTM**)
	Superconducting Tunnel Junction Photon Detector (**STJ** photon detector or **STJPD**)
	Superconducting Tunnel Junction X-ray Detector (**STJ** X-ray detector or **STJXD**)
	Superconductor Insulator Superconductor Terahertz Mixer (**SIS** terahertz mixer or **SISTM** that is equivalent to **STJTM**)
	Superconductor Normal-conductor Superconductor Mixer (**SNS** mixer or **SNSM**)
Transition Edge Sensor (**TES**) type	Transition Edge Sensor α-ray Detector (**TES** α-ray detector or **TESAD**)
	Transition Edge Sensor γ-ray Detector (**TES** γ-ray detector or **TESGD**)
	Transition Edge Sensor Photon Detector (**TES** photon detector or **TESPD**)
	Transition Edge Sensor X-ray detector (**TES** X-ray detector or **TESXD**)
Other	Specify

NOTE The nomenclature has the word order of (device structure or function) – (a measurand) – (a word of detector, magnetometer, mixer, sensor, or other words). The term "nanowire" can be used only for a special case that superconducting strips have two external dimensions in the nanoscale that is approximately 1 nm to 100 nm; the difference between the first and second external dimensions is typically less than 3 times; and the third dimension significantly larger: for example a nanowire with 10 nm × 30 nm × 1 µm. In IEC 61788-22, it is called "nanostrip" or "strip" because of a difference of considerably larger than 3 times in most cases, although nanotape or nanoribbon is possible. See also the ISO Online browsing platform: available at https://www.iso.org/obp/ui#home.

5.2 Classification

The operation of the sensors and detectors is classified into two categories: coherent detection and direct detection (Table 4). The devices used in the category of coherent detection include bolometers, sensors or mixers, while the devices used in the category of direct detection include calorimeters or detectors. For operating principles, see Annex A (coherent detection) and Annex B (direct detection).

Table 4 – Classification of detection principles

Detection principle	Type
Coherent detection for fields and physical quantities	SHEB, SQUID, STJ
Direct detection for particles	MMC, MKI, SS, STJ, TES

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It should be noted that direct detectors have a sensitivity for single particles, and they can also measure a flux of particles. The issue is a difference between time response of superconducting devices and time interval of energy absorption of individual particles. For the superconducting sensors and detectors that use temperature rise because of measurand energy absorption, they are called "bolometer" or "calorimeter" depending on the time response. When the interval of absorption events is much shorter than the time response, the term "bolometer" is appropriate for flux measurement. On the other hand, when it is much longer than the time response, the term "calorimeter" is appropriate for particle counting.

6 Cryogenic operation condition

The superconducting sensors and detectors operate in cryogenic temperatures lower than T_c or the middle of normal-superconducting transition in order to hold a superconducting state or to use a sharp normal-superconducting transition for sensing or detecting measurands. The operation temperature range depends on the types. Specific cryogenic operation condition for each sensor or detector should be described in other parts of IEC 61788-22 for various types of sensors and detectors.

The cryogenic temperature can be obtained by liquid helium or other cryogens, Gifford-McMahon (GM) coolers, pulse tube coolers, adiabatic demagnetization refrigerators (ADR), ^{3}He refrigerators, ^{4}He-^{3}He dilution refrigerators, and other cryocoolers.

Performance of sensors and detectors is influenced by both cryogenic environment and implementation. The cryogenic environment and implementation should be specified in a standard for each sensor or detector and other separate standards.

7 Marking

7.1 Device identification

The marking on the device or on the packing shall enable clear identification of the device. The device shall be provided with a traceability code which enables back-tracing of the device to a certain production or inspection lot.

7.2 Packing

Marking on the packing shall state the following:

a) the device identification code;

b) the measurand, type, name, detection principle, and other informative information in Tables 1, 2, 3, and 4;

c) the number of enclosed devices;

d) the operating temperature range;

e) the additional specification;

f) the required precautions, if any.

8 Test and measurement procedures

The test and measurement methods should be described in a standard for each sensor or detector and other separate standards.

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Annex A
(informative)

Coherent detection

A.1 Superconducting hot electron bolometric (SHEB) type

The SHEB type enables detection of sub-millimetre and far-IR radiation (0,3 THz to 10 THz). SHEBs are more often used as indirect (i.e. coherent or mixing) detectors, although direct detection is possible. In mixers, the electromagnetic field of the signal photons (ω_s) is mixed with a locally generated electromagnetic field at ω_0 frequency (called the local oscillator, LO). The result is a signal at the difference, or intermediate frequency, ω_{IF}, where $\omega_{IF} = \omega_0 - \omega_s$. The original signal in the sub-millimetre band is therefore down-converted into the microwave band, where more conventional low-noise electronics can amplify and process the signal. A SHEB is composed by a superconducting microbridge with nanometre or submicron dimensions, contacted by thick metallic pads. Sub-millimetre radiation signals are coupled into the microbridge through a lens and an on-chip antenna. The heterodyne mixing process makes use of the resistive transition between the superconducting state and the normal state of the superconducting bridge, induced by the heating of radiation signals. This transition produces a hot-spot. Two types of hot-spot relaxation are used as a detection mechanism: in the diffusion cooled SHEB the hot electrons diffuse to the surrounding thermal reservoir, while in the phonon cooled SHEB, the hot electrons are cooled through fast electron–phonon interaction.

Bolometers are electronic devices that convert measurands into heat, which can then be detected by a thermometer. Although conventional bolometers usually have antenna-shaped absorber, thermometer, heat sink, and thermal link as separate elements, in the SHEB type these various elements are combined. The thermal resistance $R = 1/G$ with the thermal conductance G provides the coefficient linking incident power P and change in temperature ΔT, such that $\Delta T = PR$. An important consideration in designing bolometers is the time taken for it to recover, given by $\tau = RC$, where C is the heat capacity. In SHEB, at a low temperature, the electron system in materials becomes decoupled from the phonon system, leading to a large R, while C of the electrons becomes small and proportional to T.

From the physics of device operation, the SHEB type can be categorized as a kind of TES. In general TES, temperature of both lattice and electron increase due to the incident photon or electromagnetic wave, while only the electron temperature does for SHEB type. Since the heat capacity C of the electron is not bigger than C of the lattice except for extremely low temperature, SHEB type can respond more quickly to the incident signal than general TES.

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