SUPERCONDUCTING MAGNET FOR PERSISTENT OPERATION

Filed July 22, 1968 2 Sheets-Sheet 1

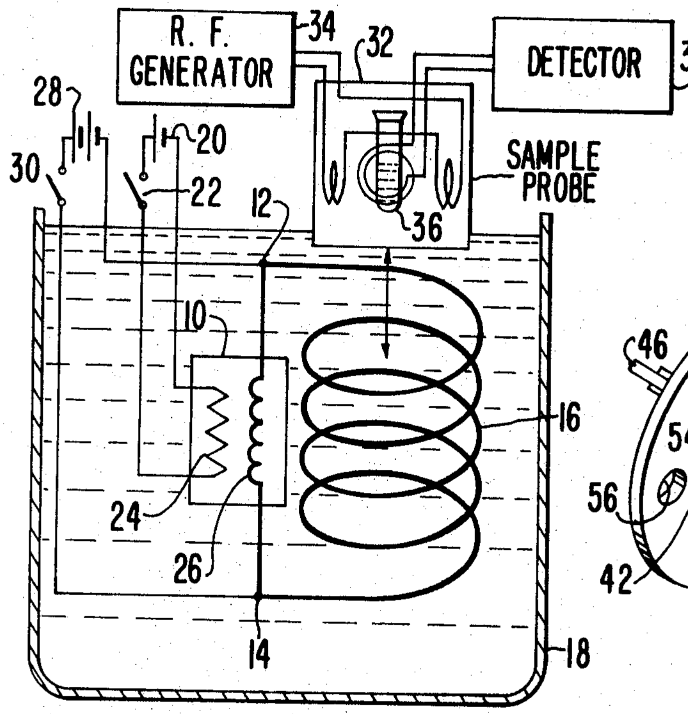

FIG. 1

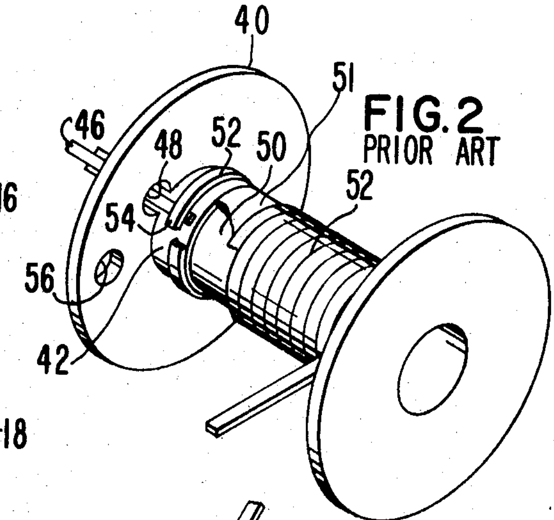

FIG. 2
PRIOR ART

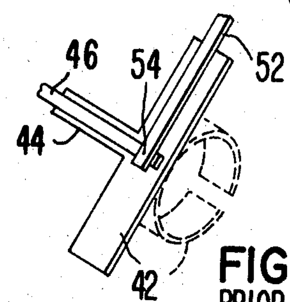

FIG. 3
PRIOR ART

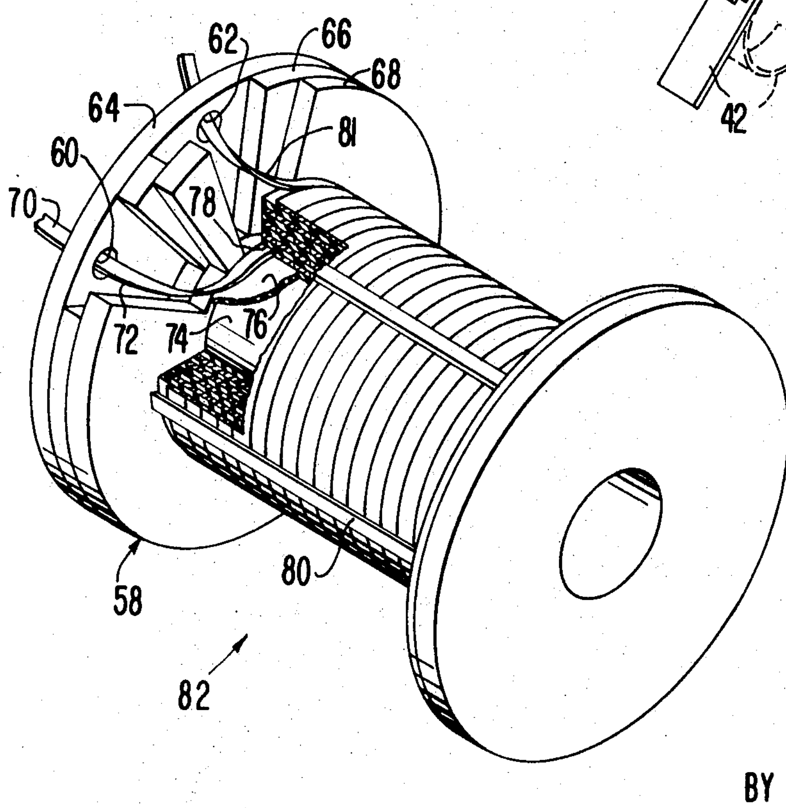

FIG. 4

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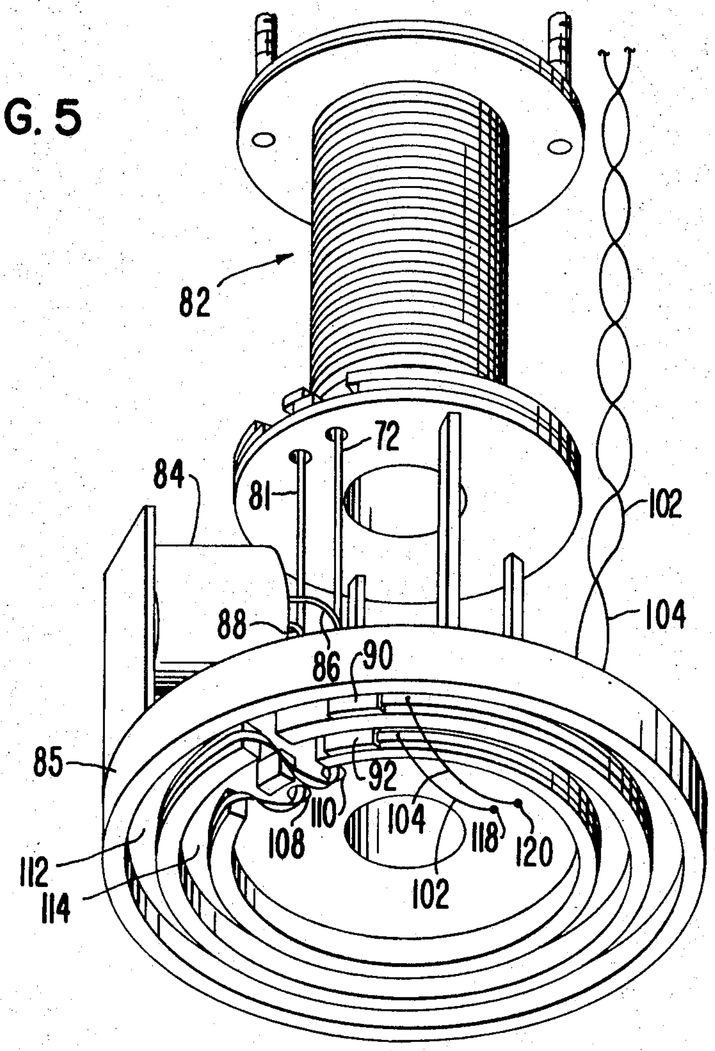
FIG. 5



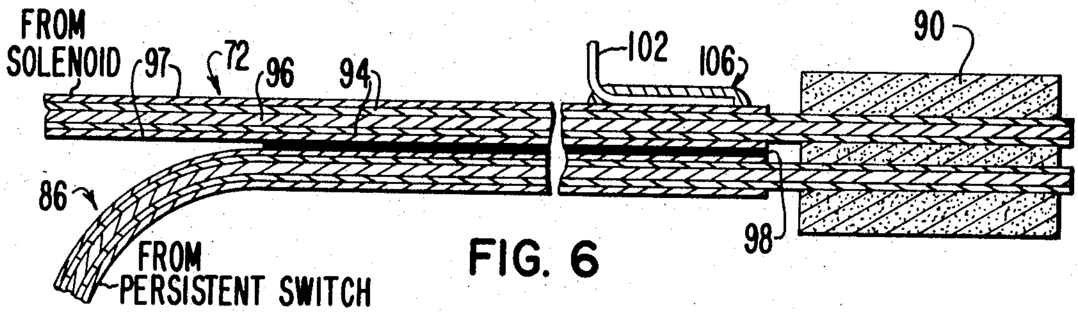
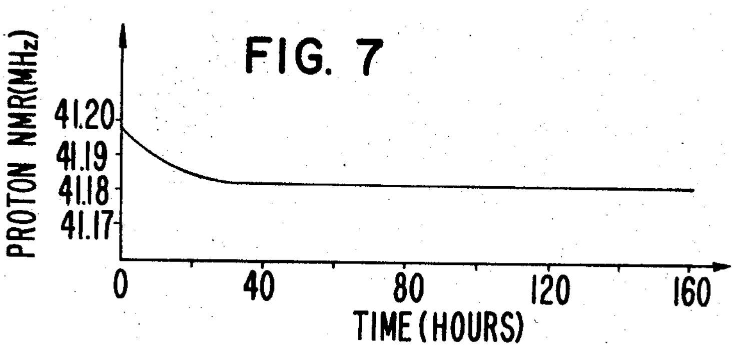


FIG. 6

FIG. 7



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SUPERCONDUCTING MAGNET FOR PERSISTENT OPERATION

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U.S. Cl. 335—216 4 Claims

ABSTRACT OF THE DISCLOSURE

An apparatus for providing a superconductive magnet of niobium-tin ribbon for persistent operation and including a novel means for allowing the coil winding ends to be extracted from the winding bobbin without kinking, a novel means of splicing the ends of the superconductive ribbon to a persistent switch means, and a means for supporting the spliced ribbon outside of the intense magnetic field produced by the solenoid.

STATEMENT OF THE INVENTION

The present invention relates generally to superconducting apparatus and more particularly to an apparatus providing a zero resistance superconductive connection between a superconductive ribbon solenoid and a persistent ribbon switch, and apparatus for supporting the same thereby enabling the persistent operation of the electromagnet formed by the solenoid.

DISCUSSION OF THE PRIOR ART

The theoretical possibility of superconducting magnets operating in a persistent mode has been known for some time. In such a device a persistent current shunt is connected across the terminals of the superconducting coil and both are placed in a Dewar filled with a cryogenic fluid such as liquid helium to provide the necessary cryogenic temperatures. A heater coil is wound about the persistent current shunt which is itself made of a superconductive material and current is supplied to the heater so as to maintain the persistent shunt above its critical temperature so that it exhibits a normal resistance. This allows the current from the main power source to flow through the superconducting coil and thus generate a strong magnetic field.

Once the coil is energized, current is no longer applied to the heater of the persistent shunt and it is allowed to cool down and become superconductive. After the shunt becomes superconductive the main power supply is turned to zero, and is then disconnected. But, due to the magnetic field previously established by the current flowing in the coil, current continues to flow through the circuit comprised of the coil and its persistent current shunt. If no resistance exists in the series circuit connecting the superconducting coil and its persistent shunt, current will flow indefinitely and no decay in the magnetic field will occur. If, however, a resistance is present in the circuit the current and consequently the magnetic field will decay with a time constant dependent on the total resistance in the circuit.

Whereas, until recently, both superconducting ribbon solenoids and superconductive ribbon persistent switch apparatus have been readily available, the two have not been convertible so as to enable a truly persistent mode of operation, but were only combinable to provide a semi-persistent mode of operation due to the resistance which inevitably occurred at the circuit connecting points wherein the two devices were joined together. Because of the difficulty of joining together the superconductive ribbon type materials comprising the shunt and the solenoid, as

well as the fact that such joints are detrimentally affected by the intense magnetic field, a truly persistent mode of operation has not generally been obtainable.

However, a method has recently been discovered for providing a high field superconductive ribbon splice having zero resistance which now enables the production of a truly persistent operating solenoid magnet. The method of forming this superconductive ribbon splice is disclosed in the copending U.S. patent application to Kinter et al., Ser. No. 734,277 assigned to the assignee of the present invention. The Kinter et al. splice is particularly applicable to solenoids wound with the superconductive ribbon manufactured by RCA and trade-named Vapodep. This material is of a high tensile strength niobium-tin superconductive ribbon which has electromagnetic properties such that field intensities at least as high as 200 kilogauss can be achieved. Although the ribbon is flexible enough to be wound into tight coil configurations of either spiral or layer type construction without loss in superconductive properties, caution must be taken to avoid sharp bends in the ribbon which might permanently distort the high strength substrate and crack the niobium-tin deposit.

Since superconducting solenoids of this type are wound from a single length of ribbon and are as a result quite expensive, i.e., as high as $10,000 or more per solenoid, it is quite important that means be provided for allowing the connections to the persistent switch to be made without damage to the portion of ribbon used in winding the solenoid and since it is not possible to insure that every superconducting splice will have 100% zero resistance, these splices must necessarily be made using a cut-and-try process. Thus, in order to allow for experimental splicing, until a suitable splice is achieved, means must be provided for permitting the ribbon ends to be let out of the solenoid winding without excessive distortion or sharp bends. And, in addition, means must be provided for supporting the extended ribbon ends as well as the splice itself.

OBJECTS OF THE INVENTION

It is therefore a principal object of the present invention to provide an apparatus by which a superconducting ribbon magnet and persistent ribbon switch may be coupled together so as to produce a zero resistance connection between the two.

Another object of the present invention is to provide an apparatus wherein a superconductive ribbon solenoid and persistent ribbon switch may be electrically connected at a point remote from the intense magnetic field created by said solenoid.

Still another object of the present invention is to provide an apparatus whereby a superconductive solenoid and persistent switch may be spliced together and physically positioned relative to one another so as to prevent damage which might occur should the cryogenic liquid level drop so low as to allow the solenoid to quench.

Still other objects and advantages of the present invention will become apparent after a reading of the following description of the preferred embodiments illustrated in the drawing wherein:

FIG. 1 is a schematic representation of a nuclear magnetic resonance apparatus utilizing superconducting ribbon magnetic apparatus in accordance with the present invention.

FIGS. 2 and 3 illustrate the manner in which the ends of a solenoid winding were heretofore spliced in accordance with the prior art.

FIG. 4 illustrates the manner and apparatus of the present invention in which the ends of the solenoid windings are let out of the winding spool so as to allow connection to the persistent switch.

FIG. 5 illustrates the completed solenoid and persistent switch structure as well as the means for supporting the extended lead and the superconductive splice.

FIG. 6 schematically illustrates a superconductive splice made in accordance with the present invention.

FIG. 7 is a performance curve showing the persistent operation of the apparatus of the present invention over an extended period of time.

DESCRIPTION OF THE PRIOR ART

Referring now to the drawing, there is shown in FIG. 1 a schematic representation of an NMR device utilizing the intense magnetic field produced by a superconductive solenoid operated in the persistent mode as enabled by the present invention. As is shown in the drawing, a persistent switch **10** is connected across the terminals **12–14** of a superconductive coil **16** and both the switch and the coil are disposed within a Dewar **18** filled with, for example, liquid helium to provide the necessary cryogenic temperature for superconductive operation. A source of current **20** and a switch **22** are connected in series with a heating element **24** so as to supply heat to the persistent switch **10**. The persistent switch **10** includes a current shunt element **26** which is initially maintained normal, or resistive, by the heat supplied from the heating element **24**. The main source of current **28** and main power switch **30** are connected in series with each other and with the parallel combination comprising the superconducting coils **16** and persistent switch **10**.

In order to initiate the superconducting operation both the heater switch **22** and the main power switch **30** are closed. With current flowing through the heater element **24** the persistent shunt winding **26** is heated above its critical temperature and exhibits a normal resistance. This allows the current of the main power source **28** to develop a voltage across the solenoid (which is cooled to its superconductive temperature) and thus create a strong magnetic field. Once the coil **16** is energized and the resulting magnetic field is created thereabout, the heater switch **22** is opened and the shunt **26** is allowed to cool down and become superconductive.

After the shunt **26** becomes superconductive the power supply current is reduced slowly to zero. As this occurs, the current builds up in the persistent switch with the solenoid current remaining substantially unchanged. Switch **30** is then opened, but because of the zero resistance path in the loop consisting of the shunt **26** and the solenoid **16** and because of the magnetic field previously established, current continues to flow through the coil **16** and its persistent shunt **26**. If no resistance exists in the series circuit consisting of the coil **16** and the shunt **26** the current will flow indefinitely and no decay in the magnetic field will occur. If, however, a resistance is present for any reason, the current and consequently the magnetic field will decay with a time constant which is dependent upon the total resistance in the circuit.

Once the superconducting operation has been achieved, and a magnetic field established within the solenoid **16** a sample probe **32** may be placed within the field created by the solenoid **16** and upon being energized by an R.F. generator **34** the nuclear magnetic resonance properties of a sample **36** carried by the probe **32** may be detected by a detector **38**. Thus, a practical application of the superconducting solenoid structure has been illustrated in an exemplary embodiment.

Referring now to FIGS. 2 and 3 of the drawing, a typical solenoid winding, using ribbon type conductor, and the prior art manner in which electrical connection was heretofore provided thereto is shown. Initially the coil form or bobbin **40** is insulated to isolate the superconductive windings from the coil form. After the bobbin **40** is insulated, an inner current contact member **42** is prepared. This contact member shown in detail in FIG. 3 consists of a 0.005" thick copper T that has a backing of 0.005" copper-plate stainless steel on its long leg **44**. The upper surface of the T is tinned and a piece of superconductive ribbon **46**, which may be connected to a persistent switch, is soldered thereto lying parallel to the leg **44** of the T. The T is then positioned about the bobbin **40** as shown so that the leg **44** thereof extends through the hole **48** in the end of the bobbin **40** and the top portion of the T is wrapped around the coil form **50** of the bobbin **40**. Insulation **51** is then wrapped around the remaining portion of the spool **50** so that the upper surface thereof is flush with the winding surface.

The first two or three inches of the superconducting ribbon **52** is then pretinned and soldered to the tinned area of the T strip already in place about the coil winding form **50**. The end **54** of the ribbon is positioned so as to overlap the superconducting strip **46** already placed on the T contact member **44** as shown in the drawings. The superconducting ribbon **52** is then wound about the spool **50** until the superconducting solenoid is completed and then a similar T shaped contact member is provided for joining the outer end of the winding **52** to an external lead through a second hole **56** in the bobbin **40**.

Referring now to FIG. 4 of the drawing, a bobbin structure and solenoid winding in accordance with the present invention will be described. A pair of holes **60** and **62** are provided in the end plate **64** of the spool **58** and a pair of insulating spacers **66** and **68** are positioned adjacent thereto. The spacer members **66** and **68** are provided with pie-shaped cut-outs or the like which coincide with the holes **62** and **64** in the end of the spool **58**. Initially, the end **70** of the superconducting ribbon is extended through the hole **60** in the end **64** of the bobbin **58** and approximately three to five feet of excess ribbon is allowed for splice purposes. The ribbon **72** is then gently twisted in the space provided by the cut-outs in the spacers **66** and **68** and is formed around the winding member **74** and over a sheet of insulation **76** which is provided around the winding member **74**.

Between each successive winding layer a sheet of electrical insulation is provided in the form of an interleaving material **78** such as bonded mylar-copper-mylar in which the mylar layers are 0.00025" thick and the copper layer is 0.0008" thick. Also positioned between the respective layers of windings as an additional safety feature are a plurality of shorting strips **80** which are placed directly in contact with and across all the turns of the superconductive ribbon at spaced intervals around the circumference of the windings. The shorting strips **80** may be spaced approximately every two inches for winding diameters up to 2.5" and approximately every three inches for winding diameters from 2.5" to 4" and approximately every four inches for diameters of four inches or larger. These shorting strips tend to minimize arcing between the windings by reducing the developed voltages between the windings when the magnet goes from the superconductive to the normal state. They also afford temporary shorting paths in the event that a portion of the superconductive ribbon becomes normal while the magnet is energized.

When the solenoid winding has been completed the end **81** thereof is gently twisted and passed through the hole **62** in the end plate **64** and an excess length of ribbon of approximately three to five feet long is provided. In FIG. 5 the completed solenoid **82** is shown mounted together with the persistent switch **84** and the circular retainer means **85** for supporting the leads **72** and **81** of the solenoid **82** to which the leads **86** and **88** of the persistent switch are soldered and superconductively spliced at **90** and **92**.

Referring now to FIG. 6 of the drawing, the manner of connection of the leads **72** and **86** and the superconducting splice **90** thereof will be described with more detail. The VAPODEP ribbon consists of the layers **94** of crystalline single-phase niobium-tin which has been vapor deposited on a high strength flexible stainless steel type substrate **96**. The composite of the deposited niobium-tin (Nb_3Sn) material **94** and the substrate **96** also includes an electroplated silver or copper coating **97** which enhances the electromagnetic performance and also simplifies the mechanical handling of the ribbon.

In order to electrically and mechanically couple the solenoid ribbon **72** and the persistent switch ribbon **86** the two are soldered together with soft solder as shown at **98** and the ends thereof are stripped of the silver coating **97** and spliced together to form a superconductive splice **90** as disclosed in the aforementioned Kinter et al. application Ser. No. 734,277. Since it is not necessary that the connection to the power source be a zero resistance connection, the electrical leads **102** and **104** are merely soldered to the silver outer layer **97** of the respective superconductive ribbons as shown at **106**.

Once the ribbons **72** and **86**, and **81** and **88** have been soldered together, a suitable superconductive splice has been provided at the ends thereof, and the leads **102** and **104** connected thereto the thusly connected leads are placed in the circular tracks **112** and **114**, and are passed through the holes **108** and **110** in the lead support structure **85**. The leads **102** and **104** are passed through the holes **118** and **120** for connection to the external power source. Having so assembled the persistent operating magnetic structure this unit may be lowered into a Dewar and properly energized as shown generally in FIG. 1 of the drawing for providing a persistent magnetic field.

In FIG. 7 there is shown a curve illustrating actual test results of persistent operation at 9672 gauss for 6 days. It will be noted that after the initial stabilization period of approximately 30 hours the magnet continued to operate persistently for the duration of the 6 day test period. This curve demonstrates that the superconductive joint formed by solder **98** is actually of zero resistance and will provide true persistent operation.

Aside from the obvious mechanical facility features, the soldering together of the extended lengths of connecting lead **72–86** and **91–88** serve another useful purpose as well. Although during normal operation at 4.2 degrees Kelvin the current passes through the sintered joints **90** and **92** due to its zero resistance, should the joint go normal the current will be allowed to flow through the soldered joint **98**. The resistance of this joint can be as low as 10^{-9} ohms so that at 100 amps only microvolts will appear thereacross in the event that the splice should go normal. This feature protects the joint **90** and provides a mechanical isolation therefore.

It will, of course, be apparent to those being of skill in the art after having read the above disclosure that many alterations and modifications of the invention might be made. It is therefore to be understood that the foregoing description of the preferred embodiments is for purposes of illustration anly and is intended in no way to be limiting. Accordingly, we intend that the appended claims be interpreted as covering all modifications, variations, alterations and the like which reasonably fall within the true spirit and scope of our invention.

We claim:

1. Superconductive magnet apparatus including a superconducting solenoid means wound from a superconductive ribbon coupled with a persistent switch means, the extended lengths of connecting leads of said solenoid superconductively spliced together comprising:

an insulated bobbin member upon which said solenoid is wound, said bobbin member including spacer means at one end thereof for spacing the windings from the end of the bobbin member, said spacer means having cut-outs therein for allowing the ends of the ribbon winding to be gently twisted away from said windings without structural distortion so as to pass through a pair of apertures in said one end of said bobbin member,

means coupled to said bobbin member for mounting a persistent switch proximate said one end of said bobbin member, and

means for supporting the lengths of superconductive ribbon coupling said solenoid to said persistent switch, as well as the superconductive splice therebetween, at a distance remote from the intense magnetic field created by said solenoid.

2. Superconductive magnet apparatus as recited in claim **1** wherein said means for supporting the lengths of superconductive ribbon inculdes a retainer means having a pair of generally circular tracks for receiving said lengths of superconducting ribbon including the superconductive splices and for retaining said splices substantially out of the intense magnetic field created by said solenoid.

3. A superconducting magnet structure for operation in the persistent mode comprising:

means supporting a superconductive solenoid formed of a plurality of windings of a superconducting ribbon, said supporting means including means mounting the extended ends of said windings to be extended away from said windings and in a direction generally parallel to the axis thereof, said ends of said ribbon being extended to a length equal to several times the circumference of said solenoid,

a persistent switch means,

another means for mounting said persistent switch means proximate the end of said solenoid, said persistent switch means having a pair of superconductive ribbon type conductors extending substantially the same length as said ends of said solenoid ribbon so as to enable the superconductive splicing thereof, the terminal portions of said ribbon and said conductors having formed thereover a superconductive splice, said spliced together conductors and ribbon being respectively soldered together over substantially their entire lengths, and

said other means for mounting the supporting superconductive splices and substantially all of said soldered together conductors remote from the intense magnetic field produced by said superconductive magnet structure.

4. A superconducting magnet structure as set forth in claim **3** wherein said means supporting the superconductive solenoid is a spool means and said means permitting the ends of the windings to be extended away from said windings includes insulated spacer means disposed at one end of said spool means for spacing said windings from the end of said spool means and having apertures therein of suitable configuration for allowing said windings to be led out of the solenoid winding path without injuriously distorting the structure of the ribbon.

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GEORGE HARRIS, Primary Examiner

U.S. Cl. X.R.

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