United States Patent

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[72] Inventor **James Dao**
Alameda, Calif.

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[73] Assignee **Air Reduction Company, Incorporated**
New York, N.Y.

[54] **ELECTROMAGNET STRUCTURE**
7 Claims, 4 Drawing Figs.

[52] **U.S. Cl.** **335/216,** 335/299
[51] **Int. Cl.** **H01f 7/22**
[50] **Field of Search** 174/DIG. 6; 336/250; 29/599; 335/299, 216

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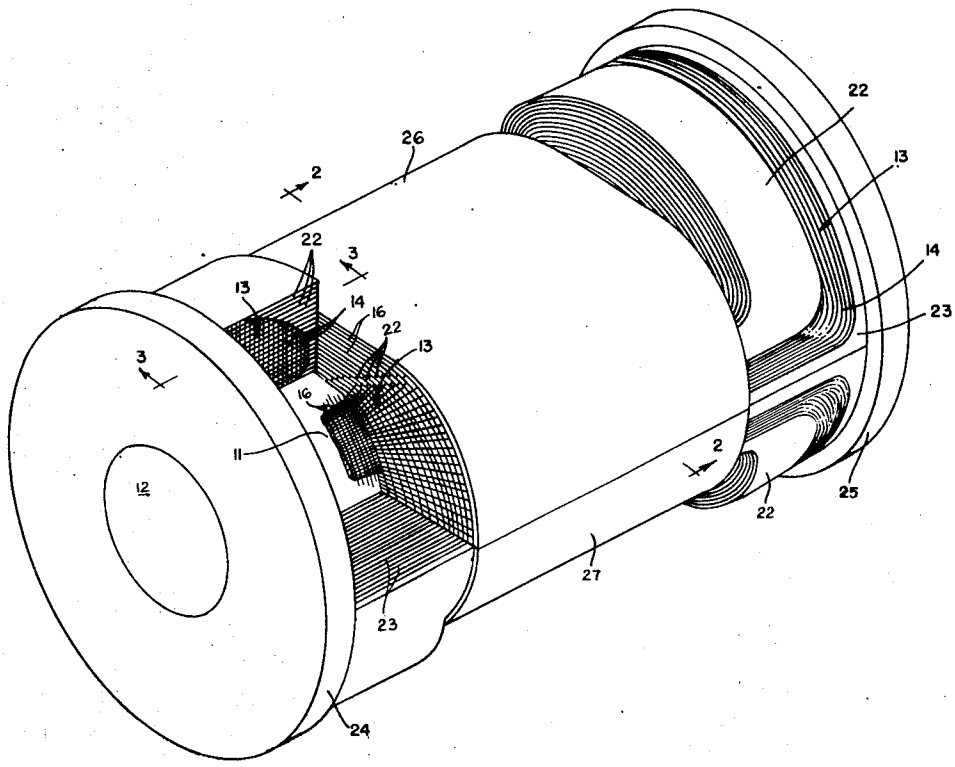
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Primary Examiner—G. Harris
Attorney—Anderson, Luedeka, Fitch, Even & Tabin

ABSTRACT: An electromagnet structure is described for producing high-strength magnetic fields. Individual layers of electrical coil layers are stacked on a support and comprise a coil structure. Each of the coil layers is individually reinforced against displacement away from the support by a wound reinforcing layer of material having substantial tensile strength.



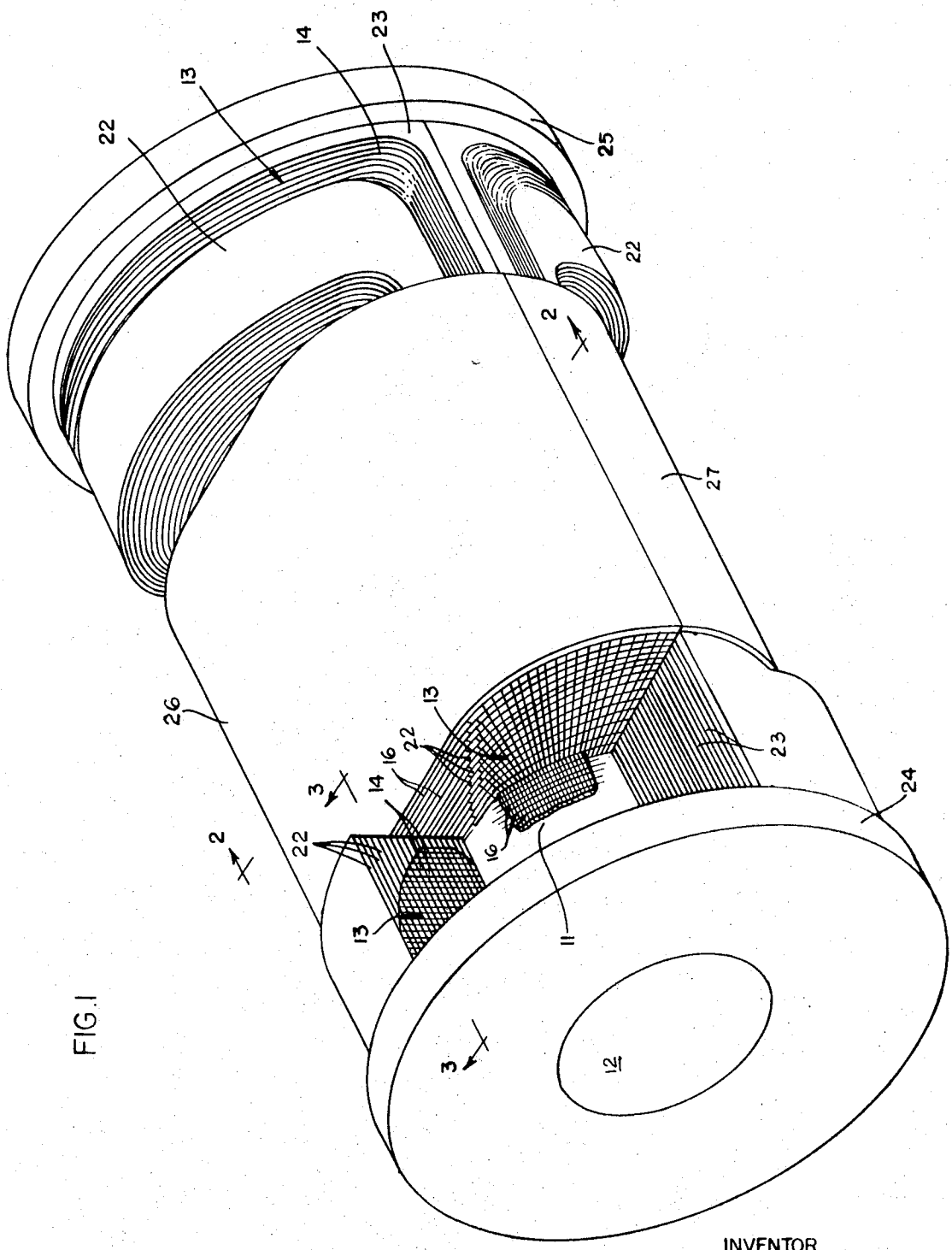


FIG. 1

INVENTOR
JAMES DAO

Anderson, Luedeka, Fitch, Even & Tabin
ATTYS.

FIG.2

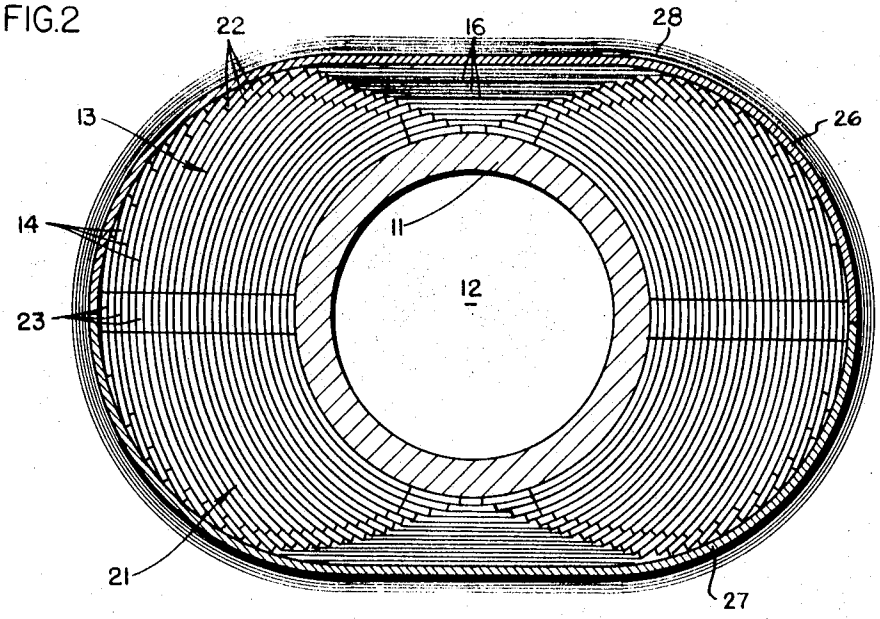


FIG.3

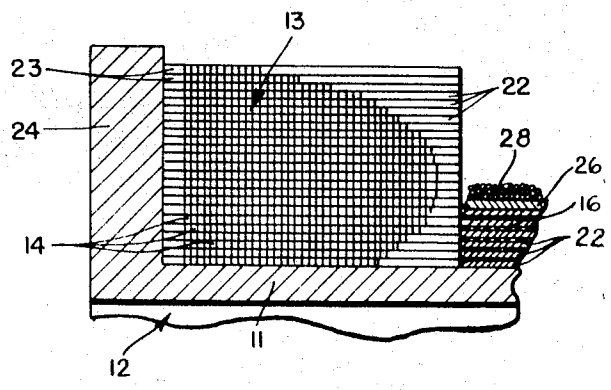
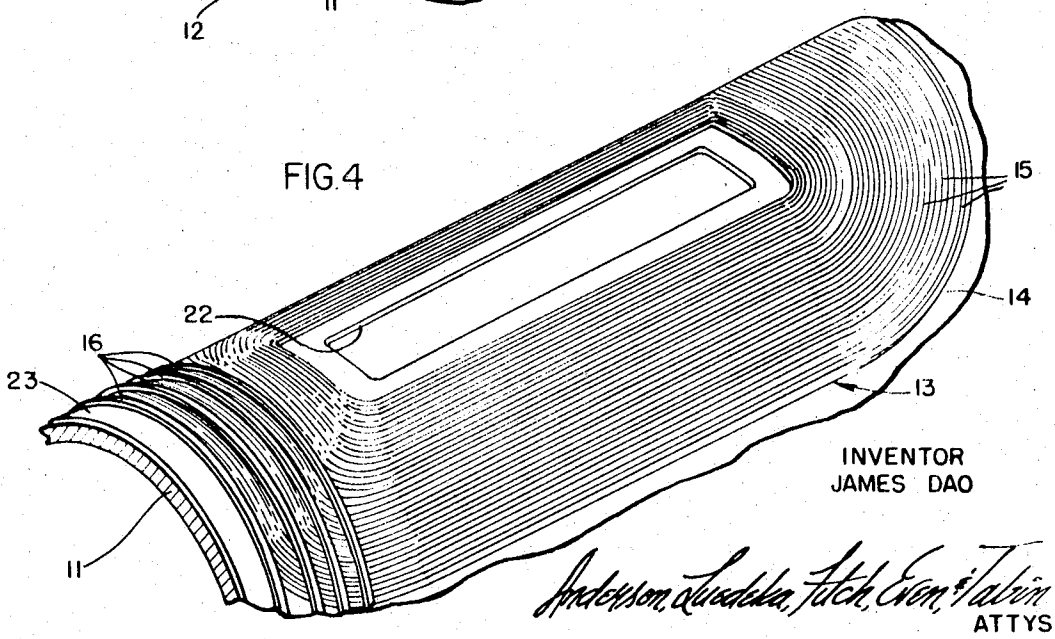


FIG.4



INVENTOR
JAMES DAO

Anderson, Luedeka, Fitch, Even & Tabin
ATTYS.

ELECTROMAGNET STRUCTURE

This invention relates to electromagnet structures for producing high strength magnetic fields and, more particularly, to an improved electromagnet structure for producing very large fields of high strength.

Superconducting electromagnets are theoretically capable of achieving magnetic fields of extremely high strength, for example, of the order of 70 kilogausses. Such high strength magnetic fields are of advantage in numerous applications such as for containing plasmas, accelerating subatomic particles, and generating electrical power directly from plasma discharge, (a process known as magneto hydrodynamics). Superconducting electromagnets are of particular advantage where high magnetic field intensities are to be produced with equipment of minimal weight.

Previously proposed designs for superconducting electromagnet structures have frequently been unsatisfactory because they are "spongy," that is, because the stress, produced in the supporting members and in the conductor in the presence of very high intensity magnetic fields, often exceeds the structural limitations of the materials. This same problem may be encountered in the design of electromagnet structures other than those of the superconducting type, and the invention is applicable also to such structures. The production of exceedingly high stress frequently leads to severe damage to an electromagnet structure. Moreover, layers of insulation in such structures, being typically of relatively soft organic materials, tend to become damaged under high stress conditions, resulting in shorting between electrically conductive elements.

Accordingly, it is an object of this invention to provide an improved electromagnet structure for producing high strength magnetic fields.

Another object of the invention is to provide an improved superconducting electromagnet structure.

A further object of the invention is to provide an electromagnet structure susceptible to a minimal amount of strain in the presence of high strength magnetic fields.

It is another object of the invention to provide a superconducting electromagnet structure wherein cooling is enchanced and in which damage to insulation due to stress is minimized.

Other objects of the invention will become apparent to those skilled in the art from the following description, taken in connection with the accompanying drawings wherein:

FIG. 1 is a schematic perspective view, with parts cut away, of an electromagnet structure constructed in accordance with the invention;

FIG. 2 is a sectional view taken along the line 2—2 of FIG. 1;

FIG. 3 is a partial sectional view taken along the line 3—3 of FIG. 1; and

FIG. 4 is an enlarged perspective view illustrating a portion of a typical layer of windings and spacers used in the structure of FIG. FIG. 1.

Very generally, the electromagnet structure of the invention comprises a tubular support **11** defining a space **12** in which a high strength magnetic field is produced. At least one coil structure **13** is provided including a plurality of coil layers **14** of turns **15** stacked along an axis which is generally perpendicular to the axis of the tubular support. A plurality of reinforcing layers **16** are formed of a material having substantial tensile strength. The reinforcing layers are wrapped around the support and over the individual coil layers, respectively, to reinforce the magnet structure against strain in the presence of high strength magnetic fields.

Referring now more particularly to the drawings, a preferred embodiment of the invention is illustrated. Some parts of FIG. 1 are not shown completely in order to clarify the drawing. The true extent of such parts may be discerned from the other FIGS. and from the description which follows. The illustrated embodiment is that of a magnet structure for producing high strength magnetic fields perpendicular to the axis of a working volume in the space or region **12**. The magnet consists of a pair of saddle coil structures **13** and **21**, each

coil structure consisting of a plurality of saddle-shaped coil layers **14**. Each coil layer **14** comprises at least one wound conductor **15**, and may comprise several wound conductors stacked together. In the illustrated embodiment, the conductors **15** are bands (i.e., thin rectangular cross section) wound with their flat sides toward each other, and the bands are spaced apart by short strips of insulation (not shown) distributed at intervals along their length. Each successive coil layer in each coil structure is of a different outer diameter. The outer diameters change in a gradation selected to cause the boundary of a cross section of the coil structure to approximate two intersecting ellipses. This is for the purpose of obtaining maximum efficiency and good field uniformity for a given volume, as is known in the art. The wound conductors in the coil layers are produced by wrapping the conductors on mandrils having appropriate diameters, and the turns of the conductors are bonded with suitable adhesive in order to produce mechanically solid pancakes.

The coil structures **13** and **21** are positioned on a cylindrical support **11** and the coil layers **14** are stacked along an axis which is generally perpendicular to the axis of the tubular support. When mounted on the support, the individual coil layers **14** of the coil structures **13** and **21** bend to conform to the outer surface of the support **11**. The individual coil layers are prevented from returning to a flat shape by means subsequently explained. The coil layers **14** are held in the proper positions by a plurality of suitable inner spacers **22** and outer spacers **23** of insulating material, and by a pair of end flanges **24** and **25**. The inner spacer and outer spacer at each level are of a configuration to fill in the region surrounding each coil layer **14**, and to fill part of the region within each coil layer. The spacers are graduated in size so that each coil structure and spacer assembly has a generally square cross section where cut by the plane of the section 3—3 of FIG. 3 even though the boundary of the coil structure, as mentioned above, approximates two intersecting ellipses.

The phenomenon of superconductivity is well known in the art. By utilizing this phenomenon, together with the traditional means of producing magnetic fields, magnetic fields of very high intensity may be generated. For example, solenoid-type magnets of 6 inch diameter bore have been built capable of successfully producing field densities of 140 kilogauss. Transverse magnetic fields have been produced with magnets utilizing a 12 inch diameter bore with field strengths of 40 kilogauss. When field strengths of higher than about 40 kilogauss in transverse fields are desirable, however, heretofore known designs for superconducting magnet structures have been incapable of producing such fields due to high internal stresses. In particular, such magnets have failed to meet their ultimate specifications because they are spongy in that they deflect out of dimension under such large magnetic forces.

In accordance with the invention, radial forces produced by high intensity magnetic fields are contained by providing a reinforcing continuous strip or band **16** wrapped helically around the support **11** and over each of the coil layers **14** and associated spacers **22** and **23** to form a plurality of reinforcing layers to reinforce each individual coil layer, respectively. By providing individual reinforcing for each coil layer, the radial force on each coil layer is contained by the reinforcing layer immediately on top of the coil layer. There is no accumulation of forces from layer to layer and therefore the compressive stress within the coil structure is minimized. The magnetic flux density and radial force per layer is maximum at the innermost region of the coil structure and decreases to minimum at he outermost layer. Therefore, the reinforcing layers may be designed to withstand the average layer force. Under such conditions, the innermost reinforcing layer will hold up to its yield point and then transmit the balance of the force onto the next succeeding reinforcing layer. Since each succeeding reinforcing layer needs to reinforce against less radial force originating from the immediately adjacent coil layer, the process of transmittal of the excess force from layer to layer

results in a gradual diminution of the excess transferred to each succeeding layer. Thus, the excess force is eventually absorbed. The material of the strip **16** which forms the reinforcing layers is selected to have substantial tensile strength at the temperature of liquid helium.

In the illustrated embodiment, the reinforcing strip **16** is continuous and is helically wound about each coil layer with a slight pressure. The strip may be of any suitable cross section. The wound reinforcing layer may be seen most clearly in FIG. **4** where the strip **16** is of generally rectangular cross section and is wound helically over both the spacers and the coil layer. Only four turns of the strip **16** are shown for clarity. The prestressing is made just sufficient to hold the coil layers in the saddle shape and conform to the cylinder, a typical amount of prestress being about 10 percent of the yield strength. The distance between turns of the reinforcing strip or band is such as to permit circulation of coolant therebetween. The continuous strip or band may be welded or mechanically terminated at the start and finish and wrapped continuously over each successive coil layer, in the manner of winding line on a fishing reel. On the other hand, a separate continuous strip or band may be used over each coil layer, attached at its respective ends to the bobbin. The ability to wrap the reinforcing strip about the coil layers eliminates the need for precise fitting or shrink fitting of reinforcing layers.

In order to minimize shear stress set up in the conductors of the coil layer or layers, the size and shape of the continuous strip or band is selected to minimize the individual spacing and maximize contact area. Although a preferred cross section for the strip or band is rectangular with slightly rounded edges, other cross sections are possible depending upon the forces encountered. Another advantage of the continuous strip or band type construction herein described is that it is readily applicable to units of very large size, for example 60 inch diameter and 65 feet long, whereas solid types of reinforcement are impractical at such sizes.

As previously mentioned, the material of the reinforcing strip should be one which is of substantial tensile strength at the temperature of liquid helium. Satisfactory materials may be glass, nonmagnetic stainless steel such as type 304, beryllium copper, and boron filaments. The support **11** material should also be selected to have similar properties and the same types of materials as mentioned above in connection with the reinforcing strip are satisfactory. Since weight is typically an important consideration in structures of this type, a satisfactory material for the support **11** may be an epoxy composite consisting of a suitable high strength epoxy resin and a plurality of single crystal filaments of boron or graphite.

Although described in connection with two coil structures and a cylindrical support, any number of coil structures may be employed in accordance with the invention, and the shape of the support is not critical to the invention. In the illustrated embodiment, further rigidity is imparted to the magnet structure by a pair of semicylindrical covers **26** and **27**, which form a sheath over the central part of the magnet structure. The sheath may be, for example, about ¼inch thick, and is wound with a band or strip **28** similar to the strip **16**. Unlike the strip **16**, however, the strip **28** is wound repeatedly back and forth along the length of the sheath until a wound layer about twice as thick as the sheath is built up.

Large magnetic forces acting on the coil layers create large bending moments in the wound conductors. High stresses are therefore set up at the contact area between the reinforcing layer and the wound conductors. Under some circumstances, organic insulation utilized for insulating the wound conductors may be damaged or forced to flow away from the contact area, thus causing shorting between the reinforcing strip and the coil layer.

In order to alleviate this problem, the reinforcing continuous strip or band, and all metal supports, may be coated with aluminum oxide. Because aluminum oxide is very hard, it is not susceptible to damage under high forces and yet provides the required insulation. Aluminum oxide may be deposited upon stainless steel parts by plasma spray processes or by vacuum deposition. By avoiding the need for organic insulation over the conductors, there is no thermal barrier to cooling and hence efficiency is improved.

A further advantage of the invention lies in the fact that aluminum stabilized superconductors are superior over copper stabilized superconductors because aluminum has lower magneto resistance, a high resistance ratio, and is lighter in weight. Heretofore, magnet designers have typically turned away from aluminum stabilized superconductors because its resistivity is affected by mechanical stresses in a much larger degree than that of copper. For example, the reaction of copper to increasing stress is light until its yield point is reached. Aluminum, on the other hand, reacts very strongly to stress above about 5 k.p.s.i. Since, in accordance with the invention, mechanical stresses are readily contained, aluminum stabilized superconductors may be utilized in the coil layers to thereby improve operational characteristics and minimize magnet weight

During operation of a superconducting magnet, an occasional difficulty may be encountered in the form of localized normalization, that is, a localized increase in temperature at some segment of the wound coil structure. Typically, such localized temperature normalization or heating may be the result of the growth of a microscopic gas bubble to a size of, for example, 1/32 inch diameter. In this event, the segment of the conductor adjacent the gas bubble is no longer superconductive and acquires a resistance. Such resistance is typically insufficient to affect overall current flow through the coil and continuing high current through this heated segment of the coil can result in overheating and eventual failure of this portion of the coil.

One known way of alleviating this problem is to provide one or more large external resistors connected across the entire superconductive coil through one or more switches. The voltage across the coil or, preferably across segments of the coil, is monitored and, when it rises to a level indicative of localized temperature normalization due to heating, the entire coil current is "dumped" through the resistor which absorbs the energy and dissipates it in the form of heat. Suitable cooling is provided for the dumping resistor to prevent it from overheating.

Large external resistors and associated cooling systems frequently occupy more volume than is desirable, and, in addition, typically add considerable weight to the superconducting magnet structure and its associated elements. In certain applications, such as airborne magnet structures, the considerable volume and weight added by large external dumping resistors and cooling systems may be undesirable.

To avoid this problem, the invention contemplates the utilization of a coil support **11** or bobbin comprised of a nonmagnetic conductive material, such as type 304 stainless steel or a structurally reinforced copper e.g., copper with boron filaments distributed therethrough). Upon the occurrence of localized temperature normalization due to heating, the changing current results in a flux jump, that is, a rapid localized change in magnetic flux with respect to time. This flux jump produces eddy currents in the conductive support which generate heat in the support. The heat is transmitted throughout the support, thereby heating the balance of the coil structure and raising its resistance to a point sufficient to drop the current. This rapid temperature normalization of the coil prevents localized overheating and possible failure. Preferably, the support or bobbin is of a material having a high heat conductivity, and good electrical conductors typically have this characteristic. By causing the entire coil structure to heat up or normalize, local current overloading is prevented without the need for large external cooled dumping resistors and corresponding connecting switches. Accordingly, less volume and weight is associated with superconducting magnet structures constructed in accordance with the invention.

It may therefore be seen that the invention provides an improved electromagnet structure for producing high strength magnetic fields. The electromagnet structure of the invention has particular application at very low temperatures and is

susceptible to a minimal amount of strain in the presence of very high strength magnetic fields. Moreover, cooling of the magnet structure of the invention is enchanced and damage to insulation due to stress may be minimized.

Various modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Such modifications are intended to fall within the scope of the appended claims.

What is claimed is :

l. An electromagnet structure for producing high strength magnetic fields comprising a cylindrical tubular support defining a space in which the field is produced, a pair of saddle coil structures, said coil structures being positioned on opposite sides of said support aligned with each other on a common axis which is perpendicular with the axis of said support, each of said coil structures including a plurality of coil layers stacked on the outer surface of said support along said common axis, and a plurality of reinforcing layers of material having substantial tensile strength, said reinforcing layers each being comprised of a continuous strip anchored at both ends to said support and wrapped helically around said support and over a respective one of said coil layers in each coil structure to reinforce each individual coil layer of said electromagnet structure against strain in the presence of high strength magnetic fields, the turns of said strip being displaced from each other along the axis of said support to form a helical passage for coolant flow.

2. An electromagnet structure according to claim 1 wherein said support includes a pair of annular flanges at respective ends, wherein said coil structure further includes a plurality of wafer type spacers arranged in layers corresponding to said coil layers, and wherein said continuous strip is wrapped over said spacers as well as said coil layers.

3. An electromagnet structure according to claim 1 wherein all metal parts are insulated by a coating of aluminum oxide.

4. An electromagnet structure according to claim 1 wherein said continuous strip is comprised of stainless steel.

5. An electromagnet structure according to claim 4 wherein said continuous strip is insulated by a coating of aluminum oxide.

6. An electromagnet structure according to claim 1 wherein said continuous strip is comprised of boron filaments.

7. An electromagnet structure according to claim 1 wherein said support is comprised of a nonmagnetic electrically conductive material.

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