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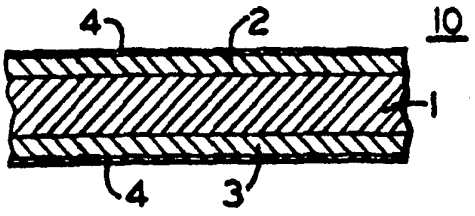
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(54) Title: STABLE FLUX JUMPING RESISTANT SUPERCONDUCTING TAPE AND SUPERCONDUCTING MAGNET

(57) Abstract

A flux jumping resistant stable superconducting tape (10) for a superconducting magnet formed in a sandwich of copper layers (2, 3) around Nb_3Sn superconductor (1). An aluminum or copper foil may be inserted between adjacent coil layers.



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STABLE FLUX JUMPING RESISTANT SUPERCONDUCTING TAPE AND SUPERCONDUCTING MAGNET

BACKGROUND OF INVENTION

This invention relates to a stable Nb_3Sn superconducting tape and magnet wound with that tape which resist flux jumping. Superconducting magnets find wide application, for example, in the field of magnetic resonance imaging.

As is well known, a magnet can be made superconducting by placing it in an extremely cold environment, such as by enclosing it in a cryostat or pressure vessel containing liquid helium or other cryogen. The extreme cold reduces the resistance in the magnet coils to negligible levels, such that after a power source, initially connected to the coil to introduce a current into the coils, is removed the current will continue to flow through the coils due to the negligible resistance, thereby maintaining a magnetic field.

However, once a superconducting magnet has been ramped up and placed in persistent mode, it is important that persistent operation be maintained. If a liquid helium cooled superconducting magnet quenches, liquid helium rapidly boils off, large amounts of helium gas are

created and significant cryostat pressures are generated. For any superconducting magnet system this is costly, has safety implications, an significantly disrupts operation resulting in down time. Also, in an MRI system the noise from the rapid rush of helium is greatly disturbing to patients and system operators.

A superconducting magnet quench not only causes a disruption of service and use of the superconducting magnet and the MRI equipment, but also a time-consuming and expensive replenishment of the liquid helium cryogen and subsequent ramping up of the superconducting magnet is required. There is obviously a significant problem in such downtime and disruption of service of the MRI equipment. Moreover, the person who normally operates the MRI equipment is generally not trained or competent to reinstitute the superconducting mode of operation, requiring an expert or MRI technician be brought in to restart the superconducting magnet.

Notwithstanding the highly undesirable results and expense of a superconducting magnet quench, occasional magnet quenches occur for unapparent and sometimes unexplained reasons. A great deal of research and development has been expended to ensure stable operation of superconducting magnets in the persistent mode.

One cause for superconducting magnet quenching and instability is a phenomenon known as flux jumping. By way of a simplified explanation, flux jumping is the quick motion of magnetic flux in a superconductor which causes undesirable heating, which raises the temperature of the superconductor and can result in the discontinuance of the superconducting mode. Flux jumping has been described as a kind of electromagnetic thermal instability affecting all high-field superconductors.

Various approaches to resisting flux jumping have involved slowing down the motion of the magnetic flux, and improving the cooling of the superconducting magnet such as by exposing the edges of the superconducting coil stack to boiling liquid helium.

Practical superconducting magnets have been fabricated using either NbTi or Nb_3Sn as the basic superconducting material in wire form or, in the case of Nb_3Sn, also in tape form. In both forms the superconductor is bonded to a stabilizer, or protective material, usually copper. Nb_3Sn is very attractive for use in superconducting magnets because of its higher critical current density, higher critical temperature, and higher critical field; however, the practical application of Nb_3Sn has been very limited because it is

very brittle and difficult to handle and use in fabricating superconducting magnet coils. Nb_3Sn tape helps to mitigate the brittleness problem, but has another inherent problem; it is not stable and suffers flux jumping in the conductor at the low temperature (4.2K) of boiling helium due to its high critical current. However, because of the desirable electrical characteristics of Nb_3Sn mentioned above, it is highly desirable to be able to effectively utilize it in a superconducting magnet. However, any use with boiling helium cooling requires a conductor which is practical to manufacture and use, and which is, however, stable at boiling helium temperature and resistant to flux jumping and magnet quenching.

In addition, utilization of the desirable properties of Nb_3Sn as compared to NbTi, namely a much higher critical current density, higher critical temperature and higher critical field, can provide superconducting magnets with equivalent performance but at a reduced cost because of the higher current density.

Accordingly, it becomes important to solve the problems of flux jumping and magnet quenching while providing a superconducting conductor which is practical to manufacture into superconducting magnet coils.

OBJECTS AND SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved Nb_3Sn superconductor tape and an improved superconducting magnet.

It is another object of the present invention to provide an improved Nb_3Sn superconductor tape and superconducting magnet which is stable and reliable in operation and which resists flux jumping.

It is still another object of the present invention to provide an improved Nb_3Sn superconductor tape which is sufficiently flexible for forming superconducting magnet coils resistant to random and undesired magnet quenching.

In accordance with one embodiment of the present invention, a stabilized superconducting magnet utilizes a superconducting magnet coil wound with Nb_3Sn tape conductor. A pair of copper stabilizing layers are bonded to the Nb_3Sn tape, which is approximately 3 mm wide, and paper insulation surrounds this sandwich conductor to enable epoxy encapsulation after winding of the magnet coil. The copper stabilizing layers are at least 0.30 mm thick, and the coil is wound in layers on a coil bobbin with a stainless steel tape wound around the exterior of the coil to restrain conductor motion.

In an alternate embodiment of the invention, the

tape conductor utilizes stabilizing layers approximately 0.075 millimeters (mm) thick with copper or pure aluminum foil 0.50 mm thick inserted between adjacent layers of the superconducting magnet coil.

DESCRIPTION OF INVENTION

FIG. 1 is a cross-sectional view of a superconducting tape conductor fabricated in accordance with the present invention.

FIG. 2 is a cross-sectional view of a coil incorporating the conductor of FIG. 1.

FIG. 3 is a diagram illustrating the fabrication and use of the superconducting tape of FIGS. 1 and 2.

Based on our flux jumping experiments, we have concluded that flux jumping generally occurs before the magnetic flux completely penetrates the superconductor and that the penetration field depends not only on the tape superconductor width and critical current of the tape superconductor, but also depends on tape conductor winding configuration and that this can be calculated approximately by:

$$B_p = 2\mu_o J_c ad/(d+c)$$

Where B_p is the penetration field, J_c is the critical current density of superconductor, a is the width of

superconductor tape, d is the thickness of superconductor tape and c is the inter-layer distance between superconductor layers in coil winding including copper stabilizer and insulation.

We also found that flux jumping more likely occurs when the applied field is changing, and stability is better in increasing fields than in decreasing fields.

This had led to the preferred embodiments of the present invention as shown in FIGS. 1-3.

Referring first to FIG. 1 and FIG. 3, conductor 1 is an Nb_3Sn tape or ribbon conductor, in the order of one inch wide. Conductor 1 is sandwiched between copper layers 2 and 3, the thickness of each being 0.3 mm or greater. The Nb_3Sn conductor 1 is 0.025 mm thick. In the preferred embodiment this is accomplished by passing Nb_3Sn conductor 1 and copper ribbons 2 and 3, which are also in the order of 1 inch wide, through a solder bath in which they are pressed and soldered together to form a composite tape. Alternatively, the layers of copper 2 and 3 could be annealed through pressure applied to the sandwich or alternatively could be plated on. A suitable method forming sandwich ribbon conductor 10 in a solder bath is disclosed in copending patent application serial number (15-NM-3769/3781) entitled "Method and Apparatus

for Laminating Foils Into a Superconducting Tape for Use in a Superconducting Magnet", assigned to the same assignee as the present invention and hereby incorporated by reference.

The sandwich formed by Nb_3Sn conductor 22 and copper layers 2 and 3 is then sliced into individual conductors 25 3 mm wide, and wrapped with 0.040 mm thickness insulating paper 26. The stable ribbon conductor 10 is then wound on coil form or bobbin 11 as shown in FIG. 2. An annular recess 13 in bobbin 11 about the circumference thereof forms an annular pocket in which the Nb_3Sn ribbon conductor 1 is wound in layers such as 34, 35 and 36. In an alternate embodiment, copper or pure aluminum foils 37 and 38, approximately 0.5 mm thick are inserted between adjacent layers such as 34, 35 and 36. In this embodiment, the Nb_3Sn tape conductor is sandwiched between copper layers 2 and 3, 0.7 mm thick. A stainless steel tape 17 is then wrapped around coil 14 to restrain motion of conductor 1 within superconducting coil assembly 15.

Superconducting magnet coil assemblies 15 fabricated in accordance with the present invention have proven to be stable at temperatures of 4.2K provided by boiling of liquid helium, with the tape critical current about 60

amperes per millimeter of width when measured at B=10 tesla (10T), where B is the magnetic flux density. The superconductor tape and superconducting magnets of the present invention have been demonstrated to be stable in operation, resistant to flux jumping and resistant to random and undesired magnet quenching. The copper stabilizing layers 2 and 3 provide an alternate or parallel path for current flow under fault conditions in which the superconducting material or tape 1 would otherwise quench. In addition, tape conductor 10 has proven to be sufficiently flexible for winding into superconducting magnet coils using conventional winding equipment, and enabling the fabrication of reduced cost superconducting magnet coils.

While the present invention has been described with respect to certain preferred embodiments thereof, it is to be understood that numerous variations in the detail of construction, the arrangement and combination of parts, and the type of materials used may be made without departing from the spirit and scope of the invention.

What we claim is:

1. A stabilized superconducting magnet suitable for operation at about 4K comprising:

a superconducting magnet coil wound of a superconducting conductor;

said superconducting conductor including a central conductor of Nb_3Sn tape sandwiched between layers of copper which are at least 0.3 mm thick;

whereby said superconducting magnet resists flux jumping.

2. The superconducting magnet of claim 1 wherein paper insulation surrounds said Nb_3Sn conductor and said copper stabilizing layers.

3. The superconducting magnet of claim 1 wherein said conductor coil is impregnated with epoxy.

4. The superconducting magnet of claim 1 wherein said coil is wound on a coil form and said superconducting conductor is on the order of 3 millimeters wide.

5. The superconducting magnet of claim 1 wherein said central conductor is in the order of 0.025 mm thick.

6. The superconducting magnet of claim 2 wherein the critical current of said superconducting conductor is

on the order of 60 amperes per millimeter of width, at B=10T.

7. The superconducting magnet of claim 2 wherein stainless steel tape is wound around the exterior of said coil to restrain conductor motion.

8. A stabilized flux jumping resistant superconducting magnet suitable for operation at about 4K comprising:

a superconducting magnet coil wound from a superconducting conductor;

said superconducting conductor including a central Nb_3Sn conductor sandwiched between layers of copper on the order of 0.075 mm thick;

said superconducting magnet coil is wound in a plurality of layers with a foil insert between adjacent layers of said coil.

9. The superconducting magnet of claim 8 wherein the foil inserts are selected from the group consisting of copper foil and aluminum foil.

10. The superconducting magnet of claim 9 wherein said foil inserts are up to 0.50 mm thick.

11. The superconducting magnet of claim 10 wherein said superconducting magnet coil is impregnated with epoxy.

12. The superconducting magnet of claim 11 wherein said superconducting conductor is on the order of 3 millimeters wide.

13. A method of fabricating a stable flux jumping resistant superconductor for use in a superconducting magnet coil comprising the steps of:

forming a Nb_3Sn conductor; and

sandwiching said conductor between two stabilizer layers of copper at least 0.3 mm thick;

said conductor being in the order of 3 millimeters wide.

14. The method of fabricating a superconductor of claim 13 in which paper is wrapped around the sandwich of said conductor and the copper layers.

15. The method of fabricating a superconductor of claim 13 wherein the sandwich of said conductor and said copper layers is soldered together in a solder bath.

16. The method of fabricating a superconductor of claim 15 wherein said sandwich is initially on the order of 25 mm wide and subsequently sliced into strips in the order of 3 millimeters wide after said sandwich is formed.

17. A method of fabricating a stable flux jumping resistant superconducting tape magnet coil capable of

operation at about 4k from a superconductor sandwich comprising the steps of:

forming a conductor sandwich of Nb_3Sn between copper stabilizer layers which are on the order of 0.003 inches thick;

winding said conductor into layers on a coil form to form a coil; and

inserting a foil between adjacent layers of said coil.

18. The method of fabricating a superconducting magnet coil of claim 17 wherein said foil is in the order of 0.020 inches thick and including the additional step of selecting said foil from the group consisting of copper and aluminum.

19. The method of fabricating a superconducting magnet coil of claim 18 including the additional step of enclosing the end of said magnet coil remote from said coil form with stainless steel tape.

20. The method of fabricating a superconducting magnet coil of claim 18 including the additional step of wrapping said sandwich with a porous insulator prior to winding said conductor into layers; and

impregnating said coil with an insulating medium.

21. The method of fabricating a superconducting magnet coil of claim 20 wherein said porous insulator is paper and said insulating medium is epoxy.

22. The method of fabricating a superconducting magnet coil of claim 18 wherein said conductor sandwich is in the order of 3 millimeters wide and a plurality of conductor sandwiches are sliced from an initial sandwich which is much wider than 3 millimeters.

23. The method of fabricating a superconducting magnet coil of claim 18 wherein said sandwich is formed in a solder bath in which said stabilizer layers are pressed toward said Nb_3Sn.

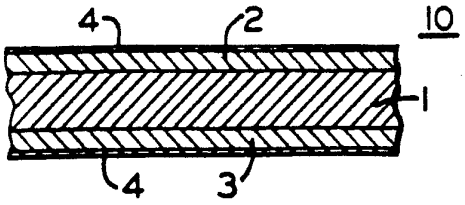


FIG_1

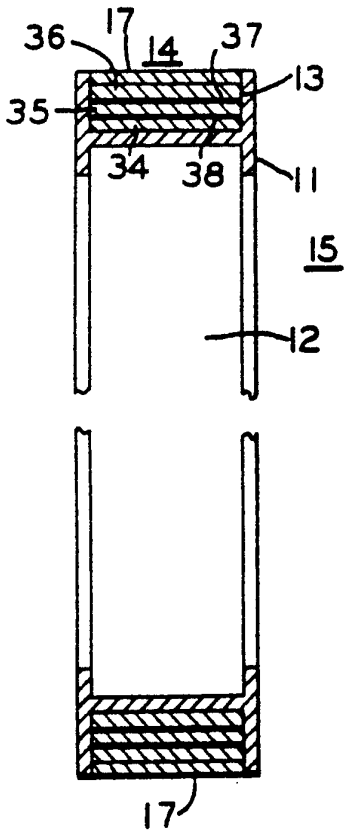


FIG_2

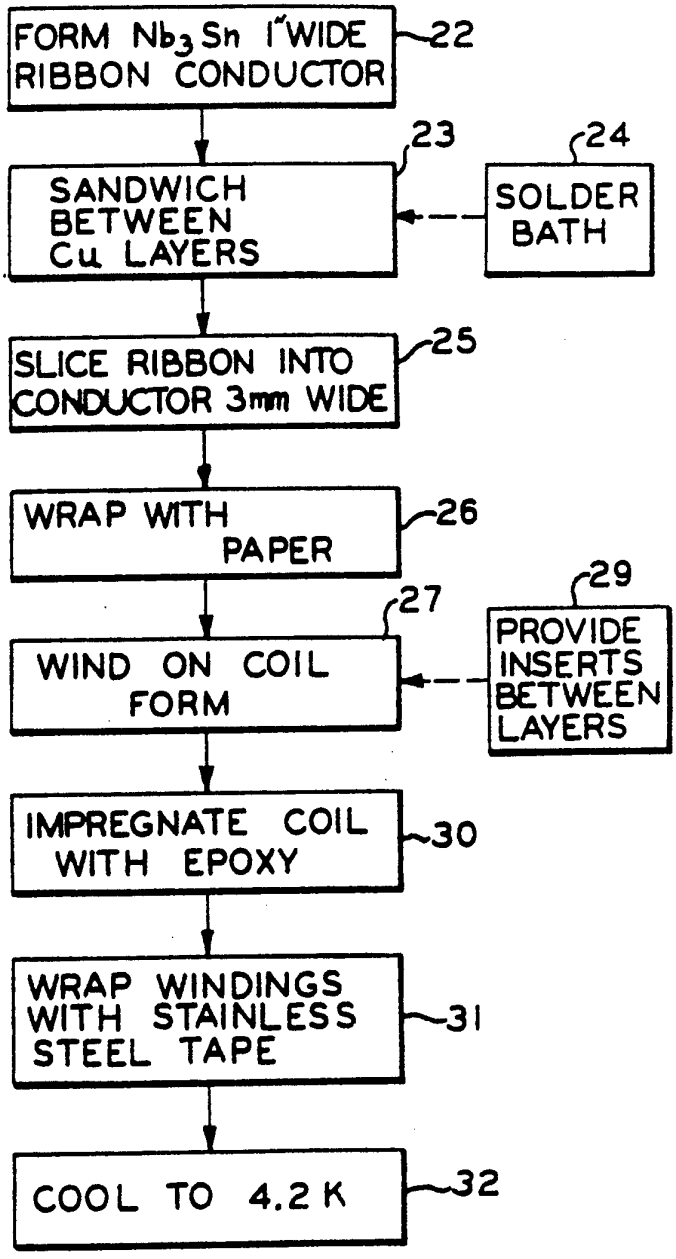


FIG_3

INTERNATIONAL SEARCH REPORT

Interi ıal Application No
PCT/US 93/11557

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 H01F5/08 H01B12/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 H01F H01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE,A,20 20 654 (GENERAL ELECTRIC) 12 November 1970 see page 9, line 1 - page 10, line 22; figures	1,8
A		13,17

Y	11TH INTERNATIONAL CONFERENCE ON MAGNET TECHNOLOGY (MT-11) vol. 2 , 1989 , TSUKUBA,JAPAN pages 985 - 990 KOBAYASHI ET AL 'Magnetic conditioning for flux jump instabilities in superconducting Nb3Sn tape magnet' see abstract	1,8
A		13,17

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE,U,66 07 640 (SIEMENS) 25 March 1971 see claims; figures	1,8
A		13,15,17
A	PATENT ABSTRACTS OF JAPAN vol. 15, no. 254 (E-1083)27 June 1991 & JP,A,03 082 105 (FURUKAWA ELECTRIC) 8 April 1991 see abstract	1-3
A	PATENT ABSTRACTS OF JAPAN vol. 13, no. 121 (E-732)24 March 1989 & JP,A,63 289 907 (HITACHI) 28 November 1988 see abstract	1,4

INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/US 93/11557

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE-A-2020654	12-11-70	FR-A- 2046576	05-03-71
		GB-A- 1247319	22-09-71
DE-U-6607640	25-03-71	NONE	