FORM 1 604119 SPRUSON & FERGUSON

COMMONWEALTH OF AUSTRALIA

PATENTS ACT 1952

APPLICATION FOR A STANDARD PATENT

International Business Machines Corporation, incorporated in New York, of Armonk, New York, New York, 10504, UNITED STATES OF AMERICA, hereby apply for the grant of a standard patent for an invention entitled:

High Current Conductors and High Field Magnets Using Anisotropic Superconductors

which is described in the accompanying complete specification.

Details of basic application(s):-

Basic Applic. No:	Country:	Application Date:
051552	US	18 May 1987

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DATED this SEVENTEENTH day of MAY 1988

International Business Machines Corporation

By: M.J. Anderson

Registered Patent Attorney

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TO: THE COMMISSIONER OF PATENTS
OUR REF: 58850
S&F CODE: 55785

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17 MAY 1988
Sydney

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APPLICATION ACCEPTED AND AMENDMENTS

ALLOWED 7.9.90

CONVENTION OR
NON-CONVENTION

FORMS 7 AND 8
(COMBINED)

COMMONWEALTH OF AUSTRALIA

PATENTS ACT 1952-1969

Declaration In Support Of Convention Or Non-Convention Application For A Patent Or Patent Of Addition

(This declaration shall be made by the applicant, or, if the applicant is a body corporate, by a person authorized by the body corporate to make the declaration on its behalf).

In support of the Application made for a patent for an invention entitled HIGH CURRENT CONDUCTORS AND HIGH FIELD MAGNETS USING ANISOTROPIC SUPERCONDUCTORS.

I, Arnold Rosen
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do solemnly and sincerely declare as follows:

1. I am authorized by International Business Machines Corporation, the applicant for the patent to make this declaration on its behalf.

2. (1) Arthur Davidson of 1463 Westview Drive, Yorktown Heights, New York, U.S.A.; (2) Timothy Rea Dinger of 177 Mill River Road, Chappaqua, New York, U.S.A.; (3) William Joseph Gallagher of 577 Ashford Avenue, Ardsley, New York, U.S.A.; (4) Thomas Kimber Worthington of 1199 Park Avenue, New York, New York, U.S.A.; are the actual inventors of the invention and the facts upon which the applicant is entitled to make the application are as follows: Applicant is entitled to apply by virtue of an Assignment dated May 22, 1987 from Arthur Davidson and an Assignment dated May 29, 1987 from Timothy Rea Dinger, William Joseph Gallagher and Thomas Kimber Worthington, to International Business Machines Corporation.

3. The basic application as defined by Section 141 of the Act was made in the United States of America on May 18, 1987 by Arthur Davidson, Timothy Rea Dinger, William Joseph Gallagher and Thomas Kimber Worthington.

4. The basic application referred to in paragraph 3 of this Declaration was the first application made in a Convention country in respect of the invention the subject of this application.

Declared at Markham, this 5th day of May, 1988.

Arnold Rosen
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Arnold Rosen

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(54) Title
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(56) Prior Art Documents
AU 25284/88 H01F 7/22
EP 210289
EP 189970

(57) Claim

1. A superconducting magnet apparatus including:

a plurality of windings through which supercurrents can flow to create a magnetic field;

current means for producing supercurrents in said windings, said windings being comprised of a superconductive composition having a transition temperature in excess of 26°K and having crystallographic planes along which said supercurrents can flow, said superconductive composition exhibiting an anisotropy in maximum supercurrent such that said supercurrents are maximum in a direction substantially parallel to said crystallographic planes, said planes being oriented substantially parallel to the direction of the magnetic field produced by said supercurrents in said windings.

21. A supercurrent structure, including:

a current source; and

a conductor for carrying electrical current from said current source, said conductor being comprised of a high T_c superconducting

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composition exhibiting a current anisotropy wherein the amount of supercurrent that can flow in a first direction is greater than the amount of supercurrent that can flow in a second direction substantially perpendicular to said first direction, said composition being substantially parallel to a direction of magnetic field produced by the supercurrent and substantially parallel to the length of said conductor so that the supercurrent flow therealong is primarily in said first direction.

27. A supercurrent conductor comprised of a conductor having a length along which a supercurrent can flow, said conductor being a high T_c copper oxide superconductor including Cu-O planes therein, said Cu-O planes being substantially parallel to one another along the length of said conductor.

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FORM 10

COMMONWEALTH OF AUSTRALIA 604119

PATENTS ACT 1952

COMPLETE SPECIFICATION

(ORIGINAL)

FOR OFFICE USE:

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Complete Specification Lodged:
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Related Art:

This document contains the amendments made under Section 49 and is correct for printing.

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Complete Specification for the invention entitled:

High Current Conductors and High Field Magnets Using Anisotropic Superconductors

The following statement is a full description of this invention, including the best method of performing it known to me/us

HIGH CURRENT CONDUCTORS AND HIGH FIELD MAGNETS USING ANISOTROPIC SUPERCONDUCTORS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to conductors and magnets for producing large magnetic fields, and more particularly to such magnets employing anisotropic superconductors where the field anisotropies in such superconductors are utilized to provide improved designs.

Description of Related Art

Superconductors of many types are known in the prior art, including both elemental metals and compounds of various types, such as oxides. The recent technical breakthrough reported by Bednorz and Mueller in Z. Phys. B, 64, 189 (1986) was the first major improvement in a superconducting material in the last decade. The materials of Bednorz and Mueller exhibited critical transition temperatures T_c that were substantially above the critical transition temperatures of materials previously known. In particular, Bednorz and Mueller described copper oxide materials including a rare earth element, or rare earth-like element, where the rare earth element could be substituted for by an alkaline earth element such as Ca, Ba, or Sr.

The work of Bednorz and Mueller has led to intensive investigation in many laboratories in order to develop materials having still higher T_c. For the most part, these high T_c oxide superconductors consist of compounds of La, Sr, Cu, and O, or compounds of Y, Ba, Cu, and O. A highlight of this activity was the attainment of superconductivity at temperatures of about 95°K, as reported by M.K. Wu et al and C.W. Chu et al, Phys. Rev. Lett. 58, 908 (1987). Later, $Y_1Ba_2Cu_3O_{7-x}$ was isolated as the superconducting phase of these Y-Ba-Cu-O mixed phase compositions, as reported by P.M. Grant et al, Phys. Rev. B, and R.J. Cava et al, Phys. Rev. Lett. 58, 1676 (1987). These materials have a layered perovskite structure comprising two dimensional CuO layers which are believed necessary for the attainment of high transition temperatures. Hidaka et al, Japanese J. Appl. Phys. 26, L377 (1987) reported upper critical field anisotropies of 5 in single crystals of $La_{2-x}Ba_xCuO_4$.

These superconducting materials are generally termed high T_c superconductors, and are materials having superconducting transition temperatures greater than 26°K. This class of superconductors includes Cu-O planes separated by rare earth or rare earth-like elements and alkaline earth elements. The crystalline structure of these materials is now well characterized as reported in the above-cited technical papers.

High T_c superconductors of many forms have been prepared by a variety of techniques, including standard ceramic processing of oxide, carbonate, nitrate, powders, etc. to form of bulk materials, vapor transport for depositing thin films, and plasma spray coating. A copending application ~~of P. Chaudhari et al, S.N. 027,584, filed March 18, 1987 and assigned to the present assignee,~~ describes a technique for producing thin films of these high T_c superconductors. Another copending application ~~to J. Cuomo et al, S.N. ________, filed ____________ and assigned to the present assignee,~~ describes a plasma spray coating technique for depositing these high T_c superconductors. More recently, epitaxial single crystal films have been reported by P. Chaudhari et al in a paper submitted to Phys. Rev. Lett.

Thus, significant technical achievements have been made in the science of superconducting materials in order to provide materials which exhibit critical transition temperatures above liquid nitrogen temperature (77°K). However, applications of these materials, being obviously desireable, have not yet been possible. As will be seen, the invention herein is an application of these materials to the design of improved superconducting magnets, and is based on a discovery of the present applicants that these high T_c superconductors can exhibit a significant critical magnetic field anisotropy and high critical currents.

Superconducting magnets are known in the art, and are conventionally used when large magnetic fields are to be produced. In fact, a great deal of speculation has occurred about the use of high T_c materials for high field magnets for such diverse applications as nuclear fusion, nuclear magnetic resonance (NMR) imaging, and vehicle propulsion systems. Generally, in order to manufacture a useful magnet, the superconductor must satisfy two criteria: (1) it must have a high upper critical field H_{c2} so that the superconductor does not lose its zero resistance due to the field produced in the windings by the current through other windings, and

(2) it must have a high critical current so that the magnetic field it creates is large. With traditional superconducting materials (i.e., non high T_c materials) the upper critical field is a composition-dependent property. However, high critical current in the presence of large magnetic fields is very dependent on the exact preparation techniques used to manufacture the material. Thus, high critical field and high critical current are not necessarily related to one another. Further, the initial studies on the new high T_c materials indicated that they exhibited a very high critical field but very low critical current. Thus, while the desireability of using these materials in magnets was apparent, it was not apparent that they could be successfully employed to make a good superconducting magnet. Still further, how one would implement them to make such a magnet was also not clear.

In their experimentation, applicants have discovered that these high T_c materials exhibit a very large critical field anisotropy and also exhibit a large critical current density along preferred directions. The nature of this anisotropy is that these materials can support large currents only in certain crystallographic planes. By proper design of the magnet windings, the current can be made to flow in the directions of large critical current, yet the field from the windings lies in directions of high critical field. This design will satisfy the two criteria previously described. Prior to the discovery of this large field anisotropy and the possibility of large critical currents, the design of an improved magnet was not possible. This was so even though small upper critical field anisotropies had been observed in some of these high T_c materials, as noted in the aforementioned Hidaka et al reference.

Accordingly, it is a primary object of the present invention to provide an improved design for a superconducting magnet.

In accordance with one aspect of the present invention there is disclosed a superconducting magnet apparatus including:

a plurality of windings through which supercurrents can flow to create a magnetic field;

current means for producing supercurrents in said windings, said windings being comprised of a superconductive composition having a transition temperature in excess of 26°K and having crystallographic planes along which said supercurrents can flow, said superconductive composition exhibiting an anisotropy in maximum supercurrent such that said supercurrents are maximum in a direction substantially parallel to said crystallographic planes, said planes being oriented substantially parallel to the direction of the magnetic field produced by said supercurrents in said windings.

In accordance with another aspect of the present invention there is disclosed a superconducting magnet, comprising:

a plurality of current-carrying windings, said windings being comprised of high T_c superconducting materials having a superconducting phase therein exhibiting a critical transition temperature greater than 26°K, said superconducting phase being characterized by an anisotropy in critical current density and having a crystallographic structure including two dimensional planes in which supercurrents flow, said superconducting phase further exhibiting critical magnetic field anisotropy such that the critical field H_{c2} is greater in a direction substantially parallel to said crystallographic planes than it is in a direction substantially normal to said crystallographic planes, said windings being arranged so that said crystallographic planes are substantially parallel to the magnetic field produced by supercurrents flowing in said planes; and

current means for providing said superconducting currents in said windings.

In accordance with another aspect of the present invention there is disclosed a superconducting magnet, including:

a plurality of windings for carrying supercurrents therethrough, said supercurrents producing a magnetic field H, said windings being comprised of a high T_c superconducting composition exhibiting a critical magnetic field anisotropy effect wherein the critical magnetic field H_{c2} required to destroy superconductivity in said windings is greater in a first direction than in a second direction, said superconducting composition being further characterized by supercurrent density anisotropy and having two dimensional planes in which said supercurrents flow to produce said magnetic field H, the direction of maximum supercurrent flow being substantially along said two-dimensional planes, the windings being arranged in a geometry wherein said two dimensional current-carrying planes are substantially parallel to said first direction of said critical magnetic field H_{c2}; and

current means for providing an electrical current in said windings.

In accordance with another aspect of the present invention there is disclosed a supercurrent structure, including:

a current source; and

a conductor for carrying electrical current from said current source, said conductor being comprised of a high T_c superconducting composition exhibiting a current anisotropy wherein the amount of supercurrent that can flow in a first direction is greater than the amount of supercurrent that can flow in a second direction substantially perpendicular to said first direction, said composition being substantially parallel to a direction of magnetic field produced by the supercurrent and substantially parallel to the length of said conductor so that the supercurrent flow therealong is primarily in said first direction.

Other aspects of the present invention are also disclosed.

Summary of the Invention

Superconducting magnets are described in which the windings are comprised of superconducting materials exhibiting critical field anisotropy, i.e., materials in which the critical field H_{c2} is larger in one direction than in another direction. A large magnetic field anisotropy has been discovered in the high T_c superconductors, and it has also been found that these materials are capable of carrying high critical currents. In the practice of this invention, these factors are utilized to provide a design in which the current flows in the directions of high critical current and produces fields in the direction of high critical field. More specifically, the magnet windings are arranged so that the current direction through the windings is substantially parallel to the direction having the largest critical magnetic field. In particular, the current-carrying planes in these high T_c superconducting materials are arranged to be parallel to the direction in which the critical magnetic field H_{c2} is largest so that the magnetic field H produced by supercurrents in the windings will be in a direction substantially parallel to the direction of maximum H_{c2}, if the windings are arranged as described in this invention.

The improved conductors and magnet windings can be comprised of a plurality of single crystals oriented in the same direction. Thin epitaxial films formed on flexible substrates are a particularly preferred embodiment to provide the magnet windings. Highly textured films, textured polycrystalline ceramics, etc. can also be utilized. A representative material for a superconductor winding in accordance with the present invention is a film or crystals of $Y_1Ba_2Cu_3O_{7-x}$, in which very large magnetic field anisotropies and high critical currents have recently been discovered.

These and other objects, features, and advantages will be apparent from the following more particular description of the preferred embodiments.

Brief Description of the Drawings

FIG. 1 schematically illustrates the directions large super currents can flow in designated crystallographic planes of a high T_c superconductor.

FIGS. 2A and 2B illustrate the field anisotropy effect for these high T_c superconductors. In FIG. 2A, the critical field H_{c2} is small in a direction perpendicular to the current-carrying planes, while in FIG. 2B the critical field H_{c2} is significantly larger in a direction parallel to the current-carrying crystallographic planes. This anisotropy difference is at least an order of magnitude in some materials.

FIG. 3A illustrates the design of a superconducting solenoid in accordance with the principles of the present invention, wherein the current-carrying planes are substantially parallel to the magnetic field produced by the magnet, thereby providing a superior high field magnet.

FIG. 3B more clearly shows the orientation of the superconducting current-carrying planes with respect to the axis of the solenoid and the magnetic field H produced by current I in the solenoid windings.

FIG. 3C schematically illustrates a portion of the solenoid of FIG. 3A, and more specifically shows a plurality of superconducting layers 20, separated by support material 22, which could be stainless steel or other structural material.

FIG. 4A schematically illustrates an inferior, alternative design for a superconducting solenoid, which does not take into account the discoveries of the present invention. This design is characterized by a very low critical magnetic field which leads to poor performance of the magnet.

FIG. 4B shows a portion of the windings of the solenoid of FIG. 4A, and more particularly illustrates the orientation of the current-carrying planes with respect to the solenoid axis, and the magnetic field H produced by the solenoid.

FIG. 5A illustrates a refinement of the solenoid design of FIG. 3A which compensates for the fringing of the magnetic field H at the ends of the solenoid, the crystallographic current-carrying planes being inclined at the ends of the solenoid to be substantially parallel to the fringing field.

FIG. 5B illustrates a layered structure which will tilt the crystallographic current-carrying planes at the ends of the solenoid.

FIGS. 6A-6C illustrate a magnetic toroid made in accordance with the present invention, where FIG. 6A schematically shows the toroid and FIGS. 6B and 6C show portions of the interior of the toroid.

Description of the Preferred Embodiments

As noted, this invention is directed to improved conductors and superconducting magnets having windings comprised of superconducting material exhibiting a critical magnetic field anisotropy, where the design of the windings is such that the critical current through the windings is maximum, thereby allowing the production of large magnetic fields. This type of anisotropy is present in high T_c superconductors such as the Y-Ba-Cu-O systems described in the references hereinabove.

The field anisotropy effect is illustrated more particularly with respect to FIGS. 1, 2A, and 2B. A representative high T_c material is $Y_1Ba_2Cu_3O_{7-x}$. A single crystal of this material can be prepared by techniques similar to those used by Iwazumi et al, Jap. J. Appl. Phys. 26, L386 (1987). A sintered powder containing three phases $Y_1Ba_2Cu_3O_{7-x}$, CuO, and $BaCuO_2$ and having a nominal composition of $Y_{0.5}Ba_{0.61}CuO_{2.62}$ is formed in a pellet and fired in a slightly reducing atmosphere at 975°C for 12 hours. During the 975°C soak, an oxidizing atmosphere is introduced to promote growth of the $Y_1Ba_2Cu_3O_{7-x}$ crystallites already present in the particompact. This technique routinely produces highly faceted crystals of high quality.

As grown, these crystals typically display superconducting diamagnetic transitions in the 40-50K region. Annealing in flowing oxygen for extended periods at 450-500°C raises the transition temperatures to about 85°K.

As is known for these materials, Cu-O planes exist which are parallel to one another and comprise the supercurrent carrying planes of the material. This is illustrated in FIG. 1, where four such superconducting planes 10A, 10B, 10C, and 10D are illustrated. These Cu-O basal planes are planes substantially perpendicular to the c-axis of the crystal that are separated by about 4 angstroms and are capable of carrying large critical currents in the x-y directions in the Cu-O planes. Supercurrent conduction in the z direction perpendicular to these planes is minimal.

FIGS. 2A and 2B illustrate the large critical field anisotropy discovered in these materials. In FIG. 2A the critical magnetic field H_{c2} is in a direction substantially perpendicular to the current carrying planes

10A-10D. In this case, the critical transition field H_{c2} in which the superconductor loses its zero resistance state is relatively low.

In contrast with the situation depicted in FIG. 2A, the magnetic field orientation in FIG. 2B is parallel to the Cu-O current-carrying planes 10A-10D. This field can be in either the x or y direction, and the critical field H_{c2} is very large, and can be an order of magnitude higher critical field than the critical field which results when the field is oriented perpendicular to the current-carrying planes.

It has also been discovered that the high T_c superconductor $Y_1Ba_2Cu_3O_{7-x}$ can carry large supercurrent densities (approximately 3 x 10^6 A/cm^2) in favorable directions at 4.5°K, and that large supercurrent carrying capability can exist in moderate fields, as indicated in FIG. 2B. These factors are utilized in the design of improved superconducting magnets, as will be illustrated in FIG. 3A-6B. It is anticipated that with improved processing these high critical currents will persist to higher temperatures as has been demonstrated for films of these materials.

The superconducting magnets of this invention have windings which are constructed such that the magnetic field produced by current in the windings is parallel to the crystallographic planes which carry the supercurrents in these materials. If this design is followed, the field produced by the windings will not easily destroy the superconductivity, so that large magnetic fields can be generated. An example of this design is illustrated by the solenoid of FIG. 3A, a portion of which is shown. It will be understood by those of skill in the art that the remaining portion of the solenoid completes the current carrying path and is generally circular about the axis A. FIG. 3B provides more details of the windings and in particular the orientation of the current-carrying planes in the superconductors comprising the windings. FIG. 3C is a sectional view of a portion of the windings, illustrating their fabrication as oriented layers.

In more detail, solenoid 12 is comprised of a plurality of windings 14, illustrated by the vertical lines which are representative of the current-carrying planes in a high T_c superconductor material. The magnetic field H produced by current I in the superconductive windings is parallel to the axis A of the solenoid and is more heavily concentrated in the hollow core 16 of the solenoid. Electrical current is provided by one or more current sources 17, as is well known in the art. In operation, the magnet would be immersed in liquid He or N, or these liquids would be passed through tubes in the structure in a manner well known in the art. When the solenoid is providing a constant field, only very little heat is produced. It is only when the field H is changed that a greater amount of heat will be produced. The superconducting windings can also be clad with copper, or some other thermally and/or electrically conductive material such as Ag, as is well known in the art. High currents would flow into the copper cladding when the field is changed, then would flow back into the superconductors when cooling is achieved.

The vertical lines 14 in FIG. 3A represent the current carrying planes of the superconductor comprising the magnet windings. These windings are used to provide circumferential currents in order to produce the axial magnetic field H. This field is most intense along the hollow core 16 of the solenoid, and diminishes in a radial direction, as indicated by the arrows 18 of diminishing length measured in a radial direction from the axis A.

FIG. 3B shows only two of the many Cu-O supercurrent conducting planes 14 which can be present in a single layer or crystal of high T_c superconductor, or in adjacent layers of such crystals. As is well known, the Cu-O planes in these materials are separated from one another by approximately 4 angstroms. As is apparent from FIG. 3B, these Cu-O planes 14 are arranged substantially parallel to one another and circumferentially about the axis A of the solenoid. Supercurrents I flow in the planes 14 in a circumferential manner around the solenoid. These supercurrents produce a magnetic field H which is parallel to the current carrying planes and therefore the critical magnetic field is not exceeded until the larger H_{c2} is reached. Since the amount of critical current that can exist in the Cu-O planes can be high, this allows the production of high magnetic fields without a loss of superconductivity in the planes 14.

FIG. 3C schematically illustrates a plurality of superconducting material layers 20, separated by support material 22, which could be stainless steel or another material. The support materials are flexible and can be formed to provide the windings of the magnet, where the superconducting materials 20 are deposited as epitaxial thin film layers. As an alternative, the superconductive layers 20 can be polycrystalline films where the crystallites are substantially aligned to provide the Cu-O superconducting planes in a direction substantially parallel to the field H. These fabrication techniques will be described in more detail later.

FIG. 4A illustrates another solenoid, except that the design of the superconductive windings in this solenoid is such that the critical magnetic field will be quite low, and at least an order of magnitude less than that obtained with the geometry of FIG. 3A. In order to contrast the designs of FIG. 3A and FIG. 4A, the same reference numerals will be used to indicate the same or functionally similar components. Accordingly, solenoid 24 of FIG. 4A is comprised of a plurality of current-carrying planes 14 which are arranged circumferentially around the hollow center portion 16 of the solenoid. The magnetic field H produced by current in the Cu-O planes is designated by the arrows H. The strength of field H is maximum in the center portion 16 of the solenoid 24, and is directed along the axis of the solenoid.

The arrangement of the current-carrying Cu-O planes 14 in the windings of the solenoid of FIG. 4A ~~are~~ is shown in more detail in FIG. 4B. These Cu-O current-carrying planes are disposed horizontally so that the magnetic field H is in a direction substantially perpendicular to the current-carrying planes. Referring to FIG. 2A, this orientation of the current-carrying planes and the magnetic field H leads to a situation where the magnetic field produced by the windings is in the direction of the lower H_{c2}. This means that the solenoid 24 of FIG. 4A cannot be used to produce magnetic fields as large as those that can be produced by the solenoid 12 of FIG. 3A.

In the design of FIG. 3A, the field produced by current in the windings is in a direction that is parallel to the current-carrying planes, while in the design of FIG. 4A the field is in a direction substantially perpendicular to the current-carrying planes. While these structures show the extremes of the design considerations, it will be appreciated by those of skill in the art that, to the extent the field is substantially parallel to the current-carrying planes, an improvement in the amount of magnetic field that can be produced by the solenoid will be achieved. Thus, even designs where the magnetic field makes an angle with the current-carrying planes will provide some enhancement of the strength of the magnetic field that can be produced. Since the easy direction for the current is along the Cu-O planes, it is believed that some misalignment of the field H and the Cu-O planes can be tolerated, as can a misalignment of the Cu-O planes themselves.

FIG. 5A illustrates a refinement of the solenoid design of FIG. 3A which compensates for the fringing of the magnetic field H at the ends of the solenoid. In order to relate FIG. 5 to FIGS. 3A and 3B, the same reference numerals will be used. Therefore, the superconducting current-carrying planes 14 are arranged in a direction substantial parallel to the magnetic field H in the center of the solenoid. This is a direction parallel to the axis A of the solenoid. As was noted with respect to FIG. 3B, the current-carrying planes 14 circumferentially wrap around the solenoid, being generally parallel to the axis A. However, in order to have these current-carrying planes be substantially parallel to the magnetic field H at the end of the solenoid where the field H is distorted from a direction perfectly parallel to the axis A, the superconducting material comprising the windings of the solenoid is oriented such that the

Cu-O current-carrying planes are tilted outwardly at the ends of the solenoid, as is schematically illustrated with respect to the planes in rows 14A, 14B, and 14C. This is easily accomplished by using conventional techniques wherein windings are stacked to make a solenoid, the substrates on which the superconducting layers are formed having a tapered width in the regions near the end of the solenoid. ~~Where the windings including current-carrying planes 14A, 14B, and 14C are located;~~ This is illustrated in FIG. 5B, where the substrates 32 have varying width so that the superconducting layers 34 are tilted somewhat from an axial direction.

As an alternative to the design of FIGS. 5A, 5B, the windings toward the ends of the solenoid can be comprised of copper or another material which has a high current-carrying capability.

A particular magnet design that is of significant advantage, as for instance in the generation of fusion power, is a toroid. A toroid is a magnet that is particularly well suited for design in accordance with the principles of the present invention, as will be illustrated in FIGS. 6A, 6B, and 6C. The toroid 26 is a generally donut-shaped magnet having an open inner portion 28 and an annular, generally circular cross-sectional opening 30 (FIGS. 6B, 6C) which extends around the circumference of the toroid. The field H produced by current I in the toroid is a circumferential field which is maximum in the annular hollow portion 30. The currents I are provided by current source 31 and flow through windings wrapped around the toroid ring in planes substantially normal to the axis of the hollow annular portion 30. Toroid 26 can also be cooled by liquid He or liquid N in known ways.

FIG. 6B is a cross-sectional view of the toroid 26 taken along line 6B-~~6C~~6B, and shows a portion of the toroid 26 of FIG. 6A, to further illustrate its geometry. In particular, the annular opening 30 in which the maximum magnetic field H is produced by the currents I, is shown.

FIG. 6C is an end view of the toroid of FIG. 6B and illustrates the arrangement of the Cu-O planes in the superconducting material which allows maximum currents to flow through the windings in order to maximize the magnetic field produced by the toroid 26. The superconductive material comprising the magnet windings is deposited in such a manner that the Cu-O current-carrying planes 33 are oriented to provide windings whose axis is concentric to the axis of the annular opening 30. That is, the Cu-O planes are disposed concentrically and parallel to the circumferential field H in the hollow annulus 30.

While a particular example ($Y_1Ba_2Cu_3O_{7-x}$) of a high T_c conductor has been described as an example of a material exhibiting a large magnetic field anisotropy, the superconductors that can be used for the magnet windings of this invention can be fabricated from any superconductors exhibiting this critical field anisotropy. It is known, for instance, that a large number of rare earth ions can be substituted for Y in $Y_1Ba_2Cu_3O_{7-y}$ and the composition will still maintain a high T_c and also the anisotropy properties of the $Y_1Ba_2Cu_3O_{7-y}$ material. However, in order to make a high field superconducting magnet, it is preferrable to have the critical field anisotrophy exhibit a high value, such as 10 or more, in order to maximize the magnitudes of the fields that can be produced. Further, materials exhibiting high critical currents are preferrable as these materials will be able to provide larger magnetic fields.

In particular, the invention can use high T_c superconductors which can be fabricated to orient the Cu-O current-carrying planes to take advantage of the large critical field anisotropy. Fabrication of the superconducting windings can utilize single crystals, epitaxial films, highly textured films in which the Cu-O planes are generally aligned, textured polycrystalline ceramics having generally ordered crystallographic Cu-O planes, or any other technique that induces the Cu-O planes to orient parallel to one another. For example, magnetic fields are commonly used to align magnetic domain patterns in magnetic films. Accordingly, yttrium or another rare earth element can be totally or partially replaced with a magnetic element such as gadolinium or holmium without detracting from the superconducting properties of the material. Since Gd and Ho have strong magnetic properties, these properties can be exploited to encourage the alignment of the magnetic ions and therefore, indirectly align the Cu-O planes in a film of this superconducting material. Further, since the radius of the superconducting windings is very large in comparison with the crystallite size in these materials, the amount of bending, and therefore strain on the crystals, will be very small and the alignments can be accomplished. For example, the orientation of the Cu-O planes can be accomplished as large 'green" sheets of superconducting material are being deposited. Alternatively, preferred orientation may be promoted by pressure-assisted densification. This alignment of the crystallographic current-carrying planes can also occur during the annealing process or during deposition of the films. However, even if the Cu-O planes are somewhat tilted with respect to one another, enhancement of magnet design will occur since the principles of the present invention will still be exploited (although to a lesser extent). That is, the general direction of current flow in the superconductive windings will produce a field ~~still~~ substantially in the direction of higher H_{c2}.

While it is believed that current flow in these high T_c materials is most likely along 2 dimensional planes, it may be that there is some supercurrent conduction along one dimensional Cu-O chains, and that these 1-dimensional chains play a role in the anisotropic superconductivity. Orientation of the planes such that the chains are along the direction of high supercurrent flow may further enhance the critical supercurrent.

While high T_c superconducting materials such as Y-Ba-Cu-O and variations thereof are particularly suitable materials in the practice of this invention, it should be understood that layered composite superconductors can be fabricated to exhibit a critical field anisotropy that could be exploited using the principles of the present invention. For example, a layered superlattice structure comprising a superconductive layer - normal metal layer - superconductive layer ... can be fabricated with sufficient orientation of the crystallographic planes to provide aligned pathways for current flow in a direction parallel to the magnetic field produced by the current flow in order to maximize the amount of magnetic field that can be produced. Further, it is known in the design of superconducting magnets that the magnetic field strength is maximum in the center of the magnet and decreases in an outwardly radial direction. In these magnets, the inner windings are often chosen to be nonsuperconducting materials which can withstand the high magnetic fields in the interior of the magnet, while the outer windings are the superconductive windings. Also, conventional magnets are made by fabricating sections and stacking the sections together to create the large magnet. These approaches can be used with the magnets of the present invention in order to facilitate fabrication and to achieve very high magnetic fields.

While the invention has been described with respect to particular embodiments thereof, it will appreciated by those of skill in the art that variations can be made therein without departing from the spirit and scope of the present invention. For example, different types of superconductive material can be utilized in addition to those specifically referenced. The important features are that the windings of the magnet are fabricated so that the magnetic field produced by current flow in the windings is in the direction of high critical field in order to maximize the amount of field that can be produced by the magnet. Another important feature is that the crystallite planes are oriented along the direction that carries a large current. This in turn is used to make an improved supercurrent conductor, as will be explained later.

In the further practice of this invention, it should be noted that these magnets can be operated over a very wide temperature range, including temperatures down to liquid helium temperatures. For example, critical currents at 4.5°K in the range of about 3 x 10^6 A/cm^2 have been measured in the direction of Cu-O planes in crystals of $Y_1Ba_2Cu_3O_{7-x}$. Combining the proper geometry utilizing the critical field anisotropy in these materials with operation at 4.5°K, where the critical currents are largest, will provide a magnet capable of producing extremely high magnetic fields.

In another aspect of this invention, the use of mixed copper oxide materials of the types known in the art ~~known~~ as high T_c superconductors provides magnets having unique properties of anisotropy and critical current, resulting in specialized magnets having superior properties.

As was noted previously, the crystallite planes of these high T_c superconductors can be oriented along the direction that carries a large current. Thus, if the crystal grains of these materials are aligned to provide this, a conductor can be fabricated which will have the capability of carrying a large current. This conductor can be fabricated as a wire, tape, flat lead, etc. and, if the current-carrying planes are substantially parallel, the amount of current that is carried can be more than 30 times that which can be carried without this orientation.

The claims defining the invention are as follows:

1. A superconducting magnet apparatus including:

a plurality of windings through which supercurrents can flow to create a magnetic field;

current means for producing supercurrents in said windings, said windings being comprised of a superconductive composition having a transition temperature in excess of 26°K and having crystallographic planes along which said supercurrents can flow, said superconductive composition exhibiting an anisotropy in maximum supercurrent such that said supercurrents are maximum in a direction substantially parallel to said crystallographic planes, said planes being oriented substantially parallel to the direction of the magnetic field produced by said supercurrents in said windings.

2. A magnet apparatus as claimed in claim 1, wherein a critical field H_{c2} required to destroy the superconducting state in said windings is larger in a direction substantially parallel to said crystallographic planes than in a direction substantially normal to said crystallographic planes.

3. A magnet apparatus as claimed in claim 2, wherein the critical magnetic field H_{c2} parallel to said crystallographic planes is at least about an order of magnitude greater than the critical magnetic field H_{c2} perpendicular to said crystallographic planes.

4. A magnet apparatus as claimed in claim 2 or 3, wherein said superconducting composition is a member of the oxide system Ln-Ba-Cu-O, where Ln is a lanthanide element.

5. A magnet apparatus as claimed in claim 4, wherein said composition includes a magnetic ion.

6. A magnet apparatus as claimed in claim 1, 2 or 3, wherein said superconductive composition is a mixed copper oxide having a layer-like structure.

7. A magnet apparatus as claimed in any one of the preceding claims, wherein said crystallographic planes are two dimensional Cu-O planes.

8. A magnet apparatus as claimed in any one of the preceding claims, wherein said apparatus has a solenoid geometry.

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9. A magnet apparatus as claimed in any one of claims 1 to 8, wherein said apparatus has a toroid geometry.

10. A superconducting magnet, comprising:

a plurality of current-carrying windings, said windings being comprised of high T_c superconducting materials having a superconducting phase therein exhibiting a critical transition temperature greater than 26°K, said superconducting phase being characterized by an anisotropy in critical current density and having a crystallographic structure including two dimensional planes in which supercurrents flow, said superconducting phase further exhibiting critical magnetic field anisotropy such that the critical field H_{c2} is greater in a direction substantially parallel to said crystallographic planes than it is in a direction substantially normal to said crystallographic planes, said windings being arranged so that said crystallographic planes are substantially parallel to the magnetic field produced by supercurrents flowing in said planes; and

current means for providing said superconducting currents in said windings.

11. A magnet as claimed in claim 10, wherein said superconducting composition is a mixed copper oxide composition.

12. A magnet as claimed in claim 11, wherein said mixed copper oxide composition includes an element selected from the group consisting of rare earth and rare earth-like elements and an alkaline earth element.

13. A magnet as claimed in claim 10, wherein said superconducting composition is an oxide in the general system Ln-Ba-Cu-O where Ln is a lanthanide element, including Y.

14. A magnet as claimed in any one of claims 10 to 13, wherein H_{c2} in a direction parallel to said crystallographic planes is at least an order of magnitude greater than H_{c2} in a direction perpendicular to said crystallographic planes.

15. A magnet as claimed in any one of claims 10 to 14, wherein said superconducting composition includes a magnetic element.

16. A magnet as claimed in any one of claims 10 to 15, wherein said windings are arranged to form a solenoid.

17. A magnet as claimed in any one of claims 10 to 15, wherein said windings are arranged to form a toroid.

18. A superconducting magnet, including:

a plurality of windings for carrying supercurrents therethrough, said supercurrents producing a magnetic field H, said windings being comprised of a high T_c superconducting composition exhibiting a critical magnetic field anisotropy effect wherein the critical magnetic field H_{c2} required to destroy superconductivity in said windings is greater in a first direction than in a second direction, said superconducting composition being further characterized by supercurrent density anisotropy and having two dimensional planes in which said supercurrents flow to produce said magnetic field H, the direction of maximum supercurrent flow being substantially along said two-dimensional planes, the windings being arranged in a geometry wherein said two dimensional current-carrying planes are substantially parallel to said first direction of said critical magnetic field H_{c2}; and

current means for providing an electrical current in said windings.

19. A magnet as claimed in claim 18, in which said crystallographic current-carrying planes are substantially parallel to the magnetic field produced by supercurrents in said windings.

20. A magnet as claimed in claim 19, wherein said superconducting composition is comprised of an oxide of a transition metal, said composition being crystalline and having a layer-like structure.

21. A supercurrent structure, including:

a current source; and

a conductor for carrying electrical current from said current source, said conductor being comprised of a high T_c superconducting composition exhibiting a current anisotropy wherein the amount of supercurrent that can flow in a first direction is greater than the amount of supercurrent that can flow in a second direction substantially perpendicular to said first direction, said composition being substantially parallel to a direction of magnetic field produced by the supercurrent and substantially parallel to the length of said conductor so that the supercurrent flow therealong is primarily in said first direction.

22. A structure as claimed in claim 21, wherein said conductor is

comprised of a crystalline superconducting composition having crystallographic current-carrying planes therein along which maximum supercurrents can flow, said current-carrying planes being substantially parallel to one another along the length of said conductor.

23. A structure as claimed in claim 21, wherein said superconducting composition is comprised of a mixed copper oxide having 2 dimensional Cu-O planes therein along which maximum supercurrent can flow, said planes being substantially aligned with one another along the length of said conductor.

24. A structure as claimed in claim 21, wherein said superconducting composition includes a transition metal oxide which is multivalent, said composition having a T_c greater than 26°K.

25. A structure as claimed in any one of claims 21 to 24, wherein the amount of supercurrent flow in said first direction is at least 10 times the amount of supercurrent flow in said second direction.

26. A supercurrent structure comprised of:

a current source for providing electrical current;

a substrate; and

a conductor on said substrate for carrying said electrical current, said conductor including a high T_c copper oxide superconductor exhibiting an anisotropy in maximum supercurrent therethrough and having Cu-O planes therein defining the direction of maximum supercurrent in said copper oxide superconductor, said superconductor being oriented along its length with said Cu-O planes being substantially parallel to said substrate.

27. A supercurrent conductor comprised of a conductor having a length along which a supercurrent can flow, said conductor being a high T_c copper oxide superconductor including Cu-O planes therein, said Cu-O planes being substantially parallel to one another along the length of said conductor.

28. A supercurrent conductor comprised of a crystalline high T_c copper oxide superconductor having crystalline grains therein, each said grain having Cu-O planes, said grains being oriented such that the Cu-O planes in said grains are substantially parallel to one another along the length of said conductor, supercurrent flow along said conductor being substantially along said Cu-O planes.

29. A supercurrent conductor, including:

a crystalline high T_c superconductor having supercurrent anisotropy and having Cu-O current-carrying planes therein, said Cu-O planes being oriented along the length of said conductor such that the primary current flow path along said conductor is along said Cu-O planes.

30. A superconducting magnet apparatus substantially as described herein with reference to Figs. 3A, 3B and 3C, or, Figs. 4A and 4B, or, Figs. 5A and 5B, or, Figs. 6A, 6B and 6C of the drawings.

31. A supercurrent conductor substantially as described herein with reference to Figs. 1 and 2A, or Figs. 1 and 2B of the drawings.

DATED this SIXTH day of AUGUST 1990
International Business Machines Corporation

Patent Attorneys for the Applicant
SPRUSON & FERGUSON

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FIG. 1

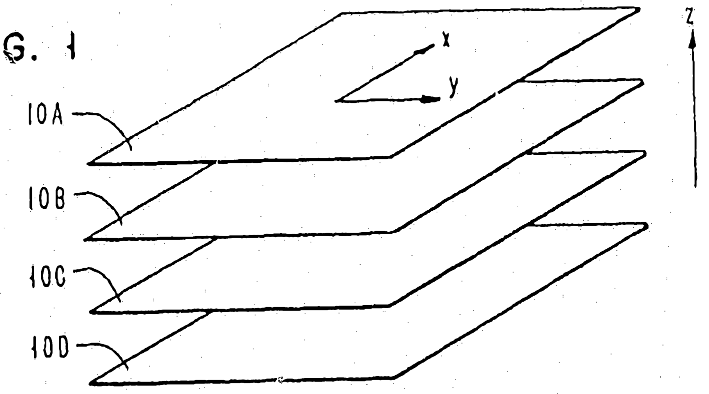

FIG. 2A

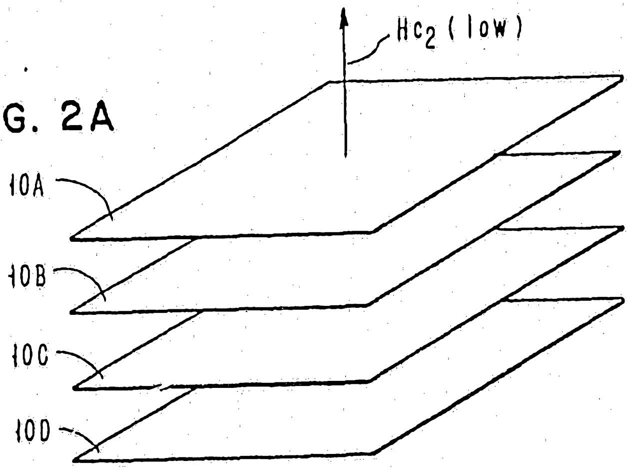

FIG. 2B

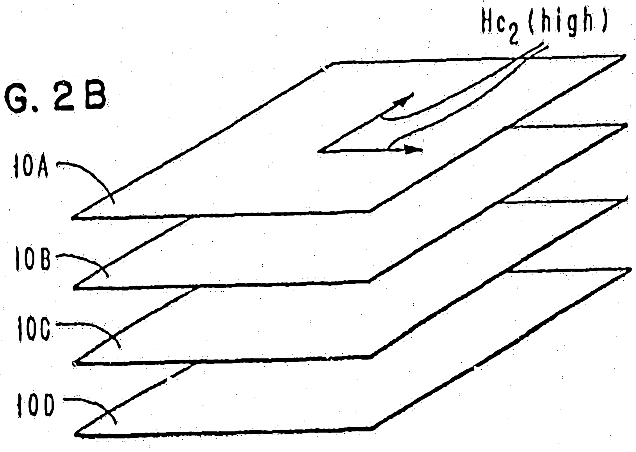

FIG. 3A

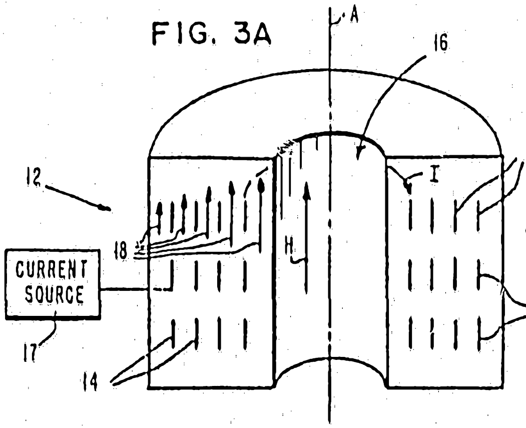

FIG. 3B

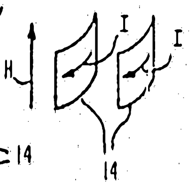

FIG. 3C

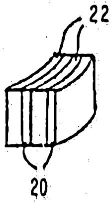

FIG. 4A

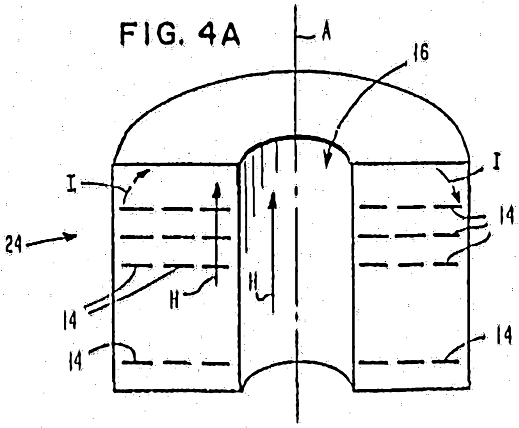

FIG. 4B

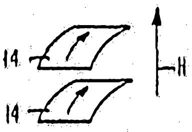

FIG. 5A

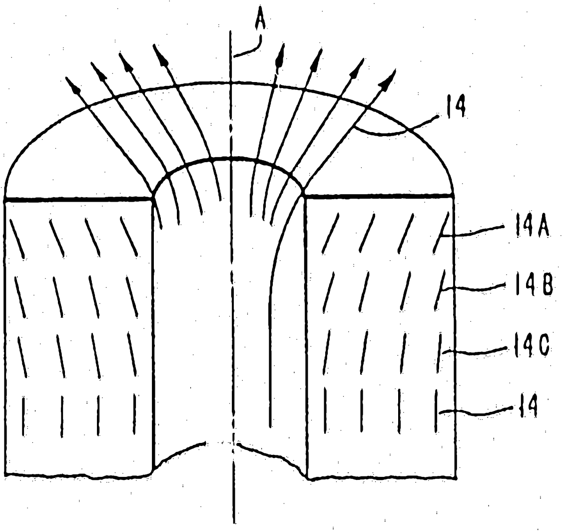

FIG. 5B

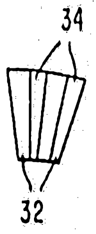

FIG. 6A

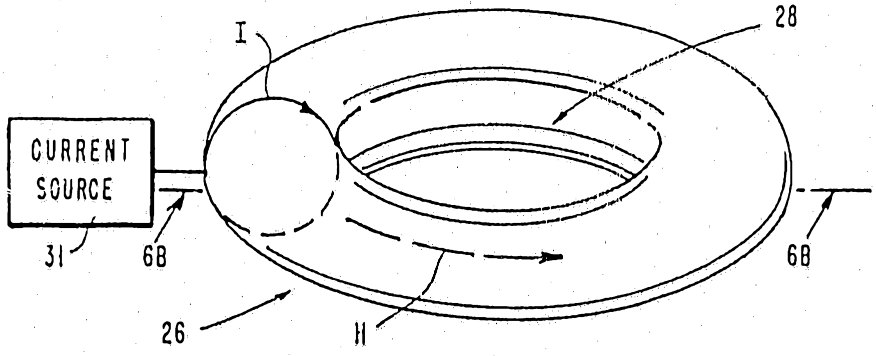

FIG. 6B

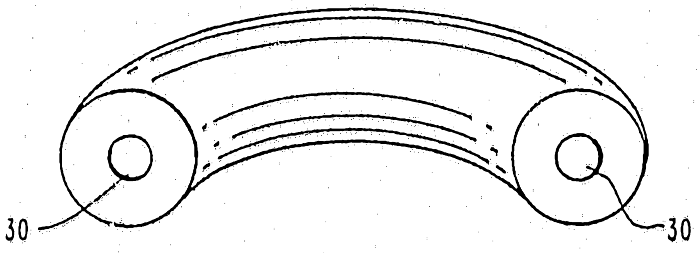

FIG. 6C