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[Continued on next page]

(54) Title: HELIUM VAPOR MAGNETIC RESONANCE MAGNET

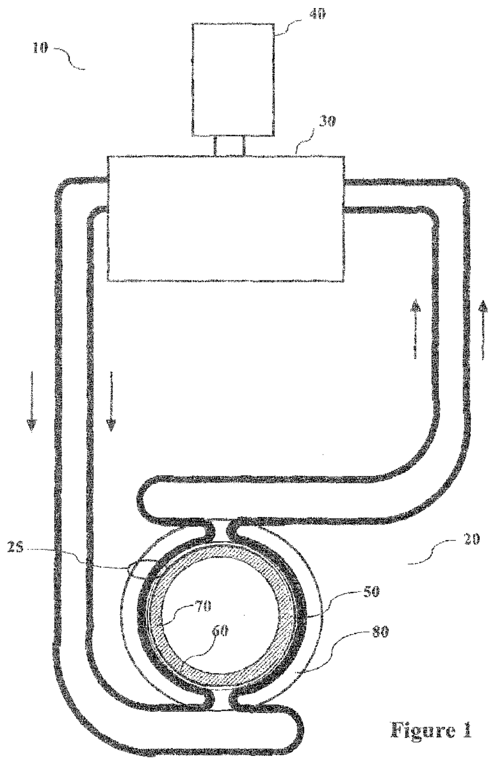

Figure 1

(57) Abstract: A magnetic resonance magnet assembly 20 has a coil form 70 shaped as a hollow cylinder. At least two thermally conductive sheets 60 are disposed circumferentially around the coil form 70, separated by a non-electrically conductive region 90. Thermally conductive tubing 50 affixed to each thermally conductive sheeting section 60 runs circumferentially around the coil form 70. At least one layer of thermally conductive electrically insulating material 110 such as fiber glass is bonded with a thermally conductive epoxy encapsulant to the thermally conductive sheets 60. A winding of superconductive wire 80 is bond together and to the electrically insulating material 110 with the thermally conductive epoxy encapsulant.

WO 2013/011440 A1

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

HELIUM VAPOR MAGNETIC RESONANCE MAGNET

DESCRIPTION

The present application relates to magnetic resonance magnets, cryomagnets, superconducting magnets, and specifically to the cooling of those types of magnets.

Magnetic resonance (MR) scanners use superconducting magnets, which are cooled to a superconducting temperature, e.g. less than 5.2^0 Kelvin. Traditionally liquid Helium has been used to cool superconductive magnets because of its thermal properties. However, liquid Helium is expensive. Many areas of the world do not have a ready supply of liquid Helium or replacement liquid Helium.

The electrical and magnetic properties of the magnet are maintained while cooling the magnet to produce a uniform static magnetic field of a magnetic resonance system. Cooling systems uniformly cool the coil without invading the integrity of the magnetic coil.

The bore of the magnet coil used for whole body MR imaging is large enough to accommodate a patient to be imaged as well as the structures which thermally separate the patient from the extreme cold temperature of the cryogenic system. Manufacturing designs accommodate a room temperature in the bore of the coil assembly while maintaining a operating temperature in the surrounding magnet below the critical temperature of the magnet. A room temperature of 70^0 F is approximately 294^0K, while the critical temperature of the magnet is typically below 5.2^0K. This extreme temperature difference creates design and manufacturing complexities.

The present application provides a new and improved Helium vapor magnetic resonance magnet which overcomes the above-referenced problems and others.

In accordance with one aspect, a magnetic resonance magnet has a coil form, thermally conductive sheets, thermally conductive tubing sections, at least one layer of thermally conductive electrically insulating material, and a winding of superconductive wire. The coil form is shaped as a hollow cylinder. At least two thermally conductive sheets extend circumferentially on the coil form, separated by non-electrically conductive regions. A thermally conductive tubing section is thermally connected to each thermally conductive sheet. At least one layer of thermally conductive electrically insulating material is disposed around and bonded to the thermally conductive sheets. A winding of superconductive wire is disposed around and bonded together and to the electrically insulating material.

In accordance with another aspect, a magnetic resonance magnet system includes at least one magnet assembly, Helium vapor which as it flows through the thermally conductive tubing around the coil cools the coil below the critical superconducting magnet temperature, and a refrigerator heat exchanger connected to the tubing which cools the Helium vapor. A magnet assembly has a coil form, thermally conductive sheets, thermally conductive tubing sections, at least one layer of thermally conductive electrically insulating material, and a winding of superconductive wire. The coil form is shaped as a hollow cylinder. At least two thermally conductive sheets extend circumferentially on the coil form, separated by non-electrically conductive regions. A thermally conductive tubing section is connected to each thermally conductive sheet. At least one layer of thermally conductive electrically insulating material is disposed around and bonded to the thermally conductive sheets. A winding of superconductive wire is disposed around and bonded together and to the electrically insulating material.

In accordance with another aspect, a magnetic resonance imaging or spectroscopy system includes a magnetic resonance magnet system, a gradient coil, a gradient amplifier, a radio frequency coil, a transmitter, a transmitter, a receiver, and a processor. The magnetic resonance magnet system has at least one magnet assembly, Helium vapor which as it flows through the thermally conductive tubing around the coil cools the coil below the critical superconducting magnet temperature, and a refrigerator heat exchanger connected to the tubing which cools the Helium vapor. A magnet assembly has a coil form, thermally conductive sheets, thermally conductive tubing sections, at least one layer of thermally conductive electrically insulating material, and a winding of superconductive wire. A gradient coil is located within a bore of the magnetic resonance magnet system. A gradient amplifier is connected to the gradient coil. A radio frequency coil is located inside the gradient coil. A transmitter is connected to the radio frequency coil. A receiver is connected to the radio frequency coil which receives the RF signals. A controller connects to the gradient amplifier and to the transmitter and controls the gradient amplifier and transmitter to excite resonance in a subject. A processor is connected to the receiver and to the controller and processes received resonance signals into an image and/or spectroscopic information.

In accordance with another aspect, a method of manufacturing a magnetic resonance magnet includes forming a cylindrical coil form. Thermally conductive tubing section is connected to thermally conductive sheets. At least one layer of electrically insulating material is bonded to the thermally conductive sheets. Superconductive wire is wound around the electrically insulating material and bonds the superconductive wire together and to the electrically insulating material.

In accordance with another aspect, a method of magnetic resonance imaging includes generating a static B_0 magnetic field in an imaging region using a helium vapor cooled magnet assembly manufactured as discussed above. Gradient magnetic fields are generated in the imaging region. An RF field is transmitted into the imaging region. Magnetic resonance signals are received from the imaging region. An image is reconstructed from the received magnetic resonance signals.

One advantage resides in the reduced volumes of helium.

Another advantage is that helium vapor is used to cool the magnet instead of liquid helium.

Another advantage is the simple and thermally efficient method of attaching heat exchanger plates to the coils without affecting either the coil's fabrication or the electrical performance.

Another advantage is the simplicity of flow of Helium vapor through the system and the ability to uniformly cool the magnet coil.

Still further advantages of the present invention will be appreciated to those of ordinary skill in the art upon reading and understand the following detailed description.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 is diagram showing one embodiment of a Helium vapor magnetic resonance magnet system.

FIGURE 2 is diagram showing one embodiment of an enlarged view of a magnet.

FIGURE 3 is diagram showing a cross section of one embodiment of a magnetic resonance magnet with an exploded view.

FIGURE 4 is a flowchart illustrating a method of manufacturing a coil assembly.

FIGURE 5 is a diagram illustrating an embodiment of a MR system with a cut-away view of a vacuum dewar showing a magnetic resonance magnet.

With reference to FIGURE 1, an embodiment of a magnetic resonance (MR) magnet in a closed loop system **10** is shown. The closed loop system **10** includes circulating Helium vapor which is heated by an MR magnet assembly **20** and cooled by a refrigerator heat exchanger **30** with an associated cryogenic refrigerator **40**, and re-circulated to the magnet assembly **20**. A suitable refrigerator heat exchanger with associated cryogenic refrigerator is described in US 2008/0209919.

The cooled Helium gas enters the magnet assembly **20** at the bottom and flows up a thermally conductive tubing **50** attached to thermally conductive sheets **60** or plates interior to the magnet. The Helium vapor is cooled in the heat exchanger **30** to approximately 4.2^0K, which provides a 1^0K margin below the critical temperature of the magnet. The cold gas from the refrigerator heat exchanger **30** is relatively dense but becomes less dense as it is warmed by the magnet assembly **20**, producing a downward flow of denser helium gas from the refrigerator heat exchanger **30** to the bottom of the magnet and an upward flow of less dense warmer helium gas through the magnet and back to the refrigerator heat exchanger. The magnet assembly **20** is mounted on a coil form **70**.

When manufactured, a coil assembly **25** is created using a winding fixture and then mounted on a coil form **70** or manufactured directly onto the coil form **70**. Multiple coils **25** of varying widths are typically used in a MR system. Each coil assembly **25** is mounted on a corresponding coil form **70**. The width of a coil **25** affects a number of windings and a strength of the magnetic field generated. The coils manufactured with the process described below vary in size, e.g. up to about 300 mm in width. The coil form **70** is manufactured from a structural metal, such as stainless steel, formed in a hollow cylinder.

As the Helium vapor travels up the tubing **50** heat is absorbed. Heat is generated by the coil assembly **25**, and conductively transferred through thermally conductive plates **60** to the thermally conductive tubing **50** and absorbed by the Helium vapor. Good thermal conduction between all components of the magnetic assembly ensures a uniform operating temperature.

With reference to FIGURE 2, an enlarged view of one embodiment of the magnet assembly **20** is shown. Two sections of thermally conductive sheeting **60** are electrically isolated by a non-electrically conductive spacer **90**. The region between the sheets **60** prevents circumferential currents in the thermally conductive sheeting **60** which would interfere with the operation of the MR system. The thermally conductive sheets are made, for example, of copper approximately .3 mm in thickness. Aluminum and other thermally conductive materials can also be used for the sheeting **60**. The space between the thermally conductive sheets **60** is approximately 6 mm which is filled with the non-electrically conductive spacer **90**, e.g. a plastic filler strip. The non-electrically conductive spacer **90** provides a uniform surface on which to wind the coil. The sheets are bent to the circumference of the coil form **70**, or if a winding fixture is used during the manufacturing process to the outside diameter of the winding fixture.

Thermally conductive tubing **50** is thermally and mechanically affixed to the thermally conductive sheets **60**. An example is 9-10mm OD refrigerator grade copper tubing. Other materials with good thermal conduction may be used such as aluminum. The size of the tubing **50** is large enough that the pressure drop in the tubing is small. With smaller diameter tubing more friction is created, and a drop in cooling capacity results. With tubing that is too small, there is greater non-uniform cooling of the magnet.

With reference to FIGURES 3 and 4, in a step **400**, the coil form **70** is fabricated, e.g. machined from stainless steel.

In a step **402,** an insulating material **100** is wrapped around the coil form **70** or a winding fixture (not shown) if used to manufacture the magnet coil. An example of the insulating material **100** is a layer of polytetrafluoroethylene, commonly known as TEFLON™, sandwiched between layers of metalized polyester, commonly found as MYLAR™. The insulation layer **100** allows movement between coil form **70** and sheeting **60** while minimizing friction.

In a step **404**, the thermally conductive tubing **50** is soldered or welded to the sheets **60** and the sheets and tubing are bent to the radius of the coil form. The tubing **50** may be attached prior to the bending of the sheets **60** or can be bent first and the thermally conductive sheets and tubing attached in their bent state. In a step **406** the thermally conductive sheet **60** and tubing is position over the insulating layer **100**. The thermally conductive sheet **60**, preferably, is not affixed to the electrically insulating sheet to accommodate thermal expansion/contraction differences. The electrically insulating spacers **90** are positioned on the electrically insulating material **100** between the thermally conductive sheets and the top and bottom of the coil assembly. The sheeting **60** is cleaned to remove any oxide present to provide for a thermally conductive bond.

In a step **410**, over the thermally conductive sheeting **60** is placed a layer of electrical insulation **110** which is thermally conductive. Electrically insulating spacers **120** are disposed on either side of where the coil is to be wound. Flanges may be added to the coil form **70** when formed to limit movement of the sheeting **60** during operation of the magnet **20** and to affix coverings and other structural components. If a flange is present, then the electrically insulating spacer is placed between the flange and the sheeting **60** prior to wrapping in step **402**. The layer of electrical insulation **110** is applied after cleaning the sheeting. A thermally conductive, electrically insulating epoxy encapsulant is applied, followed by a layer of material **110** which electrically insulates the coil from the thermally conductive sheets **60**, allows good thermal conductivity, and binds with the epoxy. A suitable material **100** is bi-directional fiber glass cloth with a surface treatment to improve bonding with the epoxy. Both sides of the fiber glass material **110** are coated with the epoxy to provide strong bonding and good thermal conduction and the fiber glass material is wrapped around the thermal conductive sheet **60**. The process can be repeated with more epoxy coatings and fiber glass material **110** to ensure that any irregularities are taken up and provide structural rigidity. Other thin flexible materials which provide electrical insulation, and permit coating and saturation of the epoxy encapsulant are also contemplated.

In a step **412**, the superconducting wire **80** is wound around the layer of encapsulated fiber glass material **110** before the epoxy dries. As each layer of wire is wound, additional thermally conductive epoxy encapsulant is applied to securely bond the wire coil **80** together and to the layer of electrically insulating material **110** which is in turn bonded to the thermally conductive sheets **60**. All the interstitial spaces in the wire coil **80** are filled with epoxy encapsulate to ensure a strong and thermally efficient bond with the sheets **60**. The epoxy, the sheets **60**, and the tubing **50** act as efficient heat exchangers. The thickness of the wire coil **80** is dictated by the magnetic field to be generated and is generally 2.5 – 5 cm. The mechanical bond of the coil assembly **25** or coil should withstand liftoff or hoop forces when current is applied. The thermally conductive sheets **60** bonded to the coil winding with an epoxy have a high peel strength and good thermal conductivity.

With reference to FIGURE 5, operational components of an embodiment of a MR system **500** are shown. A vacuum dewar **515** contains the magnet assembly **20** which generates a static B_0 field during operation. The covering of vacuum dewar attaches, e.g., using the flange previously described, and encloses the coil form **70**, sheets **60**, and coil winding **80**. A gradient coil **505** and a radio frequency (RF) coil **510** are concentrically located within the bore of the vacuum dewar. The gradient coil **505** generates gradient G_x G_y G_z magnetic fields powered by a gradient amplifier **550** during the imaging process. The gradient magnetic fields are generated under control of a sequence control **520**. The illustrated RF coil **510** is a whole body coil which transmits a B_1 magnetic field when turned on by an RF transmitter **530**. The sequence control **520** determines when the RF coil **510** operates in a transmit mode and when the RF coil **510** operates in a receive mode. When in the receive mode, a receiver **570** demodulates the RF signals. The RF signals are then reconstructed by a processor **580** and may displayed as an image on an output device **590** or stored for other access.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be constructed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

Having thus described the preferred embodiments, the invention is now claimed to be:

1. A superconductivity magnet assembly (20) comprising:

a coil form (70) shaped as a hollow cylinder;

at least two thermally conductive sheets (60) extending circumferentially on the coil form (70), and separated by non-electrically conductive regions (90);

thermally conductive tubing sectionS (50) thermally connected to the thermally conductive sheets (60);

at least one layer of thermally conductive electrically insulating material (110) disposed around and bonded to the thermally conductive sheets (60); and

a winding of superconductive wire (80) disposed around and bonded together and to the electrically insulating material (110), forming a thermally efficient unitary structure.

2. The magnet assembly (20) according to claim 1, further including:

a layer of insulating material (100) disposed between the coil form (70) and the thermally conductive sheeting (60) to minimize friction and allow the thermally conductive sheets (60) to move relative to the coil form (70).

3. The magnet assembly (20) according to claim 2, wherein the insulating material (100) includes at least:

a layer of polytetrafluoroethylene; and

a layer of metalized polyester.

4. The magnet assembly (20) according to any one of claims 1-3, further including:

a non-electrically conductive material spacer disposed between adjacent ends of the thermally conductive sheets (60).

5. The magnet assembly (20) according to any one of claims 1-4, wherein the electrically insulating material (110) is flexible.

6. The magnet assembly (20) according to any one of claims 1-5, wherein the electrically insulating material (110) includes fiberglass.

7. The magnet assembly (20) according to any one of claims 1-6, wherein the electrically insulating material (110) is saturated with a thermally conductive epoxy encapsulant.

8. The magnet assembly (20) according to any one of claims 1-7, wherein the electrically insulating material (110) includes:

a plurality of layers of woven material, the woven material, the superconductive wire (80) being bonded into a unitary construction by a thermally conductive epoxy encapsulant, which unitary construction is supported by and not bonded to the coil form (70).

9. The magnet assembly (20) according to any one of claims 1-8 wherein one of the thermally conductive sheets (60) and the thermally conductive tubing sections (50) thermally connected thereto extend from adjacent a bottom of the coil form (70) circumferentially around one side of the coil form to adjacent a top of the coil form (70) and another of the thermally conductive sheets (60) and the thermally conductive tubing sections (50) thermally connected thereto extend from adjacent the bottom of the coil form (70) circumferentially around an opposite side of the coil form to adjacent the top of the coil form (70).

10. A magnetic resonance magnet system (10) comprising:

at least one magnet assembly according to any one of claims 1-9;

Helium vapor which as it flows through the thermally conductive tubing (50) around the magnet assembly (20) to cool the superconducting wire (80) below its superconducting temperature; and a refrigerator heat exchanger (30) connected to the thermally conductive tubing section (50) which cools the Helium vapor.

11. A magnetic resonance imaging or spectroscopy system (500) comprising:

the magnetic resonance magnet system (10) according to claim 10;

a gradient coil (500) located in a bore of the magnetic resonance magnet system (10);

a gradient amplifier (550) connected to the gradient coil (500);

a radio frequency coil (510) located inside the gradient coil (500);

a transmitter (530) connected to the radio frequency coil (510);

a receiver (570) which receives magnetic resonance signals;

a controller (520) connected to the gradient amplifier and to the transmitter; and

a processor (580) connected to the receiver (570) and to the controller (520), the processor processing the received magnetic resonance signals into an image and/or spectroscopic information.

12. A method of manufacturing a magnetic resonance magnet (20) comprising:

forming a cylindrical coil form (70);

thermally connecting a thermally conductive tubing (50) to thermally conductive sheets (60);

positioning the thermally conductive sheets (60) with the connected thermally conductive tubing sections (50) circumferentially around the coil form (70);

bonding at least one layer of electrically insulating, thermally conductive material (110) to the thermally conductive sheets (60); and

winding superconductive wire (80) around the electrically insulating material (110) and bonding the superconductive wire (80) together and to the electrically insulating material (110).

13. The method according to claim 12, further including:

applying a layer of insulating material (100) over the coil form (70) which minimizes friction with and allows the thermally conductive sheets (60) to move relative the coil form (70).

14. The method according to claim 13, wherein the layer of insulating material (100) includes polytetrafluoroethylene sandwiched by metalized polyester.

15. The method according to any one of claims 12-14, further including:

removing oxides from the thermally conductive sheets (60) before bonding the electrically insulating material (110) to the thermally conductive sheeting (60).

16. The method according to any one of claims 12-15, further including:

bonding the thermally conductive sheets (60), the electrically insulating material (110), and the superconducting wire (80) into a unitary structure by:

impregnating the electrically insulating material (110) with a thermally efficient epoxy encapsulant; and

filling the interstitial spaces surrounding the superconductive wire (80) as each layer is wound with the thermally conductive epoxy encapsulant.

17. The method according to any one of claims 12-16, wherein positioning the thermally conductive sheets (60) includes:

positioning one of the thermally conductive sheets (60) and the thermally conductive tubing sections thermally connected thereto to extend from adjacent a bottom of the coil form (70) circumferential around one side of the coil form to adjacent a top of the coil form (70); and

positioning another of the thermally conductive sheets (60) and the thermally conductive tubing sections thermally connected thereto to extend from adjacent the bottom of the coil form (70) circumferential around an opposite side of the coil form to adjacent the top of the coil form (70).

18. The method according to any one of claims 12-17, further including:

connecting the thermally conductive tubing (50) with the refrigerator heat exchanger (30) allowing helium vapor to circulate between the thermally conductive tubing (50) and the refrigerator heat exchanger (30).

19. A method of magnetic resonance imaging comprising:

manufacturing a magnetic resonance magnet (20) according to any one of claims 12-18;

generating a static B_0 magnetic field through an imaging region using the magnetic resonance magnet (20);

generating gradient magnetic fields across the imaging region;

transmitting RF fields into the imaging region;

receiving magnetic resonance signals from the imaging region; and

reconstructing an image from the received magnetic resonance signals.

20. A method of manufacturing a magnetic resonance magnet (20) comprising:

attaching thermally conductive tubing sections (50) to thermally conductive sheets (60);

before or after the attaching step, bending the thermally conductive sheeting (60) and the thermally conductive tubing sections (50) to conform to a circumference of a winding fixture or form (70);

covering the winding fixture or form with a layer of insulating material (100);

placing the bent thermally conductive sheets (60) with attached thermally conductive tubing sections (50) over the insulating material (100);

adding spacers and insulator segments (120) around the bent thermally conductive sheets (60) with attached thermally conductive tubing (50);

bonding at least one layer of electrically insulating material (110) to the bent thermally conductive sheeting sections (60) with a thermally conductive epoxy encapsulant; and

before the thermally conductive epoxy encapsulant cures, winding superconductive wire (80) around the electrically insulating material (110) and bonding the superconductive wire (80) together and to the electrically insulating material (110) with the thermally conductive epoxy encapsulant to form a coil assembly(25).

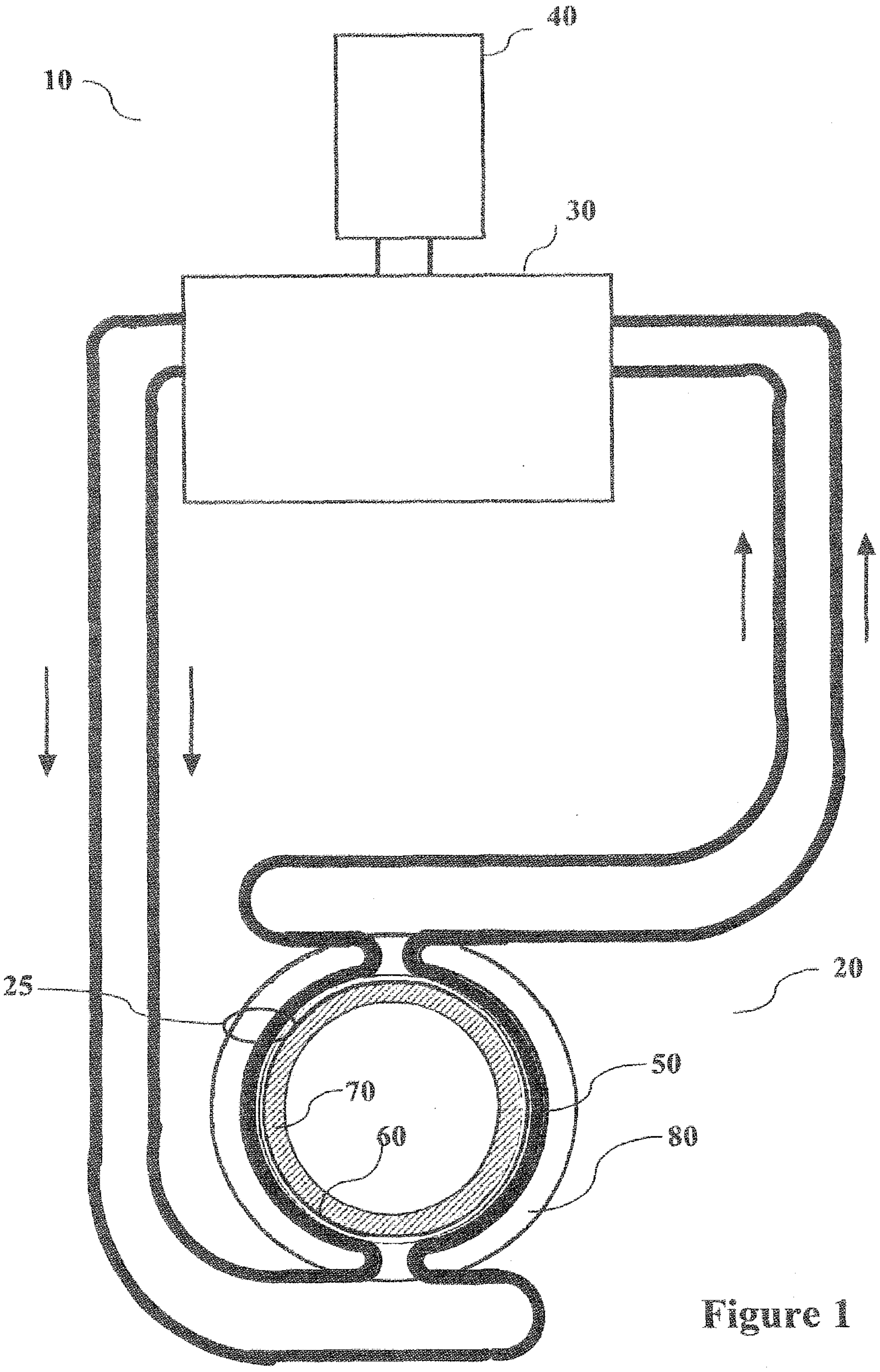

Figure 1

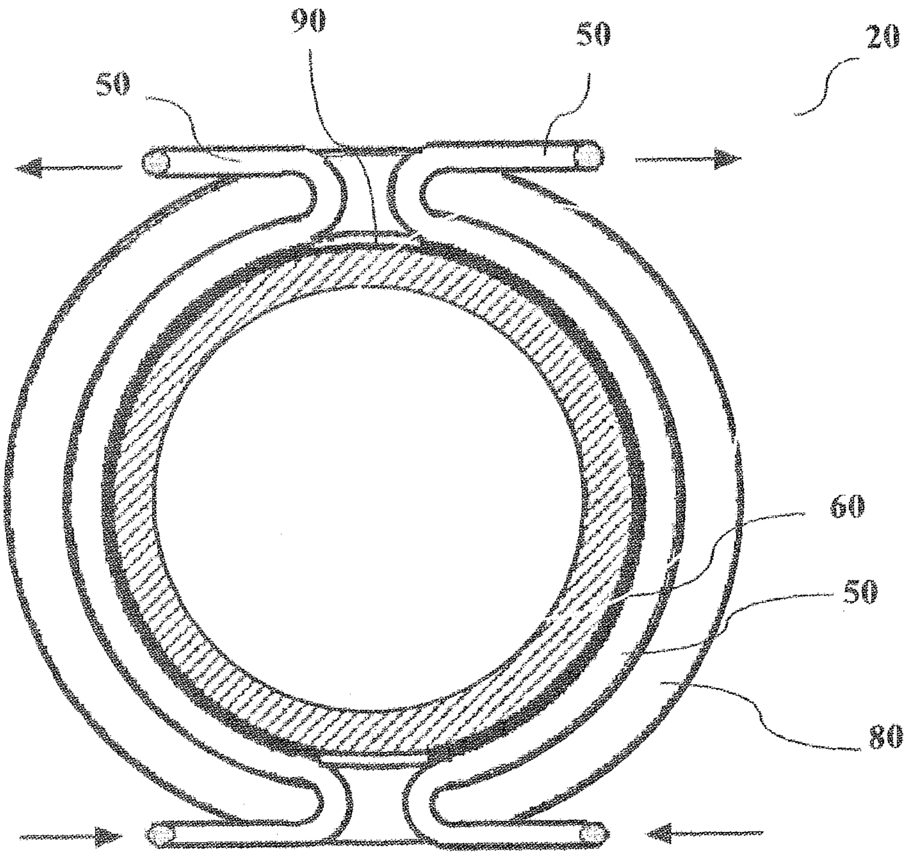

Figure 2

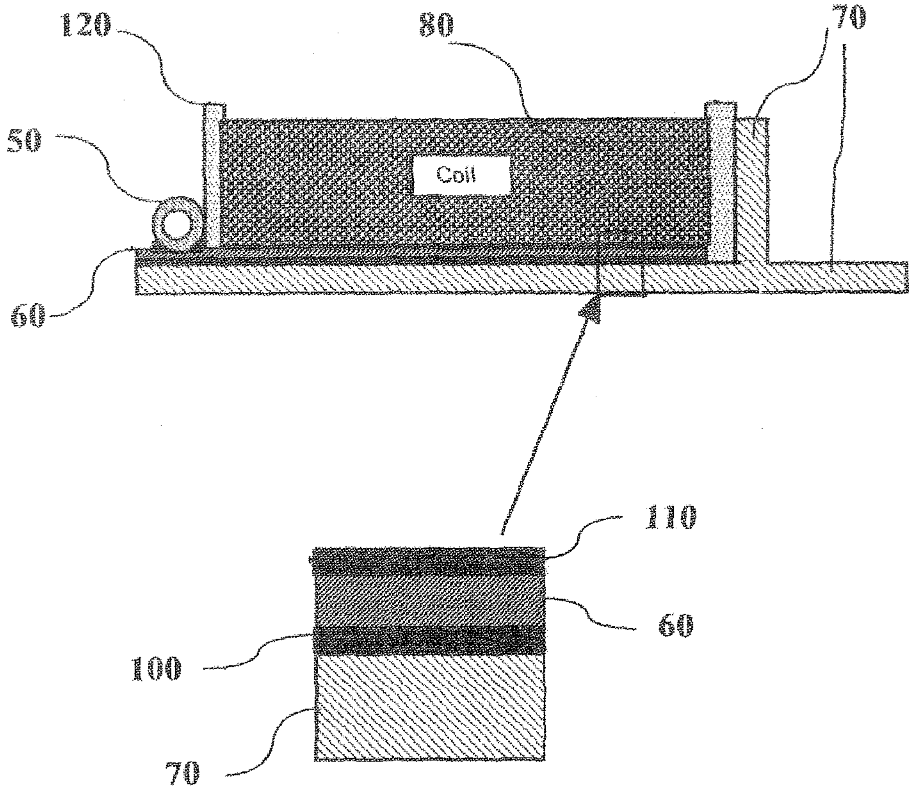

Figure 3

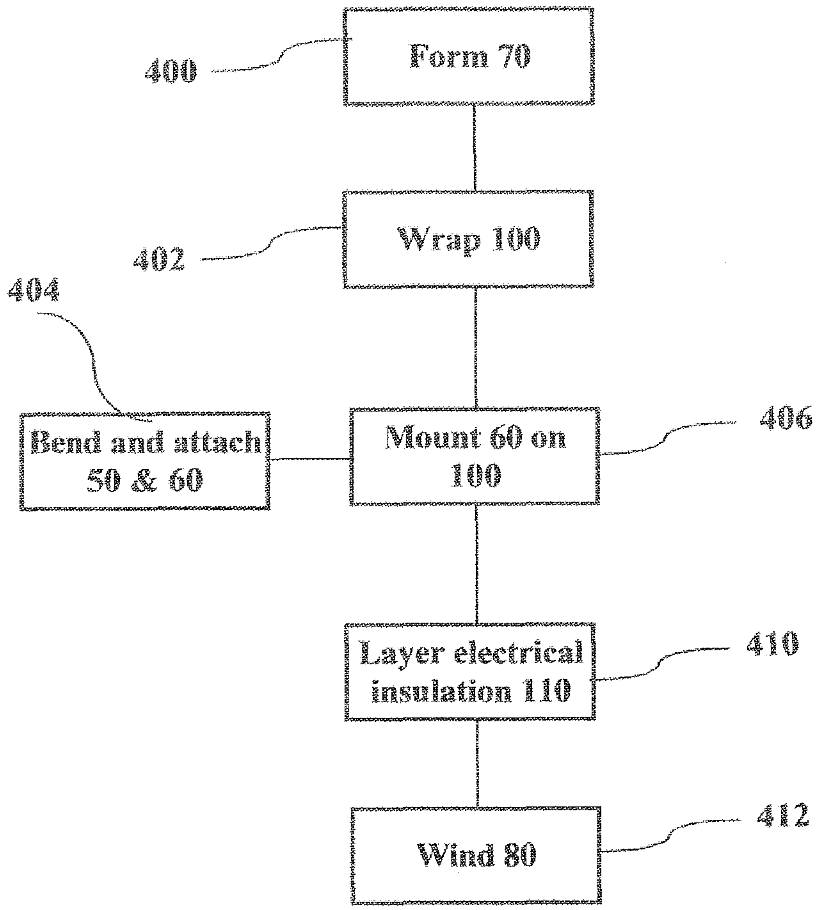
400
Form 70
402
Wrap 100
404
Bend and attach 50 & 60
Mount 60 on 100
406
Layer electrical insulation 110
410
Wind 80
412

Figure 4

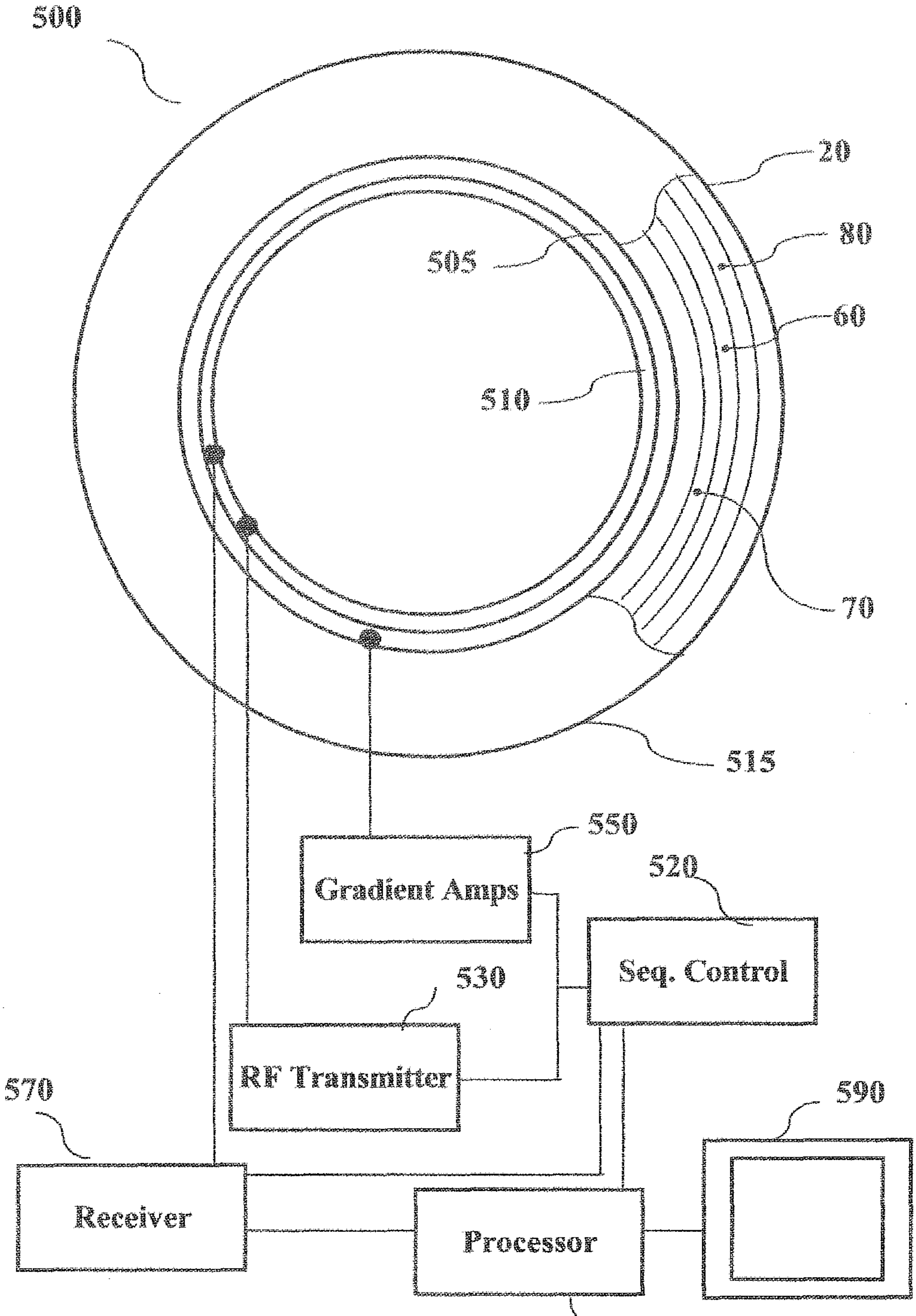
500
20
80
505
60
510
70
515
Gradient Amps
550
520
Seq. Control
530
RF Transmitter
570
590
Receiver
Processor
580

Figure 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2012/053605

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/3815 H01F6/04
ADD.

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)
G01R H01F

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 practicable, search terms used)

EPO-Internal, BIOSIS, COMPENDEX, EMBASE, INSPEC, MEDLINE, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 726 199 A (TAKANO ICHIRO [JP] ET AL) 23 February 1988 (1988-02-23) column 2, line 34 - column 3, line 28	1,11,12, 20
A	US 2010/295642 A1 (HAHN ROBERT [DE] ET AL) 25 November 2010 (2010-11-25) paragraphs [0007], [0008], [0027]	1,11,12, 20
A	WO 2006/122594 A1 (SIEMENS MAGNET TECHNOLOGY LTD [GB]; BELTON NEIL JOHN [GB]) 23 November 2006 (2006-11-23) page 2, line 29 - page 4, line 20	1,11,12, 20
A	JP 2011 125686 A (GEN ELECTRIC) 30 June 2011 (2011-06-30) abstract; figure 4	1,11,12, 20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 September 2012	02/10/2012

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2012/053605

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