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VII. Reference material

VII-1: Appendix – Terminology for superconducting materials

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The terminology defined below is intended to provide engineers in the field of superconductivity-related technologies with a common base of understanding of superconducting materials and some areas of their application.

Contents

1. Fundamentals

1-1. General

Composition:
the quantity of each of the components of a mixture: usually expressed in terms of the weight percentage, or the atomic percentage of each of the components in the mixture.

Current density, J:
current per unit area.

Diamagnetism:
magnetism where the field inside a substance is less than the field in which it is situated. In this case the magnetic susceptibility K is negative.

Magnetic susceptibility, χ:
the ratio of magnetization M to the field H producing it. That is $\chi = M/H$.

Magnetization, M:
magnetic moment per unit volume in a magnetic material, expressed in amperes per metre. Magnetization in a superconductor occurs due to the distribution of shielding currents.

Magnetic polarization:
same as magnetization, expressed in teslas or webers per square metre.

Demagnetization factor (demagnetizing factor):
the ratio of the average demagnetizing field to the average magnetization in a magnetic or superconducting material of finite size. The demagnetizing field may be thought of as arising from surface magnetic poles.

Diamagnetic material:
a material whose susceptibility is negative.

Magnetic induction, B:
synonymous with magnetic flux density or magnetic flux

per unit area. The magnetic induction B is given as $B = \mu_0(H + M) = \mu H$, where H is magnetic field, M magnetization, μ_0 magnetic permeability of a vacuum and μ magnetic permeability. B is a magnetic vector quantity which at any point in a magnetic field is measured either by the mechanical force experienced by an element of electric current at the point, or by the electromotive force induced by an elementary loop during any change in flux linkages with the loop at the point

Magnetic flux, Φ:
the product of the magnetic induction B through a surface and the area of the surface A. When the magnetic induction B is uniformly distributed and directed normal to the surface: $\Phi = B \times A$.

Magnetic flux density, B:
magnetic flux per unit area, identical to magnetic induction.

Magnetic field strength, H:
the measured intensity of a magnetic field at a point; can be defined from the magnetic field $H = 2\pi I/R$ at the centre of a circular loop of current I and radius R. The units are amperes per metre. It can be similarly defined as the field $H = I/2\pi r$ at a distance r from a very long straight wire carrying a current I.

Temperature, T:
the thermal state of matter as measured on a definite scale.

Absolute temperature:
(1) temperature measured on the thermodynamic scale, designated as kelvins (K); (2) temperature measured from absolute zero (−277.15°C or −459.67°F). The numerical values are the same for both the kelvin scale and the ideal gas scale.

Electric conductivity, σ:
the ratio of the current density to the potential gradient paralleling the current in a material. This is numerically equal to the conductance between opposite faces of a unit cube of the material. It is the reciprocal of resistivity.

Residual resistivity:
finite electric resistivity remaining at absolute zero temperature.

Skin effect:
an effect in which the intensity of an applied a.c. electric or magnetic field of angular frequency ω falls off exponentially with depth from the surface of a substance. It is characterized by a skin depth $\delta = (2/\mu\sigma\omega)^{1/2}$ at which the field intensity is reduced to 1/e of its value at the surface, where μ = magnetic permeability and σ = electric conductivity.

Supercritical helium:
^{4}He which is above a critical temperature T_c (5.22 K) and a critical pressure P_c (0.227 MPa).

Superfluidic helium:
helium exhibiting superfluidity which appears in the temperature–pressure diagram of helium within the region bounded by a tie-line connecting the λ point for saturated helium (2.18 K, 5 kPa) with the upper limit of the λ line of helium (1.76 K, 2.77 MPa).

1-2. Specific

Superconductive:
adjective describing a material exhibiting the characteristics of normal conductivity, but which shows superconductivity under appropriate conditions.

Superconducting:
adjective describing a material exhibiting superconductivity.

Superconductivity:
a property of many elements, alloys and compounds by virtue of which their electrical resistivity vanishes and they become strongly diamagnetic under appropriate conditions.

Superconducting state:
the thermodynamic state in which the material exhibits superconductivity.

Normal (conducting) state:
the thermodynamic state in which a superconducting material no longer exhibits any of the characteristics of the superconducting state.

Superconducting transition:
the combination of values of temperature T, electric current density J and magnetic field H at which a transition from the superconducting to the normal state takes place.

Perfect diamagnetism:
magnetism with a susceptibility equal to −1, exhibited by a type I superconductor below the critical magnetic field H_c, and a type II superconductor below the lower critical field H_{c1}. The bulk of a superconductor exhibiting perfect diamagnetism is shielded from magnetic fields.

Meissner effect:
the expulsion of magnetic flux from a superconductor as it enters the superconducting state.

Persistent current:
current flowing through a closed, superconducting loop circuit exhibiting no decay with time.

BCS theory:
a theory on superconductivity stating that the superconducting state is realized by the formation of Cooper pairs of electrons in the vicinity of Fermi level through lattic distortions, that is phonons.

Cooper pair:
pair of electrons, reverse to each other in wave number (momentum) vector and direction of spin. Cooper-paired electrons are free from lattice scattering, thus moving without loss in energy.

Superconducting energy gap, Δ:
one half of the minimum value of energy necessary for destroying a Cooper pair and exciting the two electrons to the normal state. In BCS theory this is given for absol-

ute zero temperature as follows: $\Delta = 1.764\,kT_c$, where k = Boltzmann's constant and T_c = critical temperature.

Superconducting condensation energy, δG:
energy necessary for converting a superconductor from the superconducting to the normal state, given as follows: $\delta G = G_N(0)-G_S(0) = (1/2)N(0)\Delta^2(0)$, where: $G_N(0)$ = free energy density of the normal conducting states under zero magnetic field; $G_S(0)$ = free energy density of the superconducting states under zero magnetic field; $N(0)$ = density of electron state at Fermi level; and $\Delta(0)$ = energy gap at absolute zero temperature.

Isotope effect:
a relation, deduced from BCS theory, that the critical temperature is inversely proportional to the square root of the atomic weight of component elements in a superconductor.

Josephson effect:
an effect in which superconducting, tunnelling current flows through a thin insulating layer separating two superconducting regions.

Josephson junction:
a device composed of a thin insulating layer separating two superconducting regions.

Ginzburg–Landau (GL) theory:
a thermodynamic theory deduced from BCS theory and interpreting magnetic properties of type II superconductors.

Type I superconductor:
a superconductor in which superconductivity with perfect diamagnetism appears below the critical magnetic field H_c but disappears above H_c.

Type II superconductor:
a superconductor in which superconductivity appears with perfect diamagnetism up to the lower critical magnetic field H_{c1} persists in a mixed state for the magnetic field range between H_{c1} and the upper critical field H_{c2} and disappears above H_{c2}.

Ginzburg–Landau (GL) parameter, κ:
the ratio of penetration depth λ to coherence length, ξ: $\kappa = \lambda/\xi$. A superconductor belongs to type I when $\kappa < 1/\sqrt{2}$, and to type II when $\kappa > 1/\sqrt{2}$.

Mixed state:
a state of coexistence of superconducting and normal conducting regions in the bulk of a type II superconductor placed in a magnetic field between the lower and the upper critical fields.

Intermediate state:
a state of coexistence of superconducting and normal conducting regions in the bulk of a superconductor with finite demagnetizing factor placed in a magnetic field below the critical field.

Order parameter:
thermodynamic quantity defined in GL theory, a measure for the density of Cooper-paired electrons, and roughly proportional to the superconducting energy gap.

Coherence length, ξ:
(1) temperature independent quantity, defined in BCS theory, describing the spatial spread of Cooper-paired electrons; (2) quantity, defined in GL theory, describing the spatial variation of order parameters and varying with temperature as follows: $\xi(T) = (\Phi_0/2\mu_0 H_{c2})^{1/2}$, where Φ_0 = flux quantum and H_{c2} = upper critical field (strength).

Penetration depth, λ:
the penetration depth of magnetic field in a superconductor that exhibits perfect diamagnetism.

Magnetic flux quantum, Φ_0:
the unit or the minimum quantity of magnetic flux distributing within a superconductor or its ring: $\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb, where h = Planck's constant = 6.6262×10^{-34} J s and e = charge of an electron = 1.60219×10^{-19} C.

Fluxoid (fluxon):
quantized magnetic flux lines distributing within a type II superconductor with the unit quantity of magnetic flux quantum Φ_0 and a radius of coherence length λ.

Surface superconductivity:
superconductivity concerned with the surface layer region of about the coherence length in depth and persisting beyond the upper critical field H_{c2} up to a magnetic field which is termed $H_{c3} = 1.69H_{c2}$.

Internal susceptibility:
dM/dH_i, where M is the magnetization and H_i is the internal field (corrected for demagnetizing factor).

External susceptibility:
dM/dH_a, where M is the magnetization and H_a is the applied field (not corrected for demagnetizing factor).

Proximity effect:
penetration of superconducting electrons into normal conducting regions adjacent to superconducting regions.

Stress effect/strain effect:
a change of superconducting properties due to a mechanical or electromagnetic stress/strain imposed on a superconductor.

Lorentz force, F:
electromagnetic force working on electrons moving in a magnetic field, with a direction perpendicular to both electron motion and magnetic field directions, and given as follows: $F = J \times B$, where F = Lorentz force per unit volume, J = current density and B = magnetic flux density. In the case of a superconductor, the Lorentz force works so as to move fluxoids pinned in the superconductor in a direction perpendicular to both the transport current and the applied magnetic field.

Residual resistivity ratio:
the ratio of the electric resistivity at 273 K to that at 4.2 K for a normal conducting metal. For a superconductor this is usually the ratio of the electric resistivity at

273 K to that at a temperature just above the critical temperature T_c.

Persistent current switch:
a thermal, magnetic or mechanical switch to cut off the power supply from a superconducting electric loop circuit which is then operated in a persistent current mode.

Magnetic shielding:
a shielding of magnetic field by using materials of high permeability or superconducting materials.

SQUID:
abbreviation for 'superconducting quantum interference device', to detect extremely weak magnetic fields using Josephson effect.

1-3. Critical parameters

Critical temperature, T_c:
the maximum temperature below which a superconductor exhibits superconductivity at zero magnetic field and current.

Transition temperature:
the maximum temperature below which a superconductor exhibits superconductivity at a given magnetic field and current.

Critical magnetic field (strength), H_c:
the maximum magnetic field below which a superconductor exhibits superconductivity at zero current and temperature. In practice it often means the upper critical field H_{c2}.

Lower critical magnetic field (strength), H_{c1}:
the magnetic field strength where Meissner effect is destroyed and magnetic fluxes start to penetrate into the bulk of a type II superconductor. H_{c1} is given as follows: $H_{c1} = (\ln\kappa + 0.081)H_c/\sqrt{2}\kappa$, where κ = Ginzburg–Landau parameter.

Upper critical magnetic field (strength), H_{C2}
the magnetic field strength where the mixed state is destroyed and transition to the normal state occurs in a type II superconductor. H_{C2} is given as follows: $H_{C2} = \sqrt{2}\kappa H_c$, where κ = Ginzburg–Landau parameter.

Thermodynamic critical magnetic field (strength), H_{cth}:
the magnetic field strength which is defined for type II superconductors as follows: $\delta G = \mu_0 H_{cth}^2/2$, where δG = superconducting condensation energy and μ_0 = magnetic permeability in vacuum. H_{cth} corresponds to H_c in the case of type I superconductors.

Critical current, I_c:
the maximum electrical current below which a superconductor exhibits superconductivity at some given temperature and magnetic field. The critical current is usually defined by means of a resistivity or an electric field criterion.

Critical current density, J_c:
the critical current divided by the cross-sectional area of the superconductor.

1-4. Pinning

Magnetic flux pinning:
the trapping of fluxoids at defects in the superconducting material.

Pinning centre:
a defect in a superconductor at which penetrating fluxoids are pinned. Defects which act as pinning centres include various lattice defects, precipitates and grain boundaries, etc.

Pinning force:
the force that pins fluxoids at pinning centres.

Pinning force density, F_p:
pinning force per unit volume of a pinning centre, given as the product of the critical current density and the corresponding magnetic flux density: $F_p = J_c \times B$.

Scaling law for pinning force density:
an empirical law for describing the dependence of the pinning force density F_p on temperature and magnetic field. It is expressed as follows: $F_p = K[B_{c2}(T)]^m b^p (1-b)^q$, where: K, m, p, q = constants; $B_{c2}(T)$ = upper critical magnetic flux density at a temperature T; and $b = B/B_{c2}(T)$ = normalized magnetic flux density.

Kramer's law:
the scaling law for pinning force density proposed by E.J. Kramer. It fairly well describes the pinning behaviour of Nb_3Sn at higher fields and is expressed as follows: $F_p = K[B_{c2}(T)]^m b^{1/2}(1-b)^2$, where: K, m = constants; $B_{c2}(T)$ = upper critical magnetic flux density at a temperature T; and $b = B/B_{c2}(T)$ = normalized magnetic flux density.

Surface pinning:
a magnetic flux pinning by which magnetic fluxoids are pinned at the interfaces between the superconducting filaments and the matrix in a multifilamentary conductor.

Peak effect:
an effect in which a critical current *versus* magnetic field curve exhibits a peak near the upper critical field.

Magnetic flux flow:
a phenomenon in which fluxoids in a superconductor move when the Lorentz force exceeds the pinning force.

Magnetic flux creep:
a phenomenon in which fluxoids pinned in a superconductor move due to thermal activation.

Critical state model:
a model for the magnetization process in type II superconductors stating that the magnetic flux density in a superconductor varies from the surface to the centre with a gradient equal to the critical current density.

Bean–London (critical state) model:
a critical state model, proposed by Bean and London, for the magnetization process in type II superconductors assuming that the critical current density is constant with respect to the magnetic field. This model may be applied to a narrow range of magnetic fields.

Kim (critical state) model:
a critical state model, proposed by Kim, Hempstead and Strnad for the magnetization process in type II superconductors which assumes that the critical current density is inversely proportional to the internal field: $J_c = \alpha(\text{constant})/(B + B_0)$: B_0 = constant. This model may be applicable to lower fields.

Trapped (magnetic) flux:
the magnetic flux retained in a superconductor when the applied magnetic field is reduced to zero.

1-5. A.c. loss

A.c. loss (transient loss):
an energy loss arising when a superconductor is used in an alternating magnetic field. According to its origin, it may be classified into three; hysteresis loss, coupling loss and eddy current loss.

Hysteresis loss (pinning loss):
an a.c. loss caused by the movement of fluxoids pinned in a superconductor in an alternating magnetic field.

Eddy current loss:
an a.c. loss caused by the Joule-type heating of eddy current which arises in the normal conducting component of a superconducting wire, cable, etc. in an alternating or pulsed magnetic field.

Coupling loss:
an a.c. loss caused by the Joule type heating of coupling current. The coupling loss is often referred to as eddy current loss.

Coupling current:
a current flowing, in an alternating or pulsed magnetic field, between superconducting filaments or strands separated by normal conducting materials.

Transport current loss:
an a.c. loss due to a transport current in combined action with an a.c. magnetic field or due to an a.c. transport current.

Coupling time constant:
a time interval for which a coupling current caused by an alternating or pulsed magnetic field decays, proportional to the square of the twist pitch and inversely proportional to the matrix resistivity in the direction perpendicular to the filament axis.

Magnetic flux jump:
the collective, discontinuous motion of fluxoids in a superconductor, produced by mechanical, thermal, magnetic or electrical disturbances.

Electromagnetic stability:
see flux-jump stabilization.

2. Conductors

2-1. Superconductive materials

Superconductor:
a material that exhibits superconductivity under appropriate conditions.

Alloy superconductor:
an alloy which exhibits superconductivity under appropriate conditions.

Compound superconductor:
a compound which exhibits superconductivity under appropriate conditions.

Oxide superconductor:
an oxide which exhibits superconductivity under appropriate conditions.

Organic superconductor:
an organic material which exhibits superconductivity under appropriate conditions.

A-15 compound:
a generic term for intermetallic compounds with a composition of A_3B, where B atoms form a body-centred cubic lattice and A atoms form a one-dimensional chain in the x, y and z directions in the cubic lattice. Superconductive materials such as Nb_3Sn, V_3Ga and Nb_3Al are of this type of crystal structure.

B-1 compound:
a generic term for transient metallic carbides, nitrides, and oxides with a NaCl type of crystal structure. Superconductive materials such as NbN, NbC and MoN are known to be of this type of crystal structure.

Laves phase compound:
a generic term for intermetallic compounds with a composition of AB_2. Typical superconductive materials of this type of crystal structure include HfV_2 and ZrV_2.

Chevrel phase compound:
a generic term for compounds with a typical composition of MMo_6X_8 where M refers to metallic elements from monovalent to quadrivalent ones such as Pb, Sn, Cu and La, while X corresponds to chalcogen elements such as S, Se and Te.

Layered perovskite compound:
a generic term for oxide compounds with a typical composition of ABO_3 where A and B refer to metallic elements, while O is oxygen. The oxygen ions form an octahedral structure, B ions entering each centre of the octahedrons and A ions entering a space built by eight octahedrons. Depending on the oxygen content, a variety of lattice stacking faults are introduced, resulting in a variety of modifications of the original crystal structure. Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O are known to be of this group of crystal structure and become superconducting above liquid nitrogen temperature.

2-2. Conductors

2-2-1. Conductor components

Conductor:
a wire or combination of wires suitable for carrying an electrical current.

Wire:
a rod or filament of drawn or rolled metal whose length is great in comparison with the major axis of its cross section.

Component:
an individual piece or a sub-assembly of individual pieces.

Filament (elementary filament):
a thin, elongated core of superconductive material contained in a composite conductor through which superconducting current flows.

Matrix (of composite superconductor):
the continuous longitudinal phase of a pure metal, a poly phase alloy, or mechanical mixture that is not in the superconducting state at the normal operating conditions of the embedded superconductor.

Mixed matrix (of composite superconductor):
matrix composed of more than one component.

Core:
a component of a composite conductor which is surrounded usually by matrix which is another component of the composite.

Matrix to superconductor volume ratio:
the volume ratio of the matrix to the superconductor in a composite conductor.

Copper to superconductor volume ratio:
the volume ratio of the copper to the superconductor in a composite conductor.

Volume per cent superconductor:
that percentage by volume of a composite superconductor which is superconducting under appropriate conditions.

Stabilizer:
a metal, but not necessarily the matrix, in electrical contact with a superconductor, to act as an electric shunt in the event that the superconductor reverts to the normal state.

Barrier:
any material limiting passage through itself of solids, liquids, semisolids, gases or forms of energy such as ultraviolet light.

Reinforcing member:
a structural material incorporated in a composite conductor for mechanical reinforcement.

2-2-2. Conductor structures

Strand:
one of the wires of any stranded conductor.

Stranded conductor:
a conductor composed of a group of wires, usually twisted together, or of any combination of such groups of wires.

Braid:
a narrow tubular or flat fabric produced by intertwining strands of materials according to a definite pattern.

Twist:
the number of turns per unit length made by a filament or strand about a conductor axis.

Twist pitch:
the length in which a filament or strand returns to its original relative position in a twisted conductor.

Transposition length:
the length in which a filament or strand returns to its original relative position in a transposed conductor.

Aspect ratio:
ratio of the longer to the shorter transverse dimensions of a rectangular composite superconductor.

2-2-3. Composite superconductors

Composite superconductor:
a conductor incorporating superconductive material. There exist several types of composite superconductors including filamentary, coreless, tape, tubular and hollow conductors.

Filamentary (multifilamentary) conductor:
a composite superconductor consisting of more than one superconductive filament embedded in a matrix.

Composite conductor:
a conductor consisting of two or more types of material, each type of material being plain, clad or coated, and asssembled together to operate mechanically and electrically as a single conductor.

Transposed conductor:
a composite conductor in which filaments or strands are plaited together to occupy different relative positions about the conductor axis in a regular manner along its length.

Monolithic conductor:
a composite conductor containing superconductor and stabilizer material, and possibly reinforcement and insulating materials, contiguously assembled with one another to form a solid structure that allows no relative motions of the components.

Three component conductor:
a composite superconductor composed of a superconductor and two different matrices. An example of this type of conductor is a NbTi based conductor with copper and

cupro-nickel matrices, the former being for thermal stabilization and the latter for coupling loss reduction.

Twisted conductor:
a composite conductor in which the filaments or strands spiral about the conductor axis.

Cable-in-conduit conductor:
a composite conductor consisting of a cable inside a metal conduit. The conduit is a disturbed mechanical structure that decreases the stress on the cable and also allows forced-flow cooling of the cable to improve the thermal stability of the conductor.

Coreless conductor:
a conductor constructed with one or more layers of helically laid wires and formed into final shape by rolling, drawing or other means.

Hollow conductor (tubular conductor):
a conductor in which the individual elements are disposed about one or more hollow passages, the direction of which is along the axial length of the conductor.

Tubular conductor:
a conductor constructed in the form of a tube.

Tape conductor:
a conductor constructed in the form of a flat ribbon or strip.

2-2-4. Cable conductors

Cable (concentric lay conductor):
a conductor constructed with a central core surrounded by one or more layers of helically laid wires. There exist several types of cables including compact round, conventional concentric, equilay, parallel core, rope-lay, unidirectional and unilay.

Compact round conductor:
a conductor constructed with a central core surrounded by one or more layers of helically laid wires and formed into final shape by rolling, drawing or other means.

Compact stranded conductor:
a conductor composed of helically laid monolithic or stranded wires and formed into a final plate-like shape by rolling, drawing or other means.

Keystone stranded conductor:
a kind of compact stranded conductor with a final shape of trapezoid.

Conventional concentric conductor:
conductor constructed with a round central core surrounded by one or more layers of helically laid round wires. The direction of lay is reversed in successive layers, and generally with an increase in length of lay for successive layers.

Equilay conductor:
conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common length of lay, direction of lay being reversed in successive layers.

Parallel core conductor:
conductor constructed with a central core of parallel-laid wires surrounded by one layer of helically laid wires.

Rope-lay conductor:
conductor constructed of a bunch-stranded or a concentric-stranded member or members as a central core, around which are laid one or more helical layers of such members.

Unidirectional conductor:
conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common direction of lay, with increase in length of lay for each successive layer.

Unilay conductor:
conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common length and direction of lay.

2-3. Fabrication processes

Surface diffusion process:
a fabrication process for compound superconductors such as V_3Ga and Nb_3Sn, where a tape of V or Nb is dipped in a Ga or Sn bath, pulled out and heat treated at a high temperature to form V_3Ga or Nb_3Sn. A second option is to hold the bath at the reaction temperature so that the V_3Ga or Nb_3Sn are formed during immersion.

Composite diffusion process:
a fabrication process for composite conductors, where members of the composite are cold-worked together into a final shape with or without intermediate anneals, and subjected to heat treatment based on solid state diffusion among the members of the composite to form a desired superconductive phase or an appropriate microstructure containing a superconductive phase with normal conducting phases.

Bronze process:
a composite diffusion process typically for Nb_3Sn and V_3Ga composite conductors, where the matrix of Cu-Sn or Cu-Ga bronze containing Nb or V cores is cold-worked into a final shape of the conductor and heat-treated to form a Nb_3Sn or V_3Ga layer at the interfaces between the matrix and the cores.

In situ process:
a fabrication process typically for Nb_3Sn and V_3Ga conductors, where a Cu-Nb or Cu-V alloy ingot containing Nb or V fine dendrites dispersed in the Cu matrix is cold-worked into a final shape. It is then coated with Sn or Ga and subjected to heat treatment which first disperse the Sn or Ga throughout the matrix and then form a Nb_3Sn or V_3Ga layer at the interfaces between the Cu matrix and the discrete, elongated Nb or V dendrites.

Powder metallurgy process:
a fabrication process for compound conductors, where powders of component elements of a desired supercon-

ductive compound and a matrix material such as Cu are mixed, compacted and cold-worked into a final shape of tape or wire which is then subjected to heat treatment to form the desired compound layer at the surface of the discrete, elongated powders. For example, powders of Nb, Sn and Cu are used for Nb_3Sn conductors, and Nb, Al and Cu for Nb_3Al conductors.

External diffusion process:
a fabrication process typically for Nb_3Sn and V_3Ga composite conductors, where a Cu jacket with drilled holes containing Nb or V rods is cold-worked into a final shape, coated on the surface with Sn or Ga and subjected to heat treatment firstly to diffuse the Sn or Ga into the matrix and then to form a Nb_3Sn or V_3Ga layer at the interfaces between the Cu matrix and the Nb or V cores.

Tube process:
a fabrication process typically for Nb_3Sn composite conductors, where a Cu tube containing Sn bars is inserted into a Nb tube which is then further inserted in a Cu tube to form a basic composite. The basic composites are inserted into a larger Cu tube, cold-worked into a final shape and subjected to heat treatment firstly to diffuse the Sn into the matrix and then to form a Nb_3Sn layer at the interfaces between the Cu and the Nb tubes.

Internal tin process:
a fabrication process typically for Nb_3Sn composite conductors, where a Cu jacket containing a Sn rod in a hole drilled in its centre and Nb rods in holes drilled in the remaining area is cold-worked into a final shape and subjected to heat treatment firstly to diffuse the Sn into the matrix and then to form a Nb_3Sn layer at the surfaces of the Nb cores.

Jelly roll process:
a fabrication process typically for Nb_3Sn conductors, where a foil of Cu-Sn bronze and a foil of Nb with slit meshes are lapped and spirally rolled into a cylinder, then cold-worked to a final shape, and subjected to heat treatment to form Nb_3Sn at the interfaces between the Cu-Sn and the Nb.

Two stage extrusion process:
a fabrication process for NbTi conductors, where a composite containing NbTi filaments and made using an extrusion, is divided into lengths which are put together side by side in a can and then extruded for a second time.

Three stage extrusion process:
a fabrication process for NbTi conductors, where a composite made by a two stage extrusion is again divided into lengths which are again put together side by side in a can and then extruded for a third time.

3. Magnets and coils

Coil:
a helically wound wire, strand or cable.

Magnet:
a device to generate magnetic fields using one or more coils.

Superconducting magnet:
a magnet using superconducting wire in its coil(s).

Solenoid coil:
a coil helically wound around an axis using a conductor wire, strand or cable to generate a more or less uniform magnetic field.

Pancake coil:
a flat whirlpool coil wound in a shape of thin-sliced pancake.

Double pancake coil:
a pair of pancake coils so connected with each other as to have their conductor ends appear at the outer circumference of the coil. A magnet is constructed by stacking double pancake coils connected in a series at their respective outer circumferences.

Split pair coil:
a pair of solenoid coils with a common axis but split by some gap distance between them.

Helmholtz coil:
a kind of split pair coil with a common radius and number of turns, and a separation gap distance which is identical with the common coil radius.

Dipole coil:
a coil to generate a magnetic field with dipolar components in one direction.

Quadrupole coil:
a coil consisting of four saddle coils arranged in a quadraxis symmetry to generate a magnetic field with quadrupolar components.

Saddle coil:
a coil wound with a shape of a saddle to generate a magnetic field in a direction perpendicular to the coil axis.

Shim coil:
a coil to compensate the inhomogeneity of a magnetic field occurring in the core region of the field.

Impregnated coil:
a coil impregnated with appropriate resin to improve mechanical stability and electrical insulation within the magnet structure.

Toroidal magnet:
a closed winding constructed such that the planes of individual equispaced turns or winding sections lie along the radii of a cylinder whose axis is outside the turns or sections. Also a line joining the centres of the turns or sections forms a closed circle with its centre on the axis of the cylinder. The solid shape thus formed is a toroidal or torus. The best known examples are the windings used to generate the steady field required for plasma confinement in a tokamak fusion reactor.

Poloidal magnet:
a pulsed field magnet used in a tokamak fusion reactor to generate a field perpendicular to the toroidal field. The poloidal field is used to heat the plasma and to maintain

stability of confinement. The axis of the coils of such a magnet is coincident with that of the torus.

Pulse magnet:
a magnet to generate a pulsed magnetic field.

Hybrid magnet:
a magnet consisting of a different kinds of magnets including normal conducting and/or superconducting magnets.

React and wind method:
a fabrication method for a superconducting coil, where a conductor containing component elements of a required superconductor is wound into a coil after having been heat treated to form the superconductor.

Wind and react method:
a fabrication method for a superconducting coil, where a conductor containing component elements of a required superconductor is wound into a coil and subsequently heat treated to form the superconductor.

Vacuum impregnation:
a fixing method for a superconducting coil against mechanical or electromagnetic forces, where a coil is impregnated with epoxy resin in vacuum so that the epoxy resin can infiltrate into the smallest recesses of the winding and no air bubbles remain.

Spacer:
a component inserted between two neighbouring components to prevent their contact.

Cooling channel:
a gap or a groove for the flow of liquid helium which is fed there to cool the superconducting magnet or conductor.

4. Cryotechnology

4-1. Cooling

Pool cooling:
a cooling method for superconducting magnets or conductors by directly immersing them in liquid helium.

Forced cooling:
a cooling method for superconducting magnets or conductors by forced flow of liquid helium through cooling channels.

Pressurized superfluidic helium:
superfluidic helium pressurized above 0.1 MPa.

Nucleate boiling:
a phenomenon in which the rate of cooling becomes large to cause the formation and detachment of bubbles of vapour at the cooled surface. As the rate of cooling is further increased nucleate boiling gives way to film boiling.

Film boiling:
a phenomenon in which the surface of a material being cooled is completely covered with a film of vaporized coolant.

Cryostat:
a vessel to keep a material or a device at low temperatures within it.

4-2. Stabilization

Quench:
the abrupt and uncontrolled loss of superconductivity produced by a disturbance.

Training effect:
an effect whereby, on first energization of a conductor or winding, a quench occurs before the critical current is reached. Similar quenches occur on subsequent energizations but the current at quench progressively increases until a plateau is reached.

Normal zone:
a region in a conductor or winding in which the superconductor has transformed to normal state.

Normal zone propagating velocity:
the velocity at which the envelope of a normal zone advances along a conductor or through a winding during a quench. This velocity is usually different in the three directions at right angles in a winding so that the normal zone is ellipsoidal until it encounters a winding boundary.

Rapid quench:
a design concept in which the normal zone propagation velocity perpendicular to the conductor is artificially enhanced. By this means the winding is protected from burnout because the stored energy is dissipated more uniformly through the winding but, since the normal zone is growing more rapidly, the quench is also more rapid.

Stabilization:
a design concept in which quenching is prevented.

Stable (stability):
a superconducting device in stable, if it retains its operating characteristics after it has been subjected to a disturbance.

Full stabilization:
a design concept in which the amount of high conductivity material included in a composite superconductor and the level of cooling provided are such that should the superconducting component quench, thus diverting all the current into the normal material, the temperature of the composite will remain below the critical temperature of the superconducting component. In these circumstances the temperature of the superconducting component will always recover to its original level and the current will then transfer back.

Steckley's stability criterion:
a superconducting magnet stability criterion which states that a superconducting magnet is in a stable condition if the heat evolved in the normal conducting metal on quench is less than that taken off from the surface of the

metal by the coolant: thermal conduction is taken into consideration essentially only for the direction perpendicular to the superconductor.

Maddock's stability criterion:
a modification of Steckley's stability criterion which also takes into account the thermal conduction along the superconductor length, resulting in the reduction in amount of the normal conducting metal surrounding the superconductor.

Adiabatic stabilization:
a superconducting magnet design concept to avoid magnetic instability by making superconducting filaments sufficiently thin.

Minimum propagation zone (MPZ) theory:
a superconducting magnet stabilization theory which defines magnet cooling conditions for not propagating the normal zone and not quenching the magnet, by estimating the magnitude of localized disturbance in the superconductor.

Dynamic stabilization:
flux jumps occur when the rate of energy dissipation during a disturbance involving the rearrangement of magnetic flux is greater than the rate of cooling. They can therefore be prevented by slowing down the rate of flux motion or by increasing the rate of cooling. Provided that the superconductive material is sufficiently subdivided, dynamic stabilization may be achieved by embedding the material in a high conductivity material, such as copper. Screening currents are induced by the flux motion in this material and these decay much more slowly than those induced in superconductive material which has a high resistivity in the normal conduction state. Thus the flux motion is slowed. In addition the thermal conductivity of high conductivity normal materials is much higher than that of superconductive materials in the normal state. Thus both requirements are met by the addition of such material and flux jumps are eliminated. Flux jumps can still occur inside large superconducting filaments but the level of subdivision required to prevent this is less than that required for flux jump stabilization of isolated filaments.

Flux-jump stabilization:
a superconducting magnet design concept to avoid instability caused by internal magnetic disturbances, that is achieved by subdividing the superconductive material into fine filaments small enough so that after an internal magnetic disturbance, the energy liberated is so small that the disturbance does not lead to a flux jump.

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