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(54) VARIABLE PROFILE SUPERCONDUCTING MAGNETIC COIL

SUPRALEITENDE MAGNETSPULE MIT VARIABLEM PROFIL

BOBINE MAGNETIQUE SUPRACONDUCTRICE A PROFIL VARIABLE

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- **PATENT ABSTRACTS OF JAPAN vol. 010, no. 255 (E-433), 2 September 1986 & JP 61 082404 A (TOSHIBA CORP), 26 April 1986,**
- **PATENT ABSTRACTS OF JAPAN vol. 016, no. 224 (E-1206), 25 May 1992 & JP 04 039909 A (TOSHIBA CORP), 10 February 1992,**

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Description

Background of the Invention

[0001] The invention relates to superconducting magnetic coils.

[0002] As is known in the art, the most spectacular property of a superconductor is the disappearance of its electrical resistance when it is cooled below a critical temperature T_c.

[0003] Below T_c and a critical magnetic field, a superconductor can carry a electrical current density up to a critical current density (J_c) of the superconductor. The critical current density is the current density at which the material loses its superconducting properties and reverts back to its normally conducting state.

[0004] Superconductors may be used to fabricate superconducting magnetic coils such as solenoids, racetrack magnets, multipole magnets, etc., in which the superconductor is wound into the shape of a coil. When the temperature of the coil is sufficiently low that the HTS conductor can exist in a superconducting state, the current carrying capacity as well as the magnitude of the magnetic field generated by the coil is significantly increased.

[0005] Typical superconducting materials include niobium- titanium, niobium- tin, and also copper oxide ceramics such as members of the rare- earth- copper- oxide family (i.e., YBCO), the thallium- barium- calcium- copper- oxide family (i.e., TBCCO), the mercury- barium- calcium- copper- oxide family (i.e., HgBCCO), and the bismuth- strontium- calcium- copper oxide family (i.e., BSCCO) . Certain BSCCO compounds, optionally containing lead,
(i.e., $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ or $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO 2223)) and $Y_1Ba_2Cu_3O_4$ (YBCO 123), perform particularly well because their superconductivity and corresponding high current density characteristics are achieved at relatively high temperatures (T_c = 115 K and 95 K respectively) .

[0006] Referring to Fig. 1, in fabricating such superconducting magnetic coils, the superconductor may be formed in the shape of a thin tape 5 which allows the conductor to be bent around the diameter of a core. In some embodiments, the thin tape is fabricated as a multi-filament composite superconductor including individual superconducting filaments 7 which extend substantially the length of the multi-filament composite conductor and are surrounded or supported by a matrix-forming material 8, which is typically silver or another noble metal. Although the matrix forming material conducts electricity, it is not superconducting. Together, the superconducting filaments and the matrix-forming material form the multi-filament composite conductor. In some applications, the superconducting filaments and the matrix-forming material are encased in an insulating layer (not shown). The ratio of superconducting material to matrix-forming material is known as the "fill factor" and is generally less than 50%. The tape may also be in other well-known forms including "powder-in-tube" (PIT) forms or coated tapes in which the superconductor is deposited on the surface of a tape-shaped substrate.

[0007] A magnetic coil can be wound with superconducting tape using generally one of two approaches. In the first approach, known as layer winding, the superconductor is wound about a core with turns being wound one next to another until a first layer is formed. Subsequent layers are then wound on top of previous layers until the desired number of layers are wound on the core.

[0008] In another approach, known as pancake winding, the superconductor tape is wound one turn on top of a preceding turn thereby forming a plane of turns perpendicular to the axis of the coil. In applications where a series of pancake coils are to be used to form a coil, the pancake coils can be wound as double pancakes.

[0009] In some applications, a superconducting magnetic coil assembly using pancake coils (whether single or double) may include several coils, coaxially disposed along the length of the coil assembly. The individual coils are interconnected using short lengths of superconducting wire or ribbon made from the superconducting materials of the type described above, for example, copper oxide ceramic.
US- A- 4499443 discloses high- field double pancake superconducting coils made from low temperature superconductor material, such as NB_3Sn, there being description as to how the magnets are cooled to 4.2K with supercritical helium.
JP- A- 61- 082404 discloses a superconducting magnet of double pancake coils having a uniform magnetic field at the centre of a magnetic coil.

Summary of the Invention

[0010] In one aspect of the invention, there is provided a superconducting magnetic coil assembly as set out in claim 1.

[0011] The interfaces between the individual pancakes of the double pancakes preferably lie generally along the inner diameter of the coil assembly and are formed of the same continuous length of superconducting wire by virtue of special winding and construction techniques. The electrical interconnections between double pancake coils, called "bridges", may be accomplished using relatively straight or "unbent" segments of a conducting tape-shaped material between the individual pancakes, of adjacent double pancake pairs, of substantially equal outer dimension. The conducting material bridging the pancakes can be either a solid piece of totally superconducting material or, preferably, is a piece of composite superconducting wire contacting the pancakes through its metallic sheath or an etched piece of superconducting wire which contacts an etched outer layer of the pancake to form a fully superconducting joint. Contact between the pancake coils may also be made using other methods including, but not limited to, soldering, pressure contact, and high temperature reaction. Although the segments of superconducting wire may have a slight bend for following the outer contour of the pancake coil in the direction perpendicular to its longitudinal axis, the segments are essentially unbent (e.g., bent less than the thickness of one composite wire) along the longitudinal axis of the coil as they span the individual coils of adjacent double pancakes. Thus, the superconducting magnetic coil assembly can have a non-uniform inner and/or outer dimension along its length for providing field shaping or field concentration while allowing the use of substantially unbent pieces of composite superconductor wire which provide a low loss electrical interconnection between the double pancake coils of the assembly.

[0012] Providing the electrical interconnection with a relatively unbent piece of superconducting wire increases both the electrical and mechanical reliability of the interconnections. This is, for the most part, due to the mechanical properties of the materials chosen to provide the desired superconducting characteristics. Such materials, like those of the copper oxide ceramic type, are generally intolerant of the application of large tensional forces (such as those created during a bending process) and may easily crack or break when excessively bent. Such materials are often characterized by their bend strain and critical strain values. The bend strain is equal to half the thickness of the conductor divided by the radius of the bend; while the critical strain of a conductor is defined as the amount of strain the material can support before experiencing a dramatic decrease in electrical performance. The critical strain value is highly dependent on the formation process used to fabricate the conductor, and is typically between 0.05%-1.0%, depending on the process used. With an increase in bend strain comes a concomitant increase in resistance and increase in voltage across the joint. If the bend strain of a conductor exceeds the critical strain of a conductor, the resistance increases to the extent that the current-carrying capability of the conductor, and hence the maximum magnetic field generated by a coil, decreases significantly.

[0013] Particular embodiments of the invention may include one or more of the following features.

[0014] In some applications, the outer dimension of the coil assembly varies along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. For example, the outer dimension of adjacent double pancake coils may be monotonically non-increasing (i.e., is constant or decreases) along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. In the same way, the outer dimension of adjacent double pancake coils may be monotonically non-decreasing (i.e., is constant or increases) along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

[0015] In the same way, the inner dimension of the coil assembly may be varied along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. For example, the inner dimension of adjacent double pancake coils may be monotonically non-increasing (i.e., is constant or decreases) along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. Similarly, the inner dimension of adjacent double pancake coils may be monotonically non-decreasing (i.e., is constant or increases) along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. A first one of the pair of individual pancake coils of at least one of the double pancakes has a differing inner dimension than the other individual pancake of the pair. A portion of the superconductor wire connecting the pair of individual pancake coils may be rigidly affixed to the pancake coil of smaller inner dimension on a side surface adjacent the other of the pair of individual pancake coils to provide mechanical support to that portion bridging the individual pancake coils.

[0016] In other embodiments, one or more of the double pancakes may have a pair of individual pancake coils with inner dimensions which are substantially the same, but different than the inner dimensions of pancakes of another double pancake coil of the coil assembly. In one example, a coil assembly may include double pancakes formed of individual pancakes, each double pancake wound to have the same inner diameter. The double pancakes, however, all have different inner diameters, and are coaxially positioned along a longitudinal axis to provide a coil assembly with a variable inner diameter.

[0017] A superconducting magnetic coil assembly having a variable inner dimension may also have its outer dimension vary along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil. For example, in such embodiments, the outer dimension of adjacent double pancake coils may monotonically decrease or increase along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

[0018] The double pancake coils may be circularly shaped with the electrical connections between individual pancake coils of adjacent double pancake coils of substantially equivalent outer diameters. Alternatively, the double pancake coils may be racetrack or saddle-shaped (i.e., outermost radial regions which droop) . The superconductor is an anisotropic high temperature superconductor, such as a member of the bismuth (e.g., $Bi_2Sr_2Ca_2Cu_3O_x$ or, $Bi_2Sr_2Ca_1Cu_2O_x$ (BSCCO 2223 or BSCCO 2212)) or yttrium families of oxide superconductors. The superconductor may be formed as a superconductor tape, using monofilament or multi- filament composite superconductor. A multi- filament composite superconductor generally includes individual superconducting filaments which extend the length of the multi-filament composite conductor and are surrounded by a matrix- forming material. The multi- filament composite superconductor may, in certain applications, be twisted. Electrically conductive bridging segments formed, for example, as a superconductor tape comprising a composite superconductor material, may be used to provide the electrical connections between individual pancake coils of adjacent double pancake coils.

[0019] In another aspect of the invention a method for providing a superconducting magnetic coil assembly is set out in claim 18. In preferred embodiments, a portion of the superconductor wire connecting the pair of pancake coils is rigidly affixed to the pancake coil of smaller inner dimension on a side surface adjacent the other of the pair of individual pancake coils. The double pancake coil may also be connected with a bridging length of superconducting material.

[0020] Double pancake coils with varying inner and outer diameters can be combined to provide a desired field distribution within a fixed volume, for example to accommodate a constrained shape or a particular superconductor volume requirement. By this method, a magnetic field may be maximized while reducing the amount of superconductor at its end regions. Thus, the overall amount of superconductor generally needed to provide the level of magnetic field at the central region can be reduced. On the other hand, inner and/or outer dimensions may be selected to provide a substantially uniform or specially shaped magnetic field along its axial length.

[0021] Other advantages and features will become apparent from the following description and the claims.

Brief Description of the Drawing

[0022]

Fig. 1 is a cross-sectional view of a multi-filament composite conductor.

Fig. 2 is a perspective view of a multiply stacked superconducting coil having double pancake coils.

Fig. 3 is a cross-sectional view of Fig. 2 taken along line 3-3 of Fig. 2.

Fig. 4 illustrates a coil winding device.

Fig. 5 is a cross-sectional view of an alternate embodiment of the invention.

Fig. 6 is a cross-sectional view of an alternate embodiment of the invention in which the inner diameter of the coil assembly varies.

Fig. 7 is a cross-sectional view of an alternate embodiment of the invention in which the inner diameter of the coil assembly varies.

Fig. 8 is a side view of a double pancake taken along lines 8-8 of Fig. 7.

Description of the Preferred Embodiments

[0023] Referring to Figs. 2- 3, a mechanically robust, high- performance superconducting coil assembly 10 combines multiple double "pancake" coils 12- 17, here, six separate double pancake sections, each having co-wound composite conductors. Each double "pancake" coil has co- wound conductors wound in parallel which are then stacked coaxially on top of each other. The illustrated conductor is a high temperature copper oxide ceramic superconducting material, such as $Bi_2Sr_2Ca_2Cu_3O_x$, commonly designated BSCCO 2223. Each double pancake coil 12- 17 includes a pancake coil 12a- 17a having a diameter smaller than its associated pancake coil 12b- 17b of the double pancake, the two coils of a pair being wound from the same continuous length of superconducting tape using the approach described below in conjunction with Fig. 4. Double pancake coils 12- 17 are shown in Figs. 2 and 3 as being circularly shaped; however, in other applications each double pancake may have other shapes commonly used for making magnetic coils, including racetrack and saddle- shaped coils.

[0024] An inner support tube 18 supports coils 12-17 with a first end member 19 attached to the top of inner support tube 18 and a second end member 20 threaded onto the opposite end of the inner support tube in order to compress the double "pancake" coils. Inner support tube 18 and end members 19, 20 are fabricated from a nonmagnetic material, such as aluminum or plastic (for example, G-10). In some applications, inner support tube 18 and end members 19, 20 can be removed to form a freestanding coil assembly. The current is assumed to flow in a counter-clockwise direction as shown in Fig. 3, with the magnetic field vector 26 along the axis (Fig. 2) being generally normal to end member 19 (in the direction of longitudinal axis 29) which forms the top of coil assembly 10.

[0025] Short bridging segments 22 of superconducting material are used to electrically connect the individual double pancake coils 12- 17 together in a series circuit and are formed of the same $Bi_2Sr_2Ca_2Cu_3O_x$ material used for winding the coils themselves. Alternatively, a heavier bridging material may be used. Furthermore, segments 22 interconnect adjacent double pancakes along interfaces where the outer diameters of the individual pancakes are substantially the same. For example, a segment 22 is shown bridging pancakes 12b and 13a of double pancakes 12 and 13, respectively. Short bridging segments 22 are only required along the outer diameter of the coil assembly because the interfaces between pancakes of different diameters lie along the inner diameter of the coil assembly 10 where no "joint" exists by virtue of the double pancake winding technique described immediately below in conjunction with Fig. 4. By providing adjacent pancake coils of substantially the same outer diameter, the superconductor bridging segments need not be bent or otherwise tensioned, thereby avoiding the undesirable effects noted above. A length of superconducting material (not shown) also connects one end of coil assembly 10 to one of the termination posts 24 located on end member 18 in order to supply current to coil assembly 10. The bridging segments may be fabricated from metal, composite superconductor, or a pure superconductor.

[0026] The distribution of superconductor along the axial length of coil assembly 10 is not uniform but includes a greater amount of superconductor at central regions of the assembly than at end regions. This configuration of double pancakes 12-17 is well suited for applications in which an increase in the magnetic field at a center region 23 of coil assembly 10 is desired and the level of magnetic field at outer end regions 25 of the coil is of less importance. Although the level of magnetic field could be accomplished using a superconducting magnetic coil having a uniform outer diameter equal to that of the largest diameter pancake of coil assembly 10, for example, pancakes 14b and 15a, this magnetic field would have been achieved using a greater amount of superconductor, which is then required to be cooled, and therefore is less energy efficient.

[0027] Referring to Fig. 4, an approach for forming each one of double "pancake" coils 12-17 is described. This approach is described more fully in WO-A-95/20826 by M.D. Manlief, G.N. Riley, Jr., J. Voccio, and A.J. Rodenbush, entitled "Superconducting Composite Wind-and-React Coils and Methods of Manufacture", assigned to the assignee of the present invention. In the approach shown in Fig. 4, a mandrel 30 is first mounted on a winding shaft 32 which is mounted in lathe chuck 31. A storage spool 36 is mounted on the winding shaft 32, and a first portion of the total length of tape 33, initially wrapped around spool 34 and needed for winding one of the pancakes (generally the larger diameter pancake), is wound onto the storage spool 36, resulting in the length of tape 33 being shared between the two spools. The spool 34 mounted to the arm 35 contains the first portion of the length of tape 33, and the storage spool 36 containing the second portion of the tape 33 is secured so that it does not rotate relative to mandrel 30. The cloth 37 wound on the insulation spool 38 is then mounted on the arm 35. The mandrel is then rotated, and the cloth 37 is co-wound onto the mandrel 30 with the first portion of the tape 33 to form a single "pancake" coil. Thermocouple wire is wrapped around the first "pancake" coil in order to secure it to the mandrel. The winding shaft 32 is then removed from the lathe chuck 31, and the storage spool 36 containing the second portion of the length of tape 33 is mounted on arm 35. A layer of insulating material is then placed against the first "pancake" coil, and the second half of the tape 33 and the cloth 37 are then co-wound on the mandrel 30 using the process described above. This results in the formation of a second "pancake" coil adjacent to the "pancake" coil formed initially, with a layer of insulating material separating the two coils. Thermocouple wire is then wrapped around the second "pancake" coil to support the coil structure during the final heat treatment. Voltage taps and thermocouple wire can be attached at various points on the tape 33 of the double "pancake" coil in order to monitor the temperature and electrical behavior of the coil. In addition, all coils can be impregnated with epoxy after heat treating in order to improve insulation properties and hold the various layers firmly in place. The double "pancake" coil allows one edge of the entire length of tape to be exposed directly to the oxidizing environment during the final heat treating step. Multiple layers of superconductor may be alternatingly wound with layers of insulating material to form the coils. Layers of strengthening material may also be wound between the layers of superconductor. Other approaches for forming the double pancake coils, such as the well-known react-and-wind method may also be used.

[0028] The arrangement of double pancake coils described above and shown in Figs 2 and 3 provides a relatively energy efficient superconducting coil assembly where the magnetic field is high at the center of the coil. The concept of the invention can also be used to provide a superconducting magnetic coil, wound with an anisotropic superconductor material, where the objective is to achieve uniformity of the current carrying capacity of the coil across its axial length.

[0029] For example, referring to Fig. 5, the outer diameters of double pancakes 60-65 become increasingly larger from a center region 67 of the coil to the end regions 69 in order to compensate for the decrease in current carrying capacity which is related to the magnitude of the perpendicular component of the magnetic field. As is well known in the art (when using anisotropic superconducting materials, such as the Cu-O-based ceramic superconductor described above) the perpendicular component of the magnetic field is at a minimum in the central region of the coil where the lines are generally parallel with the longitudinal axis of the coil and becomes increasingly perpendicular at end regions where the flux lines bend around to close the loop.

[0030] Any arrangement of pairs of pancake coils where the outer diameter of adjacent pancakes are substantially the same can be used to provide the desired magnetic field characteristic of the coil assembly. For example, coil assemblies having double pancakes wound to have pancakes of different diameters can be used equally as well with individual pancakes or with double pancake coils of uniform outer diameter. The coil assemblies may have a longitudinal, outer diameter profile which, from a central region of the coil, increases or decreases along the longitudinal axis toward the end regions of the coil. Alternatively, the outer diameter profile may be stepped up and down along the axis of the coil to provide any desired field shaping profile or to accommodate a constrained geometry, such as the rotor coil of a motor. The concept of the invention is also applicable to superconducting magnetic coils of various shapes including racetrack magnets, solenoids and multipole magnets.

[0031] Moreover, the concept is applicable to arrangements in which the inner dimension profile of a superconducting magnetic coil assembly varies with the outer profile varying as described above. A coil assembly with this arrangement may be provided using, for example, double pancakes having the same outer diameter, but each having a different inner diameter (the individual pancakes of each double pancake having the same inner diameter) . The double pancakes are then positioned along a longitudinal axis of the coil assembly so that, for example, the inner diameter of the assembly monotonically increases or decreases along the axis.

[0032] Referring to Figs. 6 and 7, in other embodiments, double pancake coils, positioned along a longitudinal axis 100 of their respective coil assemblies 80, 90, have individual pancakes of different inner diameter. Short lengths of bridging segments 81 are used to electrically interconnect the adjacent double pancakes of different inner diameter at interfaces along the outer diameter of the coil. Like those embodiments in which the outer profile is stepped, various shapes of coils and various stepped inner profiles may be used depending on the particular application. An inner support tube may or may not be used to support the individual double pancakes.

[0033] Referring to Fig. 6, superconducting magnetic coil assembly 80 includes pancake coils 82-87 arranged so that their inner diameters decrease from a center region 88 of the coil to end regions 89. Such an arrangement might be desirable for superconductive motor or superconducting accelerometer applications. For example, in a superconductive electric motor application, one or more stators may be manufactured using superconducting double pancakes having a varying inner diameter like that shown in Fig. 6. In this way, the stators can closely follow the outer shape of the rotor positioned within the inner bore.

[0034] Referring to Fig. 7, a superconducting magnetic coil assembly 90 includes pancake coils 92-97 with their inner diameters increasing from a center region 98 to end regions 99. A coil having this arrangement might be attractive in magnetic resonance imaging and chemical spectroscopy applications. Note that in this particular embodiment, the individual pancake coils 92a-92b, 97a-97b which make up outer pancake coils 92 and 97, respectively, are of the configuration, described above in conjunction with Figs. 2 and 3. That is, the inner diameters of these double pancake coils are substantially constant, with different outer diameters.

[0035] Pancake coils 82-87 and 93-96 of Figs. 6 and 7, respectively, are wound in the same general manner as described in conjunction with Fig. 4. However, the mandrel would be configured to have portions with different outer diameters, each for accommodating winding of the individual pancakes of the double pancake. For example, a first portion of the superconducting tape is wound over a first outer diameter portion of the mandrel to form the first of the "single" pancake coils. The remaining tape on the storage spool is then moved to the arm and the second of the two individual pancakes is wound over the second different outer diameter portion of the mandrel. Depending on the degree of change in the differing diameter portions of the mandrel, a guide or track element may be provided to lend support to the tape at the transition between individual pancakes. Such a guide element may be necessary to reduce possible fracturing of the tape or bending strains which can adversely effect the current carrying capability of the tape.

[0036] Referring to Fig. 8, a side view of a representative one of the double pancake coils of coil assembly 90 shows the interface between the individuals pancakes 94a and 94b of double pancake 94. As shown in the figure, a spiral portion 102 of the superconducting tape unwinds from the inner diameter of pancake 94a to the inner diameter of 94b. When the double pancake is epoxy impregnated, the spiral portion 102 of the tape is rigidly fixed to inner side surface 104 of pancake 94b to provide mechanical support to the spiral portion. In some applications, it may be appropriate to entirely epoxy impregnate that region of differing diameters between pancake coils 94a, 94b.

[0037] Thus, it should be appreciated that combining double pancake coils with varying inner and outer diameters offers coil designers a high degree of freedom in providing a desired field distribution. Such coils can be arranged to provide a field with a high level of homogeneity or one with a high magnitude level at a specific area.

[0038] Other embodiments are within the claims.

Claims

1. A superconducting magnetic coil assembly comprising:

   at least a plurality of double pancake coils, coaxially disposed along a longitudinal axis of the coil assembly, each double pancake of the plurality of double pancake coils having a pair of individual pancake coils, each individual pancake coil including an anisotropic high temperature superconductor wound about a longitudinal axis of the coil assembly and defining a bore of the superconducting magnetic coil assembly, each of the plurality of double pancake coils electrically connected to an adjacent one of the plurality of double pancake coils, the coil assembly of electrically connected pancake coils having a varying radial cross section with respect to the longitudinal axis, wherein the bore is centered about the longitudinal axis, wherein the individual coils of each of the plurality of double pancake coils have a different outer dimension from each other, and wherein the outer dimensions of adjacent pancake coils of the adjacent double pancake coils are substantially the same.

2. The superconducting magnetic coil assembly of claim 1, wherein each individual pancake includes

an outer edge parallel to the longitudinal axis, and a spacing from an outer edge of the individual pancake coils to the longitudinal axis varies along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

3. The superconducting magnetic coil assembly of claim 2, wherein the spacing from the outer edge of the individual pancake coils to the longitudinal axis is monotonically non-increasing along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

4. The superconducting magnetic coil assembly of claim 2, wherein the spacing from the outer edge of the individual pancake coils to the longitudinal axis is monotonically non-decreasing along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

5. The superconducting magnetic coil assembly of claim 2, wherein the spacing from the outer edge of the individual pancake coils to the longitudinal axis increases along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

6. The superconducting magnetic coil assembly of claim 1, wherein the individual pancake coils of each double pancake coil are electrically connected to an individual pancake coil of an adjacent double pancake coil along an outer edge of the adjacent double pancake coil.

7. The superconducting magnetic coil assembly of claim 6, wherein each individual pancake includes an outer edge parallel to the longitudinal axis, and a spacing between the outer edge of adjacent double pancake coils and the longitudinal axis is monotonically non-increasing along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

8. The superconducting magnetic coil assembly of claim 6, wherein each individual pancake includes an outer edge parallel to the longitudinal axis, and a spacing between the outer edge of the individual pancake coils and the longitudinal axis of adjacent double pancake coils is monotonically non-decreasing along the longitudinal axis of the superconducting magnetic coil from a central region to end regions of the superconducting magnetic coil.

9. The superconducting magnetic coil assembly of claim 1, wherein the double pancake coils are circularly shaped.

10. The superconducting magnetic coil assembly of claim 1, wherein the double pancake coils are racetrack shaped.

11. The superconducting magnetic coil assembly of claim 1, wherein the double pancake coils are saddle-shaped.

12. The superconducting magnetic coil assembly of claim 1, wherein the anisotropic high temperature superconductor is a member of the bismuth family of oxide superconductors.

13. The superconducting magnetic coil assembly of claim 1, wherein the anisotropic high temperature superconductor is a member of the yttrium family of oxide superconductors.

14. The superconducting magnetic coil assembly of claim 1, wherein the superconductor is formed as a superconductor tape comprising a multi-filament composite superconductor including individual superconducting filaments which extend the length of the mult-filament composite conductor and are surrounded or supported by a matrix-forming material.

15. The superconducting magnetic coil assembly of claim 1, wherein electrically conductive bridge segments provide the electrical connections between individual pancake coils of adjacent double pancake coils.

16. The superconducting magnetic coil assembly of claim 15, wherein the electrically conductive bridging segments are formed as a superconductor tape comprising a composite superconductor material.

17. The superconducting magnetic coil assembly of claim 1, wherein at least one of the double pancake coils includes a pair of pancake coils wound about the longitudinal axis from a continuous length of superconducting material.

18. A method for providing a superconducting magnetic coil assembly having a varying radial cross section along a longitudinal axis of the coil assembly comprising the steps of:

a) providing double pancake coils, each comprising a pair of pancake coils wound from a continuous length of anisotropic high temperature superconductor about the longitudinal axis of the coil assembly, each individual pancake including an outer edge and an inner edge both being parallel to the longitudinal axis, and at least one of said double pancake coils including a pair of pancake coils having a different spacing between an inner edge of the individual pancake coils and the longitudinal axis;

b) coaxially positioning the double pancake coils along the longitudinal axis so that at least one pancake coil of each double pancake coil has a spacing between an outer edge of the individual pancake coil and the longitudinal axis substantially equal to a spacing between an outer edge of the individual pancake coil and the longitudinal axis of an adjacent pancake coil of an adjacent double pancake; and

c) electrically connecting the at least one pancake coil of each double pancake to the pancake coil of the adjacent double pancake having substantially equal spacing between an outer edge of the individual pancake and the longitudinal axis.

19. The method of claim 18, further comprising the step of rigidly affixing a portion of the superconductor connecting the pair of pancake coils to the pancake coil having a smaller spacing between an inner edge of the individual pancake coil and the longitudinal axis on a side surface adjacent the other of the pair of individual pancake coils.

20. The method of claim 18, further comprising the step of connecting said double pancake coils with a substantially unbent length of superconducting material.

Patentansprüche

1. Supraleitende Magnetspulenanordnung mit:

mindestens mehreren Doppel-Flachspulen, die entlang einer Längsachse der Spulenanordnung koaxial angeordnet sind, wobei jede Doppel-Flachspule der mehreren Doppel-Flachspulen ein Paar Einzel-Flachspulen umfasst, wobei jede Einzel-Flachspule einen anisotropen Hochtemperatursupraleiter beinhaltet, der um eine Längsachse der Spulenanordnung gewikkelt ist und eine Öffnung der supraleitenden Magnetspulenanordnung definiert, wobei jede der mehreren Doppel-Flachspulen mit einer benachbarten der mehreren Doppel-Flachspulen elektrisch verbunden ist, wobei der radiale Querschnitt der Spulenanordnung aus elektrisch miteinander verbundenen Flachspulen in Bezug zur Längsachse variiert, wobei die Längsachse das Zentrum der Öffnung bildet, wobei die Einzel-Flachspulen von jeder der mehreren Doppel-Flachspulen eine unterschiedliche Außenabmessung voneinander aufweist, und wobei die Außenabmessungen von benachbarten Flachspulen der benachbarten Doppel-Flachspulen im wesentlichen gleich sind.

2. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei jede Einzel-Flachspule einen parallel zur Längsachse verlaufenden Außenrand hat, und wobei ein Abstand von einem Außenrand der Einzel-Flachspulen zur Längsachse entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule variiert.

3. Supraleitende Magnetspulenanordnung nach Anspruch 2, wobei der Abstand vom Außenrand der Einzel-Flachspulen zur Längsachse entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule monoton nicht größer wird.

4. Supraleitende Magnetspulenanordnung nach Anspruch 2, wobei der Abstand vom Außenrand der Einzel-Flachspulen zur Längsachse entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule monoton nicht kleiner wird.

5. Supraleitende Magnetspulenanordnung nach Anspruch 2, wobei der Abstand vom Außenrand der Einzel-Flachspulen zur Längsachse entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule größer wird.

6. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei die Einzel-Flachspulen jeder Doppel-Flachspule mit einer Einzel-Flachspule einer benachbarten Doppel-Flachspule entlang eines Außenrandes der benachbarten Doppel-Flachspule elektrisch verbunden sind.

7. Supraleitende Magnetspulenanordnung nach Anspruch 6, wobei jede Einzel-Flachspule einen parallel zur Längsachse verlaufenden Außenrand hat, und wobei ein Abstand zwischen dem Außenrand benachbarter Doppel-Flachspulen und der Längsachse entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule monoton nicht größer wird.

8. Supraleitende Magnetspulenanordnung nach Anspruch 6, wobei jede Einzel-Flachspule einen parallel zur Längsachse verlaufenden Außenrand hat, und wobei ein Abstand zwischen dem Außenrand der Einzel-Flachspulen und der Längsachse benachbarter Doppel-Flachspulen entlang der Längsachse der supraleitenden Magnetspule von einem zentralen Bereich zu Randbereichen der supraleitenden Magnetspule monoton nicht kleiner wird.

9. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei die Doppel-Flachspulen kreisförmig sind.

10. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei die Doppel-Flachspulen laufbahnförmig sind.

11. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei die Doppel-Flachspulen sattelförmig sind.

12. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei der anisotrope Hochtemperatursupraleiter der Wismut-Familie von Oxid-Supraleitern angehört.

13. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei der anisotrope Hochtemperatursupraleiter der Yttrium-Familie von Oxid-Supraleitern angehört.

14. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei der Supraleiter als Supraleiter-Band ausgeführt ist, das einen aus mehreren Fäden bestehenden zusammengesetzten Supraleiter umfasst, wobei einzelne supraleitende Fäden die Länge des aus mehreren Fäden bestehenden zusammengesetzten Leiters übersteigen und von einem matrixbildenden Material umgeben sind oder von diesem getragen werden.

15. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei elektrisch leitfähige Brückensegmente die elektrischen Verbindungen zwischen Einzel-Flachspulen benachbarter Doppel-Flachspulen bilden.

16. Supraleitende Magnetspulenanordnung nach Anspruch 15, wobei die elektrisch leitfähigen Brückensegmente als Supraleiter-Band, das ein zusammengesetztes supraleitendes Material enthält, ausgeführt sind.

17. Supraleitende Magnetspulenanordnung nach Anspruch 1, wobei mindestens eine der Doppel-Flachspulen ein Paar Flachspulen umfasst, die aus einer Endloslänge supraleitenden Materials um die Längsachse gewickelt sind.

18. Verfahren zum Bilden einer supraleitenden Magnetspulenanordnung mit einem radialen Querschnitt, der entlang einer Längsachse der Spulenanordnung variiert, mit den Schritten:

a) Bilden von Doppel-Flachspulen, von denen jede ein Paar Flachspulen umfasst, die aus einer Endloslänge eines anisotropen Hochtemperatursupraleiters um die Längsachse der Spulenanordnung gewickelt sind, wobei jede Einzel-Flachspule einen Außenrand und einen Innenrand hat, die beide parallel zur Längsachse verlaufen, und wobei mindestens eine der aus einem Flachspulenpaar bestehenden Doppel-Flachspulen einen unterschiedlichen Abstand zwischen einem Innenrand der Einzel-Flachspulen und der Längsachse hat;
b) koaxiales Anordnen der Doppel-Flachspulen entlang der Längsachse, so dass mindestens eine Flachspule jeder Doppel-Flachspule einen Abstand zwischen einem Außenrand der Einzel-Flachspule und der Längsachse hat, der einem Abstand zwischen einem Außenrand der Einzel-Flachspule und der Längsachse einer benachbarten Flachspule einer benachbarten Doppel-Flachspule im Wesentlichen gleich ist; und
c) elektrisches Verbinden der mindestens einen Flachspule jeder Doppel-Flachspule mit der Flachspule der benachbarten Doppel-Flachspule, deren Abstand zwischen einem Außenrand der Einzel-Flachspule und der Längsachse im Wesentlichen gleich ist.

19. Verfahren nach Anspruch 18, zusätzlich mit dem Schritt des festen Anbringens eines Abschnitts des Supraleiters, der das Flachspulenpaar mit der Flachspule mit dem kleineren Abstand zwischen einem Innenrand der Einzel-Flachspule und der Längsachse verbindet, und zwar an einer der anderen aus dem Paar von Einzel-Flachspulen benachbarten Seitenfläche.

20. Verfahren nach Anspruch 18, zusätzlich mit dem Schritt des Verbindens der Doppel-Flachspulen mit einer im Wesentlichen nicht gekrümmten Länge supraleitenden Materials.

Revendications

1. Ensemble de bobine magnétique supraconductrice, comprenant:

au moins une pluralité de bobines plates doubles, qui sont disposées de façon coaxiale le long d'un axe longitudinal de l'ensemble de bobine, chaque galette double de la pluralité de bobines plates doubles comprenant une paire de bobines plates individuelles, chaque bobine plate individuelle comprenant un supraconducteur à haute température anisotrope enroulé autour d'un axe longitudinal de l'ensemble de bobine et définissant un alésage de l'ensemble de bobine magnétique supraconductrice, chacune de la pluralité de bobines plates doubles étant électriquement connectée à une de la pluralité de bobines plates doubles voisine, l'ensemble de bobine de bobines plates électriquement connectées présentant une section radiale variable par rapport à l'axe longitudinal, dans lequel l'alésage est centré autour de l'axe longitudinal, dans lequel les bobines individuelles de chacune de la pluralité de bobines plates doubles présentent une dimension extérieure différente l'une de l'autre, et dans lequel les dimensions extérieures de bobines plates voisines des bobines plates doubles voisines sont sensiblement identiques.

2. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel chaque galette individuelle comprend un bord extérieur parallèle à l'axe longitudinal, et un espace entre un bord extérieur des bobines plates individuelles et l'axe longitudinal varie le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

3. Ensemble de bobine magnétique supraconductrice selon la revendication 2, dans lequel l'espace entre le bord extérieur des bobines plates individuelles et l'axe longitudinal est monotoniquement non-croissant le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

4. Ensemble de bobine magnétique supraconductrice selon la revendication 2, dans lequel l'espace entre le bord extérieur des bobines plates individuelles et l'axe longitudinal est monotoniquement non-décroissant le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

5. Ensemble de bobine magnétique supraconductrice selon la revendication 2, dans lequel l'espace entre le bord extérieur des bobines plates individuelles et l'axe longitudinal augmente le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

6. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel les bobines plates individuelles de chaque bobine plate double sont électriquement connectées à une bobine plate individuelle d'une bobine plate double voisine le long d'un bord extérieur de la bobine plate double voisine.

7. Ensemble de bobine magnétique supraconductrice selon la revendication 6, dans lequel chaque galette individuelle comprend un bord extérieur parallèle à l'axe longitudinal, et un espace entre le bord extérieur de bobines plates doubles voisines et l'axe longitudinal est monotoniquement non-croissant le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

8. Ensemble de bobine magnétique supraconductrice selon la revendication 6, dans lequel chaque galette individuelle comprend un bord extérieur parallèle à l'axe longitudinal, et un espace entre le bord extérieur des bobines plates individuelles et l'axe longitudinal de bobines plates doubles voisines est monotoniquement non-décroissant le long de l'axe longitudinal de la bobine magnétique supraconductrice à partir d'une région centrale jusqu'à des régions d'extrémité de la bobine magnétique supraconductrice.

9. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel les bobines plates doubles sont de forme circulaire.

10. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel les bobines plates doubles sont en forme de piste de course.

11. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel les bobines plates doubles sont en forme de selle.

12. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel le supraconducteur à haute température anisotrope est un élément de la famille du bismuth des supraconducteurs d'oxyde.

13. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel le supraconducteur à haute température anisotrope est un élément de la famille de l'yttrium des supraconducteurs d'oxyde.

14. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel le supraconducteur est formé comme un ruban supraconducteur comprenant un supraconducteur composite à filaments multiples comprenant des filaments supraconducteurs individuels qui étendent la longueur du conducteur composite à filaments multiples et qui sont entourés ou supportés par un matériau de formation de matrice.

15. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel des segments de pont électriquement conducteurs assurent les connexions électriques entre des bobines plates individuelles de bobines plates doubles voisines.

16. Ensemble de bobine magnétique supraconductrice selon la revendication 15, dans lequel les segments de pont électriquement conducteurs sont formés comme un ruban supraconducteur comprenant un matériau supraconducteur composite.

17. Ensemble de bobine magnétique supraconductrice selon la revendication 1, dans lequel au moins une des bobines plates doubles comprend une paire de bobines plates qui sont enroulées autour de l'axe longitudinal à partir d'une longueur continue de matériau supraconducteur.

18. Procédé pour former un ensemble de bobine magnétique supraconductrice présentant une section radiale variable le long d'un axe longitudinal de l'ensemble de bobine, comprenant les étapes suivantes:

a) fournir des bobines plates doubles, comprenant chacune une paire de bobines plates qui sont enroulées à partir d'une longueur continue d'un supraconducteur à haute température anisotrope autour de l'axe longitudinal de l'ensemble de bobine, chaque galette individuelle comprenant un bord extérieur et un bord intérieur tous les deux parallèles à l'axe longitudinal, et au moins une desdites bobines plates doubles comprenant une paire de bobines plates présentant un espace différent entre un bord intérieur des bobines plates individuelles et l'axe longitudinal;
b) positionner de façon coaxiale les bobines plates doubles le long de l'axe longitudinal de telle sorte qu'au moins une bobine plate de chaque bobine plate double présente un espace entre un bord extérieur de la bobine plate individuelle et l'axe longitudinal qui est sensiblement égal à un espace entre un bord extérieur de la bobine plate individuelle et l'axe longitudinal d'une bobine plate voisine d'une galette double voisine; et
c) connecter électriquement ladite au moins une bobine plate de chaque galette double à la bobine plate de la galette double voisine qui présente un espace sensiblement égal entre un bord extérieur de la galette individuelle et l'axe longitudinal.

19. Procédé selon la revendication 18, comprenant en outre l'étape de fixation rigide d'une partie du supraconducteur pour connecter la paire de bobines plates à la bobine plate qui présente un espace plus petit entre un bord intérieur de la bobine plate individuelle et l'axe longitudinal sur une surface latérale voisine à l'autre de la paire de bobines plates individuelles.

20. Procédé selon la revendication 18, comprenant en outre l'étape de connexion desdites bobines plates doubles avec une longueur sensiblement non pliée de matériau supraconducteur.

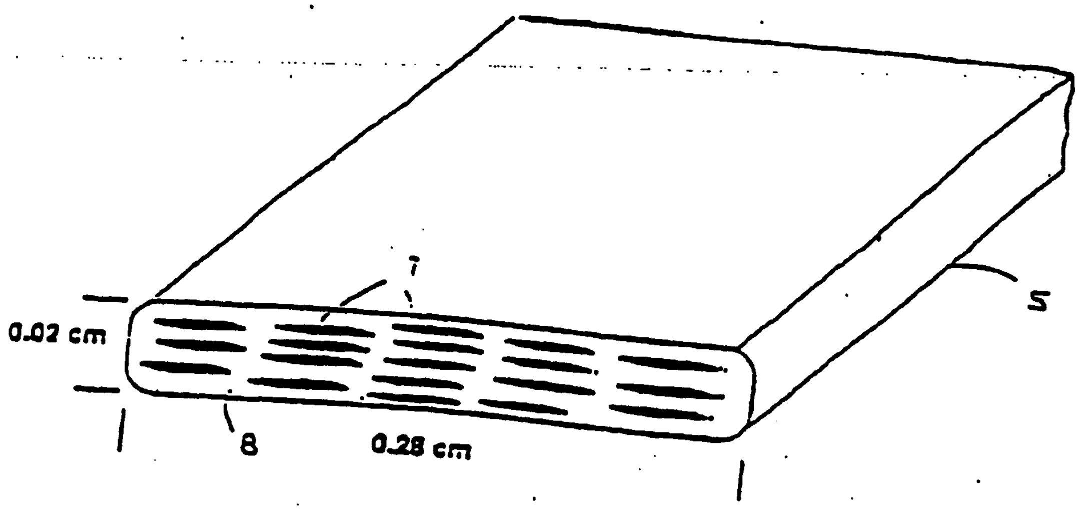

Fig. 1
(PRIOR ART)

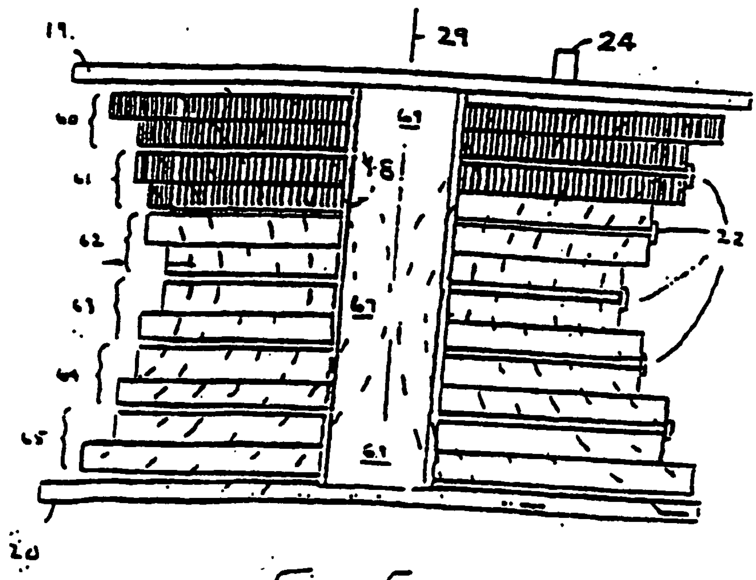

Fig. 5

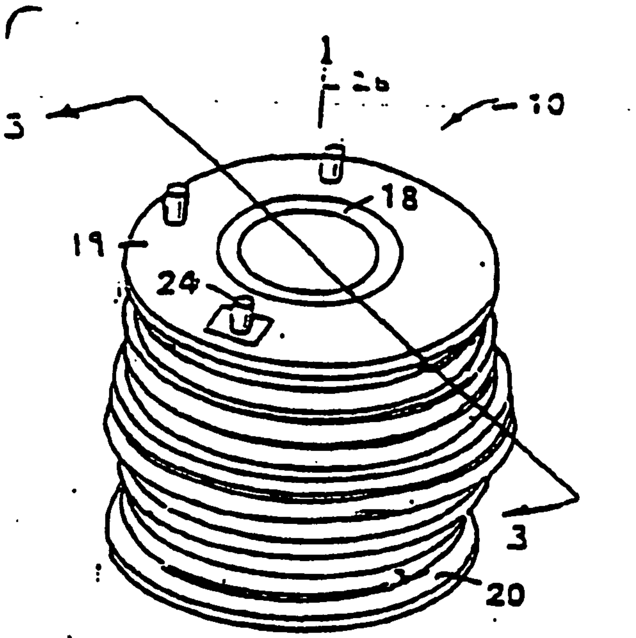

FIG. 2

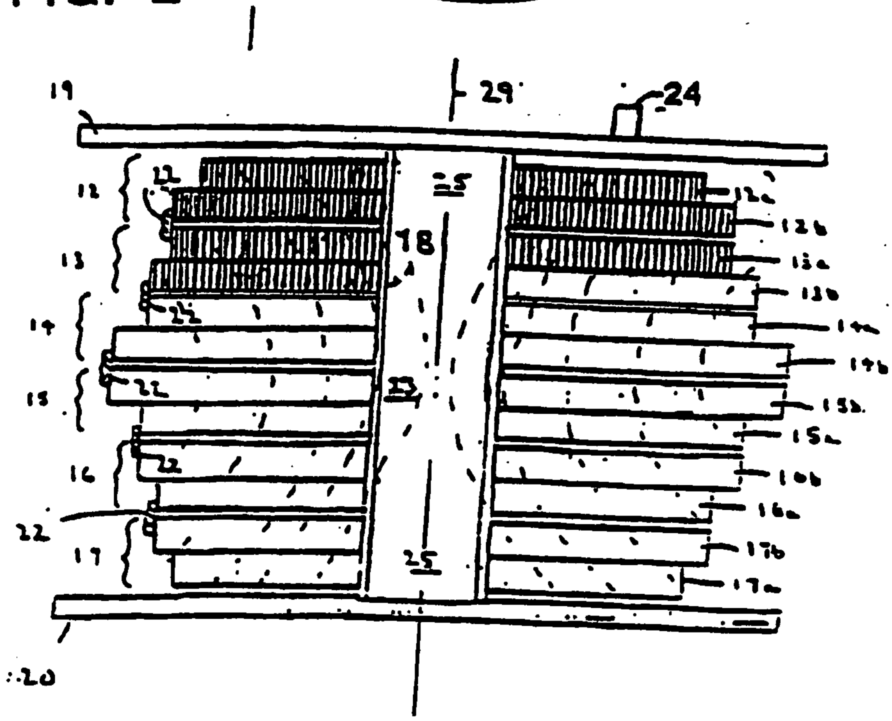

FIG. 3

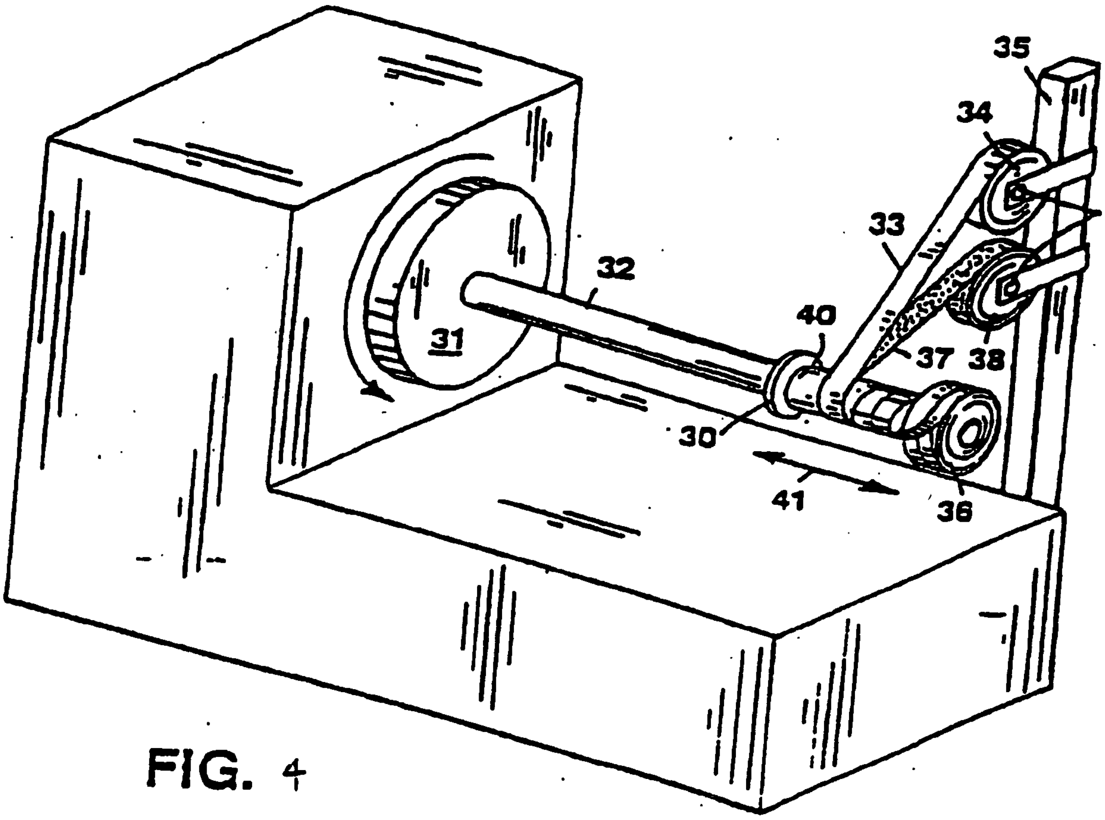

FIG. 4

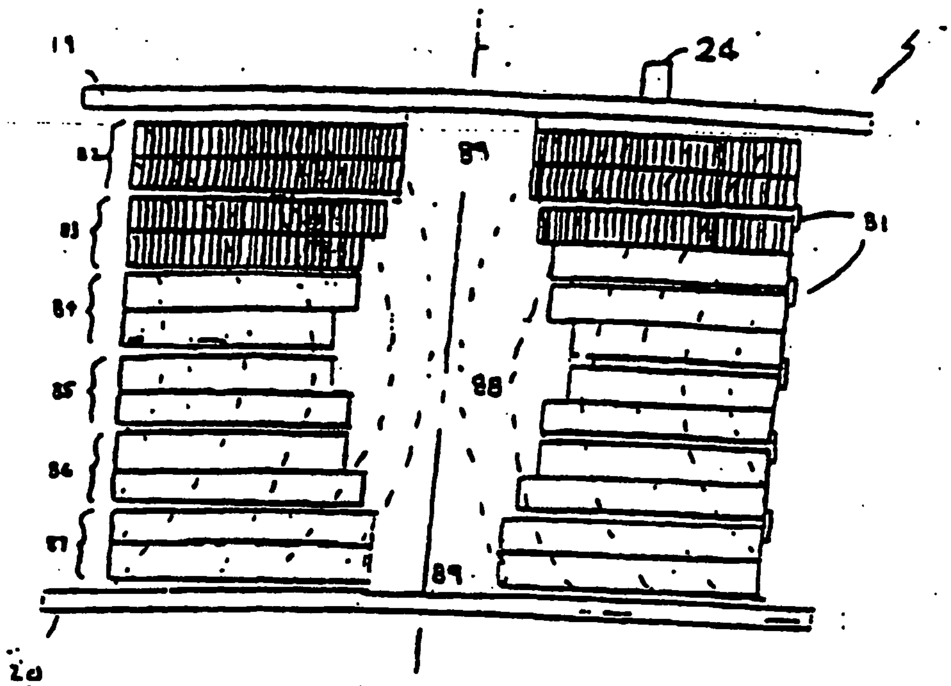

Fig. 6

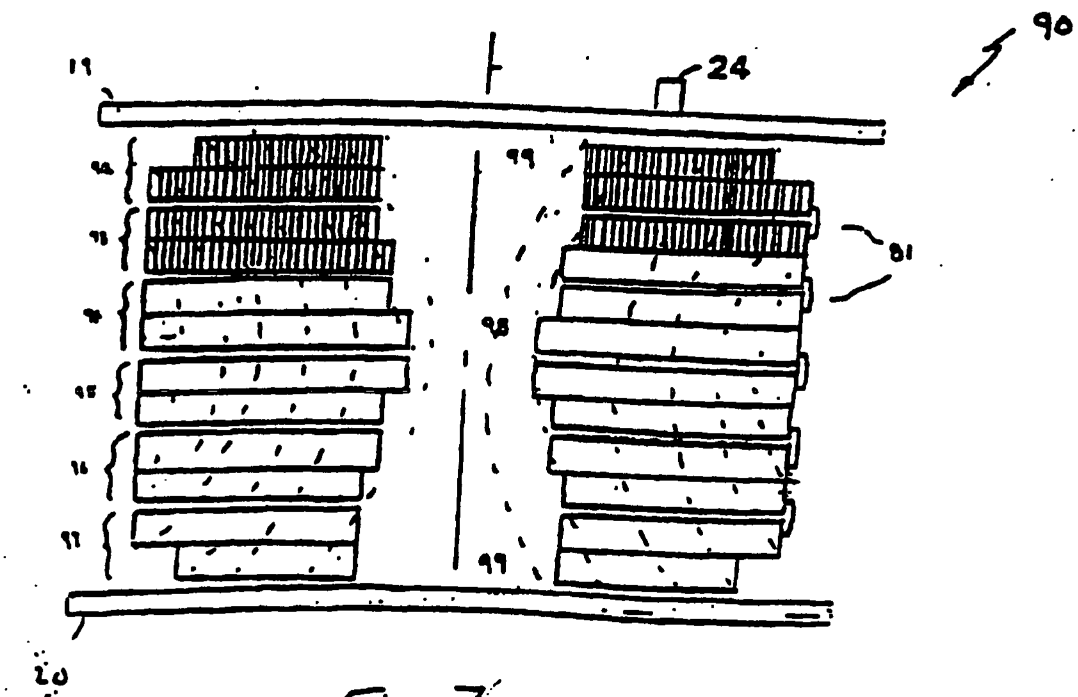

Fig. 7

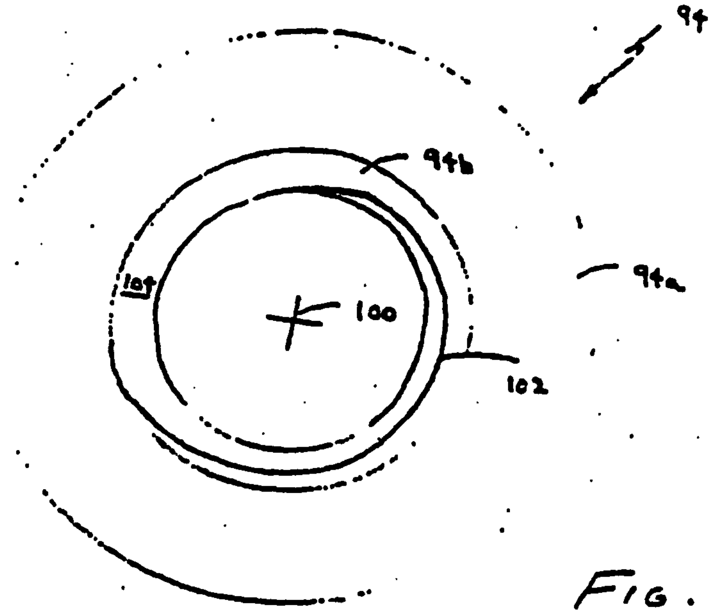

FIG. 8

REFERENCES CITED IN THE DESCRIPTION

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