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(54) **Improved cooling of electrical coil structure**

(57) An electrical coil assembly comprising a plurality of windings of an insulated electrically conducting wire arranged around a central region such that, when extremities of the wire are connected to an electrical power source, an electrical current flows through the wire and generates a magnetic field in at least said central region, wherein the coil comprises at least one body of thermally conducting material (BTCM) that is:

- Interspersed among and co-wound with at least a portion of said windings;
- Thermally connected to a heat sink;
- Not embodied to be connected to an electrical power source.

Examples of such a BTCM include a thermally conductive (e.g. copper) fiber, foil or fabric, or a coating (e.g. of copper) on said wire.

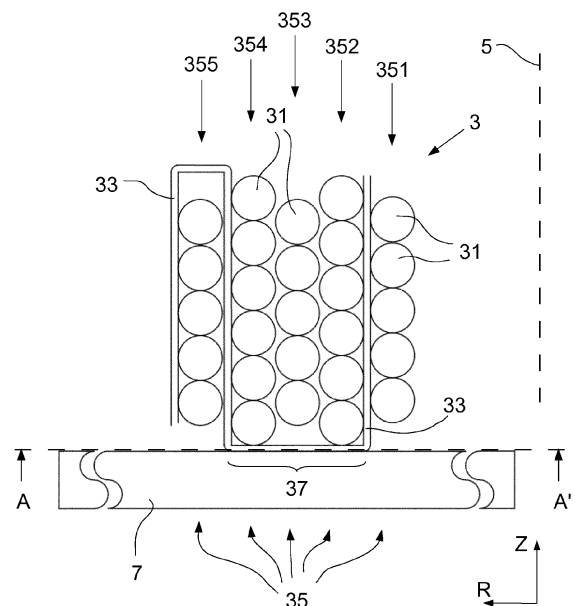


Fig. 2

Description

[0001] The invention relates to an electrical coil assembly comprising a plurality of windings of an insulated electrically conducting wire arranged around a central region such that, when extremities of the wire are connected to an electrical power source, an electrical current flows through the wire and generates a magnetic field in at least said central region.

[0002] The invention also relates to a method of operating such an electrical coil assembly.

[0003] The invention additionally relates to a charged-particle microscope comprising:

- A charged-particle source for producing a beam of charged particles;
- A sample holder for holding a sample;
- A particle-optical column for performing at least one of the following functions:

- Directing said beam onto said sample;

- Focusing charged particles emerging from said sample onto a detector,

wherein the particle-optical column comprises at least one such electrical coil assembly.

[0004] As used throughout this text, the ensuing terms should be interpreted consistent with the following explanation:

- A "wire" may have various cross-sections, such as circular, oval, square or rectangular, for example, and it may take the form of an elongated ribbon or foil, for instance (as in a so-called "full foil coil"). Such a wire may be insulated by providing it with a coating of a material that is a poor electrical conductor, such as a suitable plastic/polymer or vitreous/ceramic/enamel material, for example; in many instances, this material will be provided in the form of a thin coating of insulating "varnish". Alternatively or supplementally, the wire windings of the coil may be immersed in / permeated by a mass of insulating material, such as rubber, resin or putty (which, for example, may have set into a solid state after being poured into place in a liquid state).
- The term "coil assembly" can refer to just a coil on its own, but typically refers to a coil together with structurally associated features, such as a winding/carrying frame, core/yoke, casing, heat sink / cooling jacket, *etc.* In situations where the magnetic field produced by the coil is to be spatially confined (*e.g.* to a volume proximal a particle-optical axis of a charged-particle microscope), the coil assembly may, for example, comprise an external jacketing yoke.
- The phrase "charged particle" encompasses an electron or ion (generally a positive ion, such as a Gallium ion or Helium ion, for example, although a negative ion is also possible; the ion in question may be a charged atom or molecule). The term may also refer to a proton, for example.
- The term "microscope" refers to an apparatus that is used to create a magnified image of an object, feature or component that is generally too small to be seen in satisfactory detail with the naked human eye. In a charged-particle microscope (CPM), an imaging beam of charged particles is directed onto a sample using a so-called "particle-optical column", which comprises a collection of electrostatic and/or magnetic lenses that can be used to manipulate said beam, serving to provide it with a certain focus or deflection, for example, and/or to mitigate one or more aberrations therein. In certain types of CPM, a different particle-optical column may also be used to focus charged particles emanating from the sample onto a detector. In addition to imaging, a CPM may also have other functionalities, such as performing spectroscopy, examining diffractograms, performing (localized) surface modification (*e.g.* milling, etching, deposition), *etc.*

[0005] There are many fields in which an electrical coil assembly is employed as an electromagnet to generate a controllable magnetic field, *e.g.* in motors, generators, transformers, *etc.* Such applications exploit the fact that an electrical conductor that carries an electrical current I will generate a magnetic field B whose strength is proportional to I . If the conductor in question takes the form of a (wire) loop, then B will take the form of a (quasi-)uniform field perpendicular to the plane of the loop. By winding the conductor into a plurality n of such loops - thereby forming a coil with a plurality of windings - the generated magnetic field strength can be increased by a factor n . If desired, the coil may be wound around a (laminated) core of magnetic material, so as to concentrate/confine the generated magnetic flux.

[0006] However, an electrical current flowing through a coil will experience an electrical impedance, which will lead to the generation of heat in the coil windings. The magnitude of such thermal dissipation is proportional to I^2R , where R is the electrical resistance of the coil; making the wire in the coil thinner and/or increasing the number of windings will tend to increase R , thus increasing thermal dissipation, and increasing I so as to enlarge B will further exacerbate this problem. In a situation in which only a given, maximally exploited volume is available for a coil, the interplay between these factors will cause the thermal dissipation to basically depend on the coil volume/diameter and the filling factor of the wire in the coil (see, for example, the relation in Embodiment 2 below). In many applications, so much resistive heat may be generated in the coil that it leads to localized melting of the insulating layer on the coil wire and/or of the wire itself - particularly at or near the core (hereinafter referred to as the "coil interior") of a transverse cross-section of the coil

windings. Such melting will generally render the coil unusable, and can lead to dangerous situations, such as short-circuit, arc-over, smoke production and/or fire.

[0007] To address this problem, some form of coil cooling means may be employed. For example, a heat sink may be placed in intimate thermal contact with a surface of the coil. Such a heat sink may be passive (e.g. as in the case of a metallic structure with dissipative "fins") and/or active (e.g. as in the case of a cooling conduit/jacket through which a fluid coolant (such as water, oil or refrigerant gas) is caused to flow). However, a shortcoming of such an approach is that it only directly cools the exterior of the coil: heat from the coil interior is "shielded" from the cooling means by the outer regions of the coil, so that heat generated in the coil interior may not be able to migrate outward fast/effectively enough to prevent melting. To mitigate this effect, one can embody a surfacial heat sink to comprise thermally conductive (e.g. metallic) "peninsulas" that protrude into the bulk of the coil, serving to conduct heat outwards toward the heat sink. However, such an approach tends to be disadvantageous (*inter alia*) in that:

- It complicates the structure/shape of the coil (whose windings need to divert around / steer clear of the peninsulas);
- The intrusive peninsulas occupy volume that could otherwise be occupied by coil windings. Reducing the "wire volume" of the coil in this manner tends to reduce the attainable magnetic field at a given thermal dissipation or, conversely, lead to increased dissipation for a given magnetic field.

[0008] The issues set forth above are of particular (but not exclusive) importance in charged-particle microscopy. Here, in general, multiple types/shapes/sizes of electrical coil are employed in the particle-optical column of the microscope, e.g. in dipole, quadrupole, sextupole or octupole magnetic lenses/stigmators, deflectors, beam choppers, etc. This particle-optical column (often alluded to using alternative jargon such as "condenser lens", "objective/projection lens", "optical column" etc.) is generally a very confined/crowded environment, with strict limitations on permissible stray fields and thermal dissipation, and very high demands as regards the accuracy (in shape and strength) of the coil-produced magnetic fields that it exploits. Consequently, any measures that affect quantities such as coil (assembly) volume, coil temperature, shape/strength of the produced magnetic field, etc., can have a major effect on the design, operation and reliability of the microscope.

[0009] As a general comment, charged-particle microscopy is a well-known and increasingly important technique for imaging microscopic objects, particularly in the form of electron microscopy. Historically, the basic genus of electron microscope has undergone evolution into a number of well-known apparatus species, such as the Transmission Electron Microscope (TEM), Scanning Electron Microscope (SEM), and Scanning Transmission Electron Microscope (STEM). In a TEM, the electron beam used to irradiate a sample will generally be of significantly higher energy than in the case of a SEM (e.g. 300 keV vs. 10 keV), so as to allow its constituent electrons to penetrate the full depth of the sample; for related reasons, a sample investigated in a TEM will also generally need to be thinner than one investigated in a SEM. In traditional electron microscopes, the imaging beam is "on" for an extended period of time during a given imaging session; however, electron microscopes are also available in which imaging occurs on the basis of a relatively short "flash" or "burst" of electrons, such an approach being of potential benefit when attempting to image moving samples or radiation-sensitive specimens, for example.

[0010] For a detailed discussion of the problem of heat generation in coils, one can, for example, refer to the article by Max Jakob in Transactions of the American Society of Mechanical Engineers 65, pp. 593-605, August 1943.

[0011] It is an object of the invention to address the issues set forth above. In particular, it is an object of the invention to provide an electrical coil assembly in which thermal dissipation effects can be more efficiently mitigated. More specifically, it is an object of the invention that, in such a coil assembly, heat generated in the coil interior should be more effectively transported out of the coil. Furthermore, it is an object of the invention that this should be achieved in a manner that entails minimal reduction of the volume available for coil windings, and has minimal impact on the overall geometry of the coil assembly and the magnetic field produced thereby. In particular, it is an object of the invention that the resulting coil assembly should particularly lend itself to application in the particle-optical column of a charged-particle microscope.

[0012] These and other objects are achieved in an electrical coil assembly as set forth in the opening paragraph, **characterized in that** the coil comprises at least one body of thermally conducting material (hereinafter: BTCM) that is:

- Interspersed among and co-wound with at least a portion of said windings;
- Thermally connected to a heat sink;
- Not embodied to be connected to an electrical power source.

The basic idea behind the invention is that, instead of having a few relatively large and crude cooling peninsulas protruding into (and substantially disturbing the geometry of) the coil, it is better to have a more distributed, more integrated, finer-scale, co-wound system of thermal pathways within the coil structure, which efficiently drain heat from the windings along an interwoven network of thermal "capillaries". The inventors have demonstrated that, surprisingly, such an arrangement can achieve the seemingly incompatible effects of drastically increasing thermal drain from the coil while at the same time minimally affecting the coil volume/geometry. The invention therefore

achieves significant thermal benefit in a manner that is substantially "non-invasive" in electromagnetic terms. For example, in tests, the inventors observed that the inventive approach could be used to achieve a coil assembly in which:

- Only 5% of the coil volume is sacrificed to accommodate said BTCM (e.g. in the form of an interleaved (metallic) foil);
- The power dissipated to achieve the same magnetic field accordingly increases by an amount $(1/0.95 - 1) \times 100\% = 5.26\%$;
- But, spectacularly, the thermal conductance/drain out of the coil is increased more than *tenfold* ($= 1000\%$), thus substantially reducing the risk of thermal runaway.

[0013] In the context of the current invention, the following should be noted:

- The term "co-wound" refers to the fact that the inventive BTCM is so intimately interspersed/interleaved/intertwined with (at least some of) the windings of the coil that it can only be efficiently worked into the coil by feeding it into the coil structure as part of the winding process (co-weaving). Removing the BTCM (without severing it) after the coil is manufactured would generally entail (partially) unraveling the coil.
- The term "heat sink" should be broadly interpreted to encompass any suitable drain (sink) of heat. Depending on the particulars of a given situation, it may, for example, be a large mass of material, a radiative structure with cooling fins/ribs/fingers, a temperature-controlled jacket, *etc.* It may also simply refer to a situation whereby parts of the inventive BTCM run along an (exposed) outside surface of the coil, allowing them to transfer heat to the coil surroundings (by radiation, convection and/or conduction). The employed heat sink may be flat or more complex in shape, and may be employed on one or more sides of the coil. The skilled artisan will understand these points, and will be able to implement various types of suitable heat sink.
- The inventive BTCM is not intended to carry current through the coil: its intended function is as a thermal collector/drain. As such, it is therefore not embodied to be connected to an electrical power source, e.g. in that it is not provided with accessible electrical connection terminals. Put another way, the BTCM is an electrically isolated structure, through which electrical current does not pass when the coil assembly is in use; note, in this context, that eddy currents potentially produced in the BTCM as a result of an AC current in the coil windings do not entail current flow *through* the BTCM.
- The inventive BTCM can comprise various suitable materials, e.g. metals (such as (alloys of) copper, aluminum, silver, gold, *etc.*), thermally conductive polymers, certain oxides/ceramics (such as aluminum oxide or beryllium oxide, for example), *etc.* It may be a compound (e.g. sandwiched or layered) structure if desired, but can also be non-compound. In principle, it does not require an electrically insulating coating (since the wires surrounding it in the coil are generally electrically insulated), though such a coating may be present if desired. It may be interspersed through the whole of the coil, or a major portion thereof, or a relatively minor portion thereof, according to choice.
- The BTCM comprises "thermally conducting" material in that the thermal conductivity of the BTCM (from the coil interior to the heat sink) is greater than the thermal conductivity of the insulation on/around the wire from which the coil is wound (from the longitudinal axis of the wire outward through the insulation). This will generally be the case for a BTCM comprising metallic material, for instance.

[0014] The BTCM according to the current invention can take various possible forms. For example, the BTCM can be selected to be one (or more) of the following:

- (i) A fiber. For example, a wire/cable of ductile material, such as copper or silver, which may be single-stranded or woven/braided. Alternatively, one could conceive a glass, cotton or polymer fiber that is coated with metal, for example. The fiber in question need not have a round cross-section: it could, for example, take the form of a ribbon.
- (ii) A foil. For example, a relatively thin sheet of (malleable) material, such as copper or aluminum. Alternatively, one could conceive a polymer that is (partially) coated on one or both major surfaces with metal, for example. Or one could use a thermally conductive polymer sheet, for instance. To give a specific example, one could conceive a copper foil with a thickness of the order of a few tens of microns, produced by an electroplating process or by rolling a copper sheet, for instance.
- (iii) A fabric. For example, a metallic cloth that is (partially) woven from strands of metallic fiber. Or a woven cloth of carrier material (such as polyester or cotton) that is interlaced with metallic strands and/or coated with metallic material, for example.
- (iv) A coating on said wire. Here, the wire from which the coil is wound - which wire comprises an electrically conducting core with an insulating coating - is provided on its outer surface with a supplemental layer of thermally conducting material (e.g. copper).

[0015] When such wire is wound into a coil, the external coating will necessarily be co-wound, right into the heart of

the coil.

[0016] Various combinations/hybrids of these examples are also conceivable.

[0017] There are various ways in which the BTCM of the present invention can be co-wound into the coil. For example:

- If the BTCM takes the form of a coating on the coil wire (option (iv) above), then co-winding occurs automatically/intrinsically. The external coating on the surface of the wire is then exposed and readily accessible at the surface of the coil, and can easily be thermally connected to a heat sink (see further explanation later).
- If the BTCM takes the form of a fiber (option (i) above) then, for example, it can be drawn from a separate bobbin/reel and fed together with the coil wire into a winder. An extremity of the BTCM (or multiple extremities, if multiple BTCMs are used) can be left protruding from the coil, and connected after the winding process to a heat sink.
- If the BTCM takes the form of a foil or fabric (options (ii) or (iii) above), then, for example, it may be (partially) wrapped around an external surface of one or more embryonic, pre-finished precursor coils that are accessed by interrupting the winding process at one or more stages [such a procedure being somewhat similar to a *papier-mâché* process, whereby sheets of paper are (partially) wrapped around a form that has been coated with glue, after which one proceeds to a next layer of glue (and, possible, a next layer of paper)]. If a portion of the (or each) layer of foil/fabric is left protruding from the coil, these can be connected after the winding process to a heat sink.

[0018] A skilled artisan in the field of coil winding will, on the basis of these examples and the previously elucidated *crux* of the invention, be able to conceive possible alternatives to / variants of these exemplary procedures, all falling within the scope of the current invention.

[0019] In an embodiment of the present invention, the BTCM is thermally connected to said heat sink by a method selected from the group comprising:

- Soldering;
- Localized melting of the BTCM onto the heat sink;
- Gluing;
- Attaching using adhesive tape,

and combinations hereof. As already alluded to above, the heat sink referred to in the current invention can take various forms. In one embodiment, one or more protruding portions/extremities of the BTCM are folded onto / wrapped around / pressed against (part of) a surface of the coil, from where they can dissipate heat to the coil surroundings; such a construction involves a relatively rudimentary "implicit" heat sink. However, in other embodiments, the heat sink may comprise an "explicit" structure (such as a metal block or sheet, cooling jacket, array of cooling fins, *etc.*) that is arranged so as to be in thermal contact with the coil; in such a case, part of the BTCM (*e.g.* an extremity, or surfacial portion) is preferably in intimate thermal contact with (part of) the heat sink. Such contact can be achieved in various ways. For example, one could conceive one or more of the following approaches (severally or in combination):

- Purely by applying pressure. In this case, the heat sink is pressed tightly against an exposed part of the BTCM, and this tight contact results in a good thermal connection.
- By soldering (which term is intended to include welding). In this approach, a molten assistive material (solder) is used to ensure good thermal contact between an exposed part of the BTCM and the heat sink.
- Localized melting of the BTCM onto the heat sink. When a locally melted portion of exposed BTCM is pressed against the heat sink and allowed to re-solidify, it will form a good thermal contact.
- Gluing. Here, an adhesive is used to secure an exposed portion of the BTCM to the heat sink. If the adhesive is used between the two, then it should preferably be thermally conducting.
- Taping. Here, an adhesive tape (such as duct tape) is used to press (and hold) an exposed portion of the BTCM against the heat sink.

[0020] The skilled artisan will be able to conceive possible alternatives to / variants of these exemplary techniques, all falling within the scope of the current invention. The skilled artisan will also appreciate that, in situations in which the coil generates substantial heat and/or in applications involving strict thermal control of the coil surroundings, the employed heat sink may comprise a conduit through which a coolant fluid (such as water, oil or refrigerant gas, for example) can be caused to flow; this point has already been mentioned above.

[0021] It should be noted that, because the BTCM of the current invention is so effective at draining heat out of the coil, it can allow one to use a smaller heat sink and/or to employ a heat sink on fewer external surfaces/sides of the coil. This can be of great advantage in situations where the ratio of space to dissipated power is at a premium, such as in the particle-optical column of a CPM, for example.

[0022] A coil assembly according to the present invention can be used as an AC (alternating current) coil, by connecting

it to a power supply that delivers an oscillating current/voltage. However, an important application of the inventive coil assembly is as a current-driven DC (direct current) coil, whereby the coil is connected to a power supply that delivers/maintains a flat-value, constant current (a so-called "constant current source"). Such an embodiment is, for example, of importance in particle-optical lenses (e.g. in a CPM), in which a very accurate, stable magnetic field has to be generated - thus requiring a stable electrical current through the coil. A constant current source will regulate/maintain its output current independent of the voltage/resistance across which it is connected. This can lead to a potentially dangerous situation if the material of the wire in the coil has a positive temperature coefficient of resistivity (which is the case for copper, for example): as the coil gets hot (from dissipated ohmic heat), its resistance will increase, leading to a further increase in dissipated heat (at constant current), and potentially resulting in a "thermal runaway" effect that causes the coil to (locally) melt. In such a situation, it is of great importance to be able to effectively drain heat out of the coil, so as to prevent a thermal runaway cycle. The current invention provides an efficient means of achieving such thermal drain.

[0023] An important difference between AC and DC applications of a coil deserves mention here.

- In AC applications (where the coil is connected to an AC power supply), a coil is often essentially used as a temporary "energy storage device" as part of a cyclical energy conversion process (e.g. conversion of electrical into mechanical energy in a motor, conversion of one electrical voltage to another in a transformer, etc.). The efficiency of this energy conversion process will suffer if unwanted energy losses occur in the coil (e.g. due to ohmic dissipation in the coil windings, eddy currents/hysteresis in a coil yoke, etc.). Therefore, in AC applications, there tends to be an emphasis on *avoiding* (reducing) heat production in the coil - e.g. by using thick windings with a relatively low resistance value. This will generally involve using a larger coil, but this tends to be less of an issue than the risk of thermal losses in the coil.
- In contrast, in DC applications (where the coil is connected to a DC power supply), the coil is not used as a temporary storage device in this manner, and there is less concern about efficiency reduction due to parasitic losses. The main emphasis is on the production of an acceptable magnetic field, and thermal losses in the coil are accepted as an inevitable side effect. Often (as in the case of the optical column in a CPM, for example), cramped conditions mean that one does not have the luxury of using a bigger coil: so, in contrast to the situation in AC applications, a hot coil tends to be less of an issue than a big coil.

[0024] Bearing these differences in mind, one can grasp the particular importance of the current invention in the case of DC applications, where an efficient technique is needed to prevent a hot coil from overheating. However, this certainly does not preclude application of the present invention in AC applications - e.g. to control thermal dissipation in situations where the employed coil is necessarily "lossy".

[0025] The invention will now be elucidated in more detail on the basis of exemplary embodiments and the accompanying schematic drawings, in which:

Figure 1 renders a cross-sectional view of an embodiment of an electrical coil assembly according to the present invention.

Figure 2 renders a more detailed view of part of the subject of Figure 1.

Figure 3 depicts part of the subject of Figures 1 and 2, viewed from beneath.

Figure 4 is a photograph of a transverse cross-section of a prior-art electrical coil assembly in which localized melting has occurred.

Figure 5 shows a cross-sectional view of an electrical coil assembly according to the prior art.

Figure 6 renders a detailed cross-sectional view of part of another embodiment of an electrical coil assembly according to the present invention.

Figure 7 renders a detailed cross-sectional view of part of still another embodiment of an electrical coil assembly according to the present invention.

Figure 8 renders an elevational view of an embodiment of a charged-particle microscope according to the current invention.

[0026] In the Figures, where pertinent, corresponding parts are indicated using corresponding reference symbols. It should be noted that, in general, the Figures are not to scale.

Embodiment 1

[0027] Figure 1 renders a cross-sectional view of an embodiment of an electrical coil assembly 1 according to the present invention. The coil assembly 1 comprises a coil 3 that is (in terms of its basic geometry) circularly symmetric about a central axis 5 and (quasi)toroidal in form, the depicted cross-section having been taken along a diameter of the associated circle/torus. Also shown is a heat sink 7, which is arranged so as to intimately contact a surface of the coil

3 (possibly *via* the intermediary of a film of thermally conducting material, such as solder or adhesive, for example); in this case, the heat sink is annulus-shaped, and contacts an annular face of the coil 3. A more detailed view of part of the subject of Figure 1 is given by Figure 2, in which said intimate contact between items 7 and 3 is more clearly depicted than in the more schematic rendition of Figure 1. The coil 3 surrounds a cylindrical central region 9 that is centered on the axis 5. This central region 9 may be left empty, but it may alternatively accommodate a (laminated) iron core, for example. As will be discussed in more detail with respect to Figure 2, the coil 3 comprises a plurality of windings (loops) that are basically concentric about axis 5. The coil 3 may, for example, be formed by spooling/spiraling/spinning an electrically insulated electrically conducting wire 31 about a bobbin (not depicted) that defines the central region 9; this bobbin may be removed or may be left in place after said spooling/spiraling/spinning operation has been completed. Symbolically depicted in Figures 1 and 2 is a cylindrical coordinate system that comprises a linear Z direction along the axis 5, a radial direction R outward from the axis 5, and an angular Θ direction that is not depicted but is orbital about the axis 5.

[0028] Turning now to Figure 2, this shows a more detailed view of part of the subject of Figure 1, to the left of the axis 5 (see the cross-section B-B' indicated in Figure 3). More specifically, the coil 3 is seen to be comprised of wire 31, which in this case has a circular cross-section (but could also have other cross-sections, such as square, for example). The wire 31 is, for example, comprised of copper, with an electrically insulating coating of, for example, enamel or plastic. In this particular case, the conducting core of the wire 31 has a diameter of ca. 0.5 mm, and the insulating coating thereon has a thickness of a few tens of microns, for example (which figures should not in any way be interpreted as limiting). The skilled artisan will understand that there are many ways in which the wire 31 can be wound into a coil 3 of the type depicted, such as by utilizing the following (non-limiting) procedure, for example:

- During the winding process, the wire 31 is stacked onto itself (in the Z direction) with each new turn, thus forming a "column" 35 of windings, such as column 351.
- When one such column is complete, the wire 31 is shifted outward (in the R direction) and then wound in a similar way around the outside of that column, thus forming a new column (*e.g.* column 352), which closely surrounds the column inside it.
- And so forth for successive columns 353, 354, 355, *etc.*
- To ensure optimum packing density of the wire 31 within the volume of the coil 3, successive columns 35 can be "staggered" back and forth in Z (by half the diameter of the wire 31) [orthocyclic winding].

[0029] The skilled artisan will understand that, when extremities of the wire 31 are connected to an electrical power source (not depicted), an electrical current will flow through the wire 31 and generate a magnetic field (not depicted) in at least the central region 9.

[0030] In accordance with the present invention, the coil 3 comprises at least one body of thermally conducting material (BTCM) 33 that is:

- Interspersed among and co-wound with at least a portion of the windings of the wire 31;
- Thermally connected to the heat sink 7;
- Not (going to be) connected to an electrical power source.

[0031] In this particular case (among many other possibilities), the BTCM 33 takes the form of a ribbon-like strip 39 (see Figure 3) of copper foil that meanders among the columns 35 of the coil 3. For example, in the depicted set-up:

- The foil 33 is laid along the outside of column 351 after it is wound, leaving a long tail of foil hanging outside the coil 3 for subsequent use.
- Columns 352, 353 and 354 are then wound, after which (said tail of) the foil 33 is stretched along the bottom of these columns and up the outside surface of column 354.
- Column 355 is then wound, after which (said tail of) the foil 33 is stretched along the top of this column and down the outside surface of column 355.
- And so forth.

[0032] In this particular example, a repetitive "1-3-1 duty cycle" is chosen when winding the foil 33 amongst the columns 35 but this does not have to be the case, and other duty cycles - or, indeed, other completely different interspersing geometries - could also be employed. In any case, as here depicted, after winding is completed, there will be one or more portions 37 of foil 33 that run along the bottom of the coil 3, and such portions 37 can be pressed intimately against heat sink 7 (directly, or with the intermediary of a layer of adhesive or solder, for example), so as to form thermal contact zones between the heat sink 7 and foil 33. In this particular example, the foil 33 has a thickness of ca. 15-50 microns, and a width (perpendicular to the plane of Figure 2) of 5 mm (which figures should not in any way be interpreted as limiting).

[0033] Turning now to Figure 3, this shows part of the subjects of Figures 1 and 2 when viewed upward from a space between the heat sink 7 and coil 3 (see the cross-section A-A' indicated in Figure 2). This figure reveals a BTCM 33 that in fact comprises several ribbon-like strips 39 of copper foil, all meandered/interspersed among the coil windings with the aforementioned basic "1-3-1 duty cycle", but with different "phases"; for example, when viewed from axis 5 radially outward, the first portion 37 has a radial extent of:

- One winding, in the case of strips 391;
- Two windings, in the case of strips 392;
- Three windings, in the case of strips 393.

[0034] Note that successive strips 39 occur at 30° intervals around axis 5 (in the Θ direction). Once again, it should be explicitly noted that the number/arrangement of strips 39 depicted in Figure 3 is purely a matter of choice, and that many other alternatives are possible.

Embodiment 2

[0035] To illustrate how effective the invention is, consider the situation illustrated in Figures 1-3 with the following (approximate) values:

- Height (h) of coil 3 (in Z direction): 11.5 mm.
- Inner diameter (Di) of coil 3 (in R direction): 10 mm (= diameter of central region 9).
- Outer diameter (Do) of coil 3 (in R direction): 44 mm.
- Number of stacked turns/windings in each column 35 (in Z direction): 32.
- Number of columns 35 (in R direction, from axis 5 outward): 52.
- Diameter of conducting core of wire 31: 0.32 mm.
- Electrical resistance of coil 3 at 20 °C: 32.2 Ω .
- Electrical current (I) in coil 3: 0.96 A.
- Current density (J) in coil 3: 13.16 A/mm².
- Number of Ampere turns (nI): 1600.
- Heat sink 7: copper plate of thickness 2 mm, maintained at a temperature of 20 °C (e.g. with the aid of a non-depicted water cooling conduit).
- Thermal resistance at zones 37: 0.333 K/W (assuming a (cumulative) contact area (at portions 37) of ca. 1000 mm² between the BTCM 33 and heat sink 7).

[0036] The BTCM 33 then occupies ca. 5 % of the volume of the coil 3, and one obtains the following:

- ΔP : Dissipated ohmic power in coil 3 at 20 °C: 31.2 W.
- ΔT : Temperature rise at top of coil 3 (furthest from heat sink 7) w.r.t. the heat sink 7: 47 °C.

[0037] These values of ΔP and ΔT are relatively low, particularly in view of the fact that the coil 3 in Figures 1-3 is cooled only from below (so-called one-sided cooling, using a rudimentary flat heat sink 7). This will be made clearer by reference to the following Comparative Example.

[0038] It is noted that the functional dependence of ΔP on various other parameters set forth above can be described by the following relation:

$$\Delta P \sim (nI)^2 \pi \rho_0 (1 + \alpha \Delta T) [(Do + Di) / (Do - Di)] (1/h)$$

in which:

- ρ_0 is the resistivity of the material of the coil wire at 20 °C;
- α is the temperature coefficient of resistivity for the material of the coil wire.

Comparative Example

[0039] If one were to take the same coil/scenario described in Embodiments 1 and 2 above and completely remove the BTCM 33 prescribed by the current invention, the temperature rise at/near the heart/core/interior of the bunched

windings in the coil cross-section could reach a point where thermal runaway is triggered, causing localized melting of the coil wire. The result of such thermal runaway is depicted in Figure 4, which is a photograph of a transverse cross-section of part of a coil 3" of wire 31", and which clearly shows a melt region 41" in a location at/near the heart of the coil 3" (see the region within the black oval).

[0040] To avoid such melting, the prior art has traditionally resorted to a set-up as illustrated in Figure 5 (compare to Figure 1), in which heat sink 7' has peninsulas 71' that protrude outward from it in a direction parallel to the Z axis, in a configuration aimed at achieving multi-sided cooling (in this case, three-sided cooling). These peninsulas 71' invade the volume that would otherwise be available for the coil, and the geometry of the coil has to be modified to make allowances for this. In the situation shown in Figure 5, the coil has been split into two (series-connected) subcoils - an inner subcoil 3a' and an outer subcoil 3b' - which are both concentric about axis 5' (and central region 9'). The peninsulas 71' are also concentric about axis 5'. To arrive at a specific comparison, the following values are considered:

- Height (h) of subcoils 3a', 3b' (in Z direction): 11.5 mm.
- Inner diameter of subcoils (in R direction): 15.6 mm (3a') and 29.8 mm (3b').
- Outer diameter of subcoils (in R direction): 27.3 mm (3a') and 40 mm (3b').
- Number of stacked windings in each column of each subcoil (in Z direction): 32.
- Number of columns (in R direction, from axis 5' outward): 18 (3a') and 16 (3b').
- Diameter of conducting core of coil wire: 0.32 mm.
- Electrical resistance at 20 °C: 8.85 Ω (3a') and 13.26 Ω (3b').
- Electrical current (I) in subcoils: 1.45 A.
- Current density (J) in subcoils: 19.85 A/mm².
- Number of Ampere turns (nI): 1600.
- Heat sink 7 (and peninsulas 71'): copper plate of thickness 2 mm, maintained at a temperature of 20 °C (e.g. with the aid of a non-depicted water cooling conduit).

[0041] Note that I and J have to be larger than in Embodiment 2, so as to produce the same magnetic field strength from a smaller available coil volume. In this case, one obtains:

- $\Delta P'$: Dissipated (total) ohmic power in coil at 20 °C: 46.5 W.
- $\Delta T'$: Temperature rise at heart of each subcoil w.r.t. the heat sink 7: 60 °C.

[0042] Both of these values are significantly higher than the corresponding values in Embodiment 2, despite the use of three-sided cooling as opposed to the one-sided cooling in Embodiment 2. This shows how effectively the BTCM of the current invention drains heat out of the coil.

Embodiment 3

[0043] As already set forth above, there are many different ways in which the BTCM of the current invention can be embodied/configured. A possible alternative to the situation shown in Figure 2 is depicted in Figure 6. Here, the BTCM 33 takes the form of a copper foil or cloth, which runs along the interface between each pair of columns 35 in coil 3. Such a set-up can, for example, be manufactured as follows:

- When column 351 has been wound (from wire 31), a sheet of copper foil/cloth is wrapped around its exterior surface to form a snug cylindrical jacket, with a small protruding "skirt" at the bottom of the coil 3.
- Column 352 is now wound around the exterior of this jacket. When it has been wound, another sheet of copper foil/cloth is wrapped around its exterior surface to form another snug cylindrical jacket, with a small protruding "skirt" at the bottom of the coil 3.
- And so forth for columns 353, 354, etc.

[0044] The protruding skirts of BTCM 33 can, for example, be attached to heat sink 7 using solder, or by taping them in place. In this way, thermal contact zones 37 are formed, which, for example, comprise concentric circles of solder that serve to ensure intimate thermal contact between the abovementioned skirts of the BTCM 33 and the heat sink 7.

Embodiment 4

[0045] Figure 7 renders a detailed cross-sectional view of part of still another embodiment of an electrical coil assembly according to the present invention (see example (iv) given above). The Figure again shows a coil 3 comprising windings of wire 31 that are concentric about an axis 5 and are juxtaposed (on one face of the coil 3) against a heat sink 7.

However, as is shown by the magnified view of one of the wires 31, the BTCM 33 in the current embodiment takes a substantially different form to that set forth in the previous Embodiments. Here, each wire 31 comprises:

- A core 31C of electrically conducting material, such as copper.
- A surrounding sheath 31S of electrically insulating material.
- An external jacket 31J of thermally conducting material, such as copper. This is what forms the BTCM 33.

[0046] The jacket 31J is electrically insulated from the core 31C by the sheath 31S. When the coil 3 is wound, adjacent windings of wire 31 abut against each other, whereby the jackets 31J on each of the windings are pressed against one another, forming a complex BTCM 33 that is intimately co-wound with (and thoroughly interspersed in) the coil 3. When the coil 3 is pressed against heat sink 7, the jackets 31J on the windings at the edge/bottom of the coil 3 press against the heat sink 7, forming thermal contact zones 37. The intimacy of the contact in these zones 37 may, if desired, be augmented by using a layer of solder/adhesive between the coil 3 and heat sink 7.

Embodiment 5

[0047] Figure 8 is a highly schematic depiction of an embodiment of charged-particle microscope M according to the current invention, in which at least one coil assembly according to the current invention is employed. In the Figure, a vacuum enclosure 2 encapsulates a CPM, which in this case is a TEM. In the depicted TEM, an electron source 4 (such as a Schottky gun, for example) produces a beam of electrons that traverse an electron-optical column 6 that serves to direct/focus them onto a chosen region of a sample S. This electron-optical column 6 has an electron-optical axis 8, and will generally comprise a variety of electrostatic / magnetic lenses, deflectors, correctors (such as stigmators), *etc.* In the case of a TEM, the electron-optical column 6 may be referred to as (comprising) a condenser system.

[0048] The sample S is held on a sample holder 10 than can be positioned in multiple degrees of freedom by a positioning device (stage) 12; for example, the sample holder 10 may comprise an arm that can be moved (*inter alia*) in the XY plane (see the depicted Cartesian coordinate system). Such movement allows different regions of the sample S to be irradiated / imaged / inspected by the electron beam traveling along axis 8, and also allows scanning motion to be performed in STEM mode.

[0049] The focused electron beam traveling along axis 8 will interact with the sample S in such a manner as to cause various types of "stimulated" radiation to be emitted from the sample S, including (for example) secondary electrons, backscattered electrons, X-rays and optical radiation (cathodoluminescence); if desired, one or more of these radiation types can be detected with the aid of detector 22, which might be a combined scintillator/photomultiplier or EDX (Energy-Dispersive X-Ray Spectroscopy) detector, for instance. However, of predominant interest in a TEM are electrons that pass through the sample S, emerge from it and continue to propagate along axis 8. Such transmitted electrons enter an electron-optical projection system 24, which will generally comprise a variety of electrostatic / magnetic lenses, deflectors, correctors (such as stigmators), *etc.* This lens system 24 focuses the transmitted electrons onto a fluorescent screen 26, which, if desired, can be retracted/withdrawn (as schematically indicated by arrows 28) so as to get it out of the way of axis 8. An image of (part of) the sample S will be formed by lens system 24 on screen 26, and this may be viewed through viewing port 30 located in a suitable portion of the wall 2. The retraction mechanism for screen 26 may, for example, be mechanical and/or electrical in nature, and is not depicted here.

[0050] As an alternative to viewing an image on screen 26, one can instead make use of pixelated electron detector 32, such as a CMOS or CCD detector, for example. To this end, screen 26 is retracted (see previous paragraph), and electron-optical system 34 is enacted so as to shift the focus of the electrons emerging from lens system 24 and redirect/focus them onto detector 32 (instead of screen 26). Here, the electrons can form an image that can be processed by controller 50 and displayed on a display device (not depicted), such as a flat panel display, for example. Alternatively, electron-optical system 34 can play the role of an EELS deflector, for example, serving to split the beam of electrons from lens system 24 into a plurality of (energy-selected) sub-beams, which impinge on different regions of detector 32. As yet another alternative, the detector 32 may be used to register a diffraction pattern produced by sample S, for example. The skilled artisan will be very familiar with these various possibilities, which require no further elucidation here. He will also realize that, if desired, detector 22 may be a pixelated detector of a type similar/identical to detector 32.

[0051] Note that the controller (computer processor) 50 is connected to various illustrated components *via* control lines (buses) 50'. This controller 50 can provide a variety of functions, such as synchronizing actions, providing setpoints, processing signals, performing calculations, and displaying messages/information on a display device (not depicted). The skilled artisan will understand that the interior of the enclosure 2 does not have to be kept at a strict vacuum; for example, in a so-called "Environmental TEM", a background atmosphere of a given gas is deliberately introduced/maintained within the enclosure 2.

[0052] Turning now more specifically to the current invention, particle-optical columns 6, 24 and 34 tend to be very cluttered, and to have high tolerances as regards thermal stability. They will generally contain one or more coil-based

particle-optical elements (such as multipole magnetic lenses, stigmators, *etc.*), in which electrical coil assemblies are used to perform manipulation of the electron beam propagating along axis 8. Any measure that can reduce thermal dissipation in such elements and/or allow them to be made more compact can be of great benefit. In this regard, use of the inventive coil assembly in such elements can offer substantial advantages.

[0053] For some general information regarding this subject matter, reference is made to the following links:

http://en.wikipedia.org/wiki/Magnetic_lens

http://en.wikipedia.org/wiki/Electron_optics

http://en.wikipedia.org/wiki/Electron_microscope

Claims

1. An electrical coil assembly comprising a plurality of windings of an insulated electrically conducting wire arranged around a central region such that, when extremities of the wire are connected to an electrical power source, an electrical current flows through the wire and generates a magnetic field in at least said central region, **characterized in that** the coil comprises at least one body of thermally conducting material that is:

- Interspersed among and co-wound with at least a portion of said windings;
- Thermally connected to a heat sink;
- Not embodied to be connected to an electrical power source.

2. An electrical coil assembly according to claim 1, wherein said body is selected from the group comprising:

- A fiber;
- A foil;
- A fabric;
- A coating on said wire,

and combinations hereof.

3. An electrical coil assembly according to claim 1 or 2, wherein said body is thermally connected to said heat sink by a method selected from the group comprising:

- Soldering;
- Localized melting of the body onto the heat sink;
- Gluing;
- Attaching using adhesive tape,

and combinations hereof.

4. An electrical coil assembly according to any of claims 1-3, wherein said heat sink comprises a conduit through which a coolant fluid can be caused to flow.

5. A method of operating an electrical coil assembly comprising a plurality of windings of an insulated electrically conducting wire arranged around a central region, wherein extremities of the wire are connected to an electrical power source, thus causing an electrical current to flow through the wire and generate a magnetic field in at least said central region,

characterized by employing at least one body of non-current-carrying thermally conducting material that has been:

- Interspersed among and co-wound with at least a portion of said windings;
- Thermally connected to a heat sink,

to conduct dissipated heat out of the coil and to said heat sink.

6. A method according to claim 5, wherein said electrical power source is selected to be a DC current source.

7. A charged-particle microscope comprising:

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- A charged-particle source for producing a beam of charged particles;
- A sample holder for holding a sample;
- A particle-optical column for performing at least one of the following functions:

- 5 ■ Directing said beam onto said sample;
- Focusing charged particles emerging from said sample onto a detector, **characterized in that** said particle-optical column comprises at least one coil assembly as claimed in any of claims 1-4.

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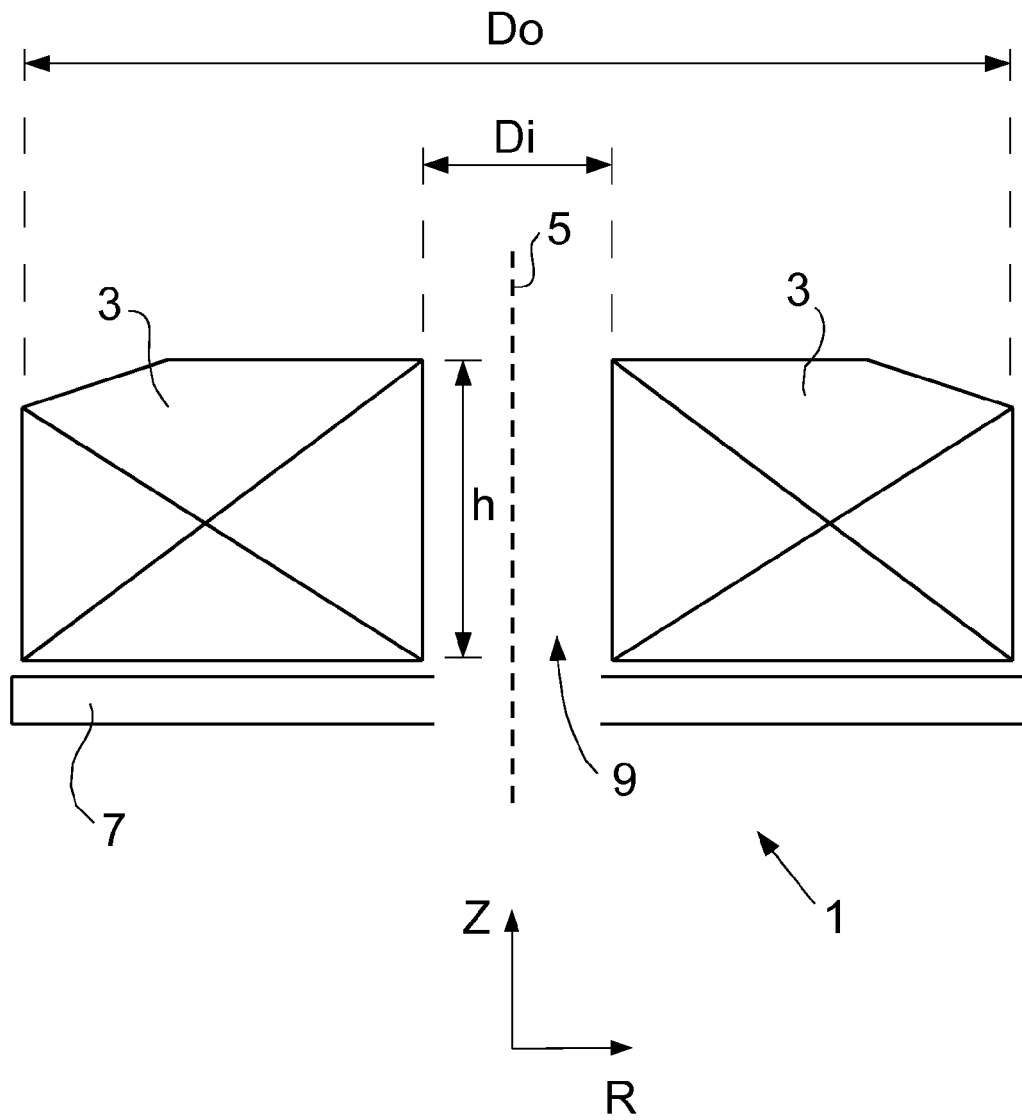


Fig. 1

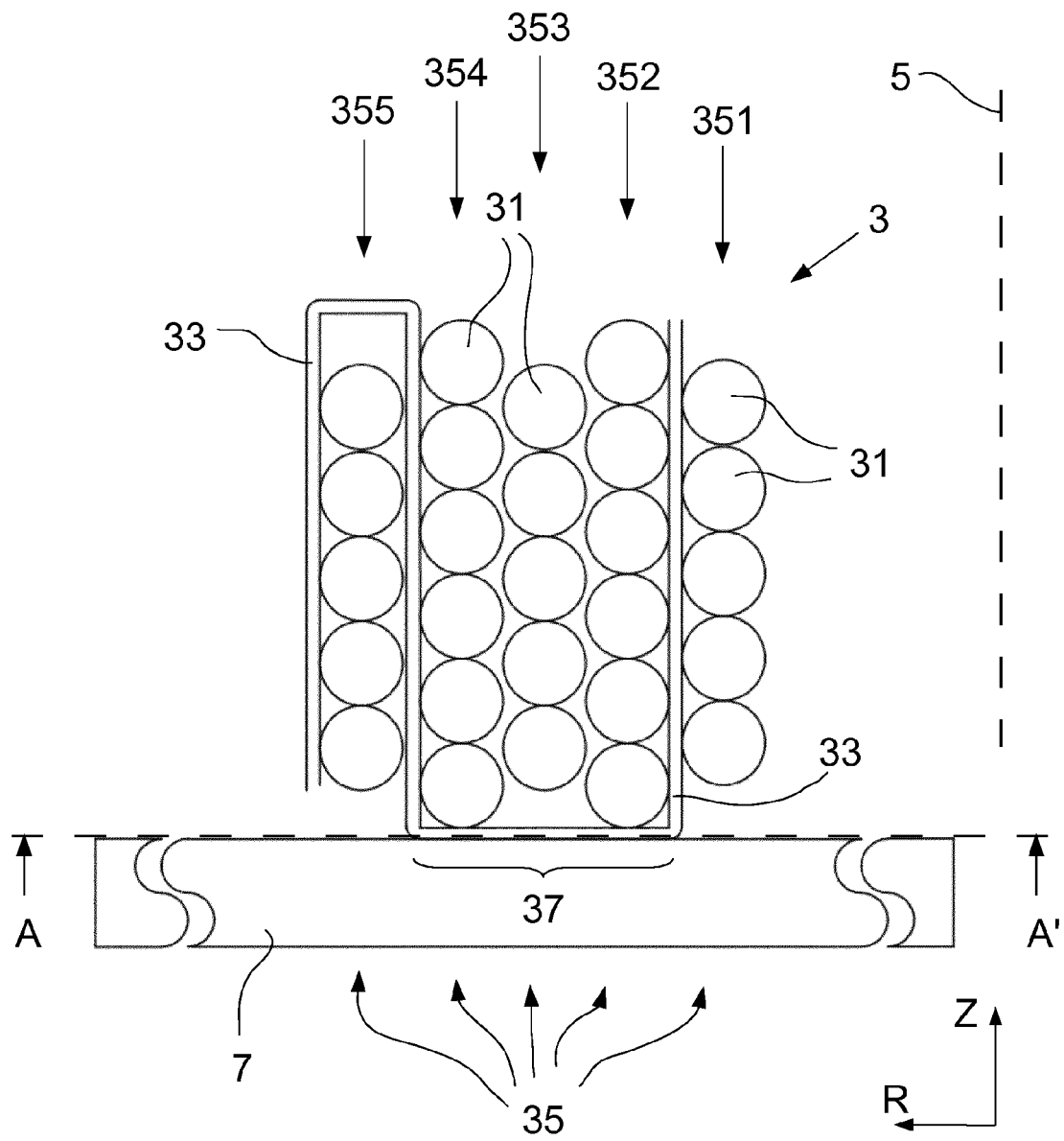


Fig. 2

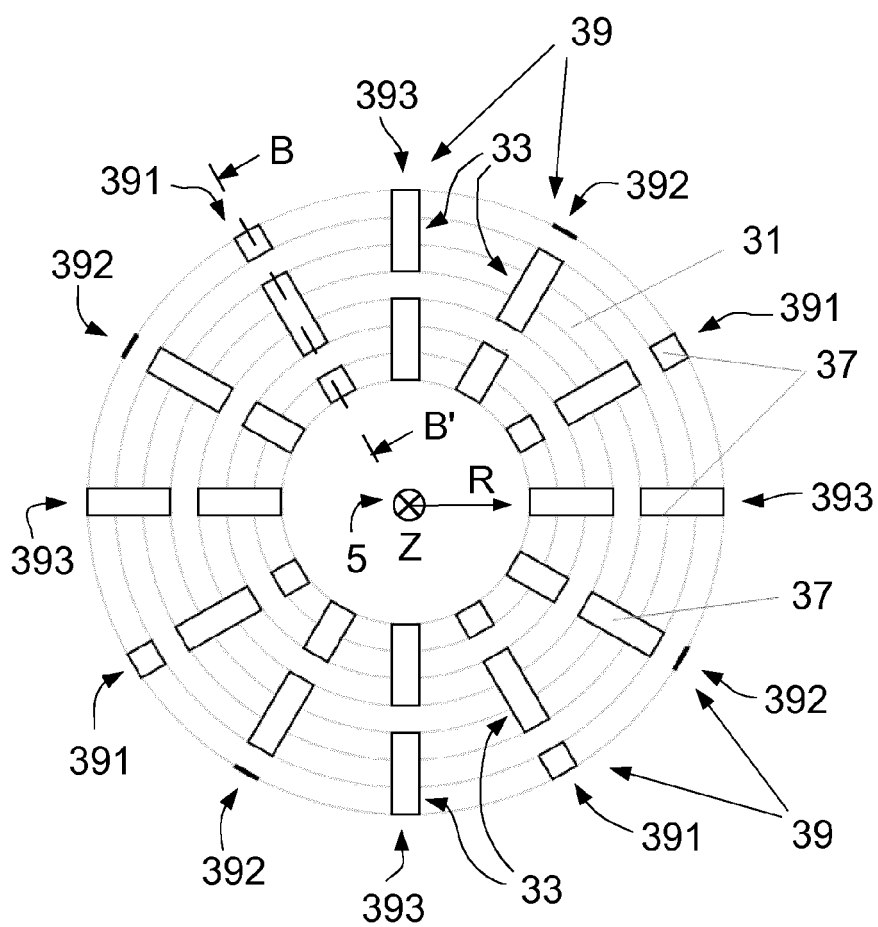


Fig. 3

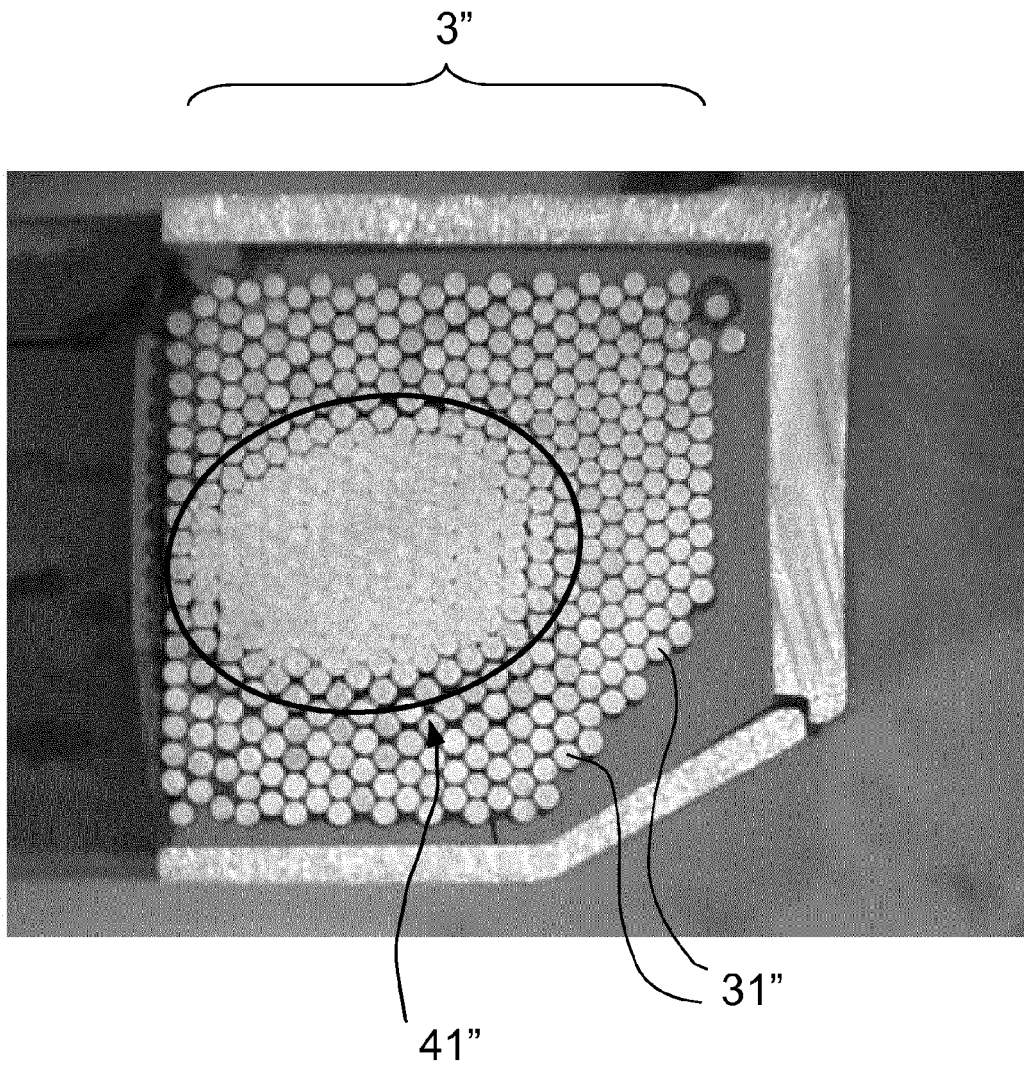


Fig. 4

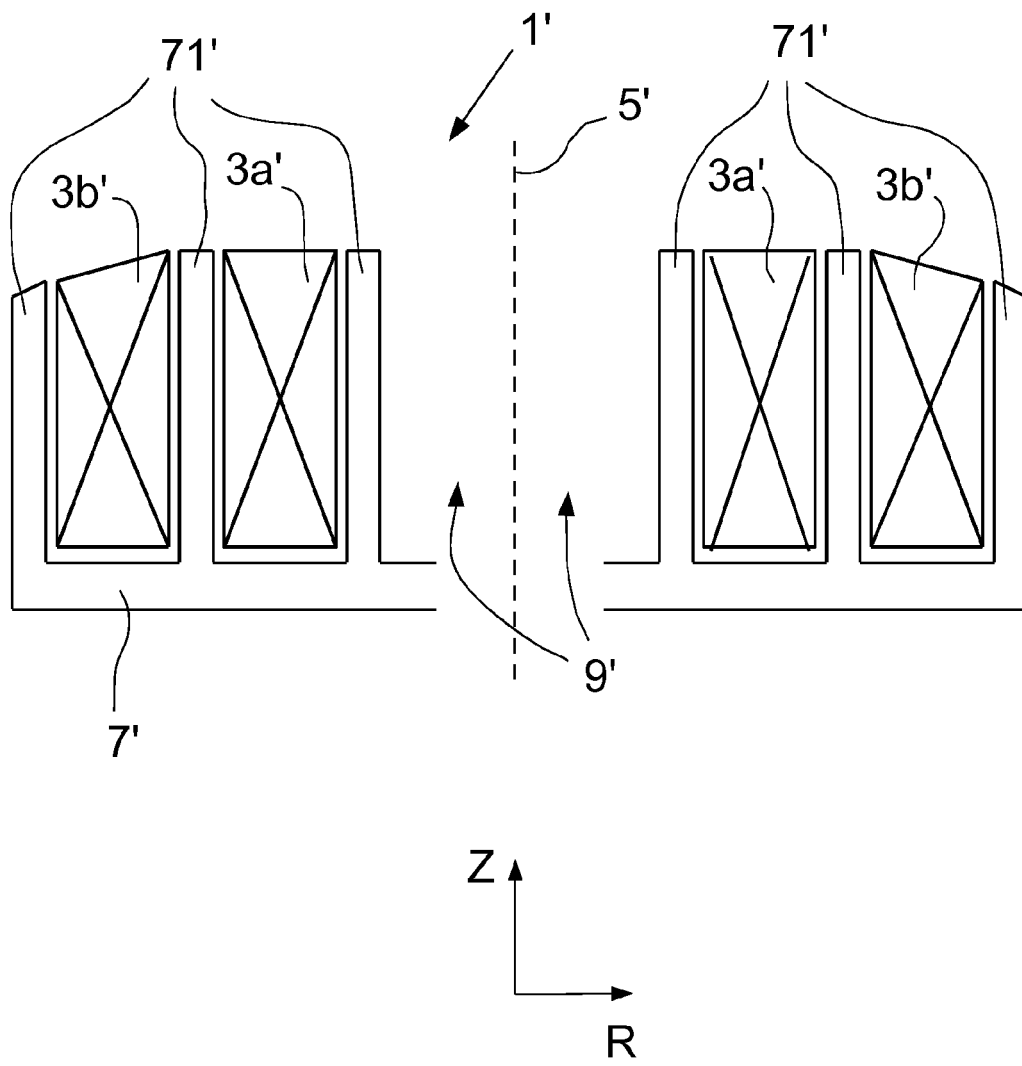


Fig. 5

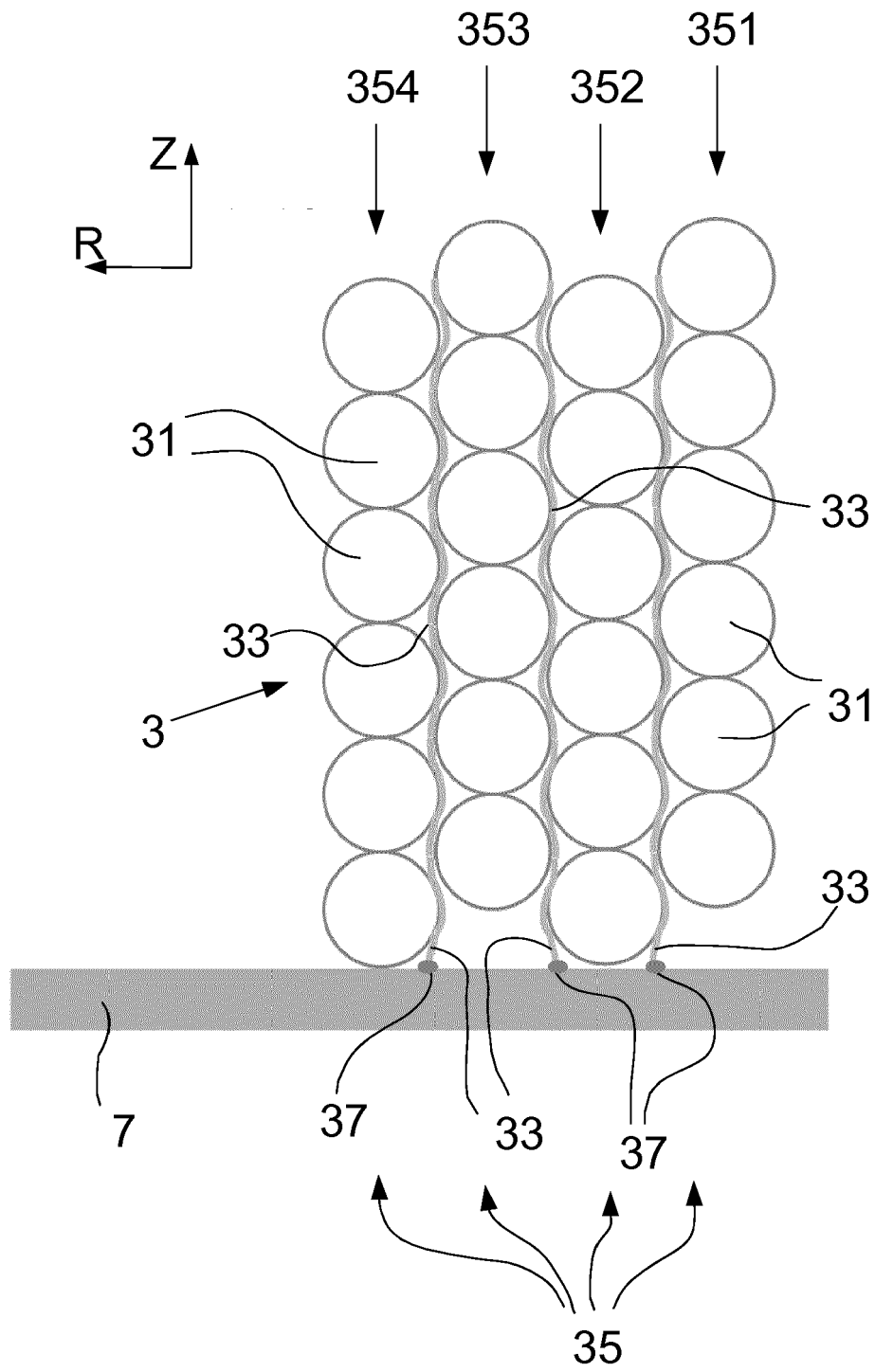


Fig. 6

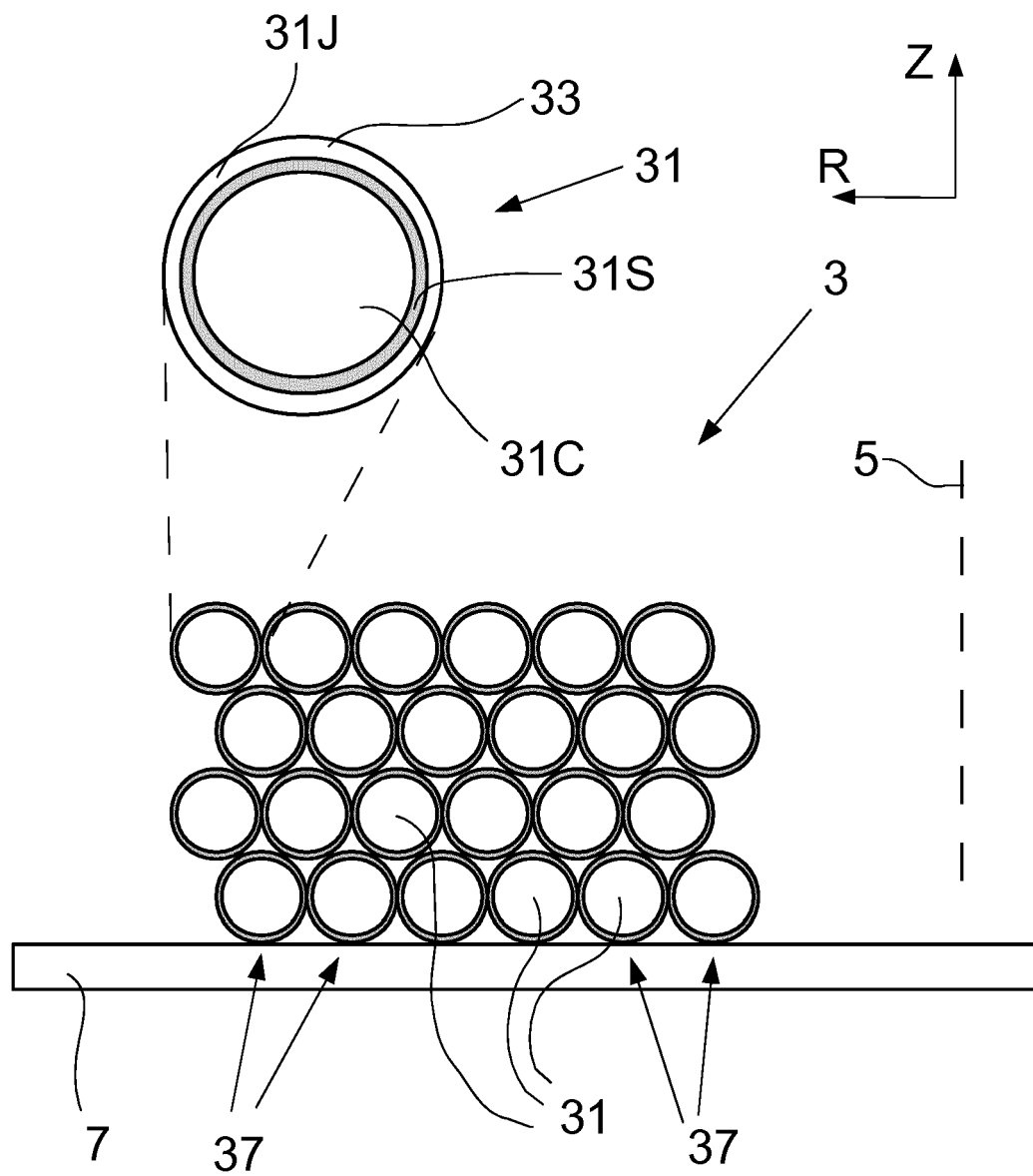


Fig. 7

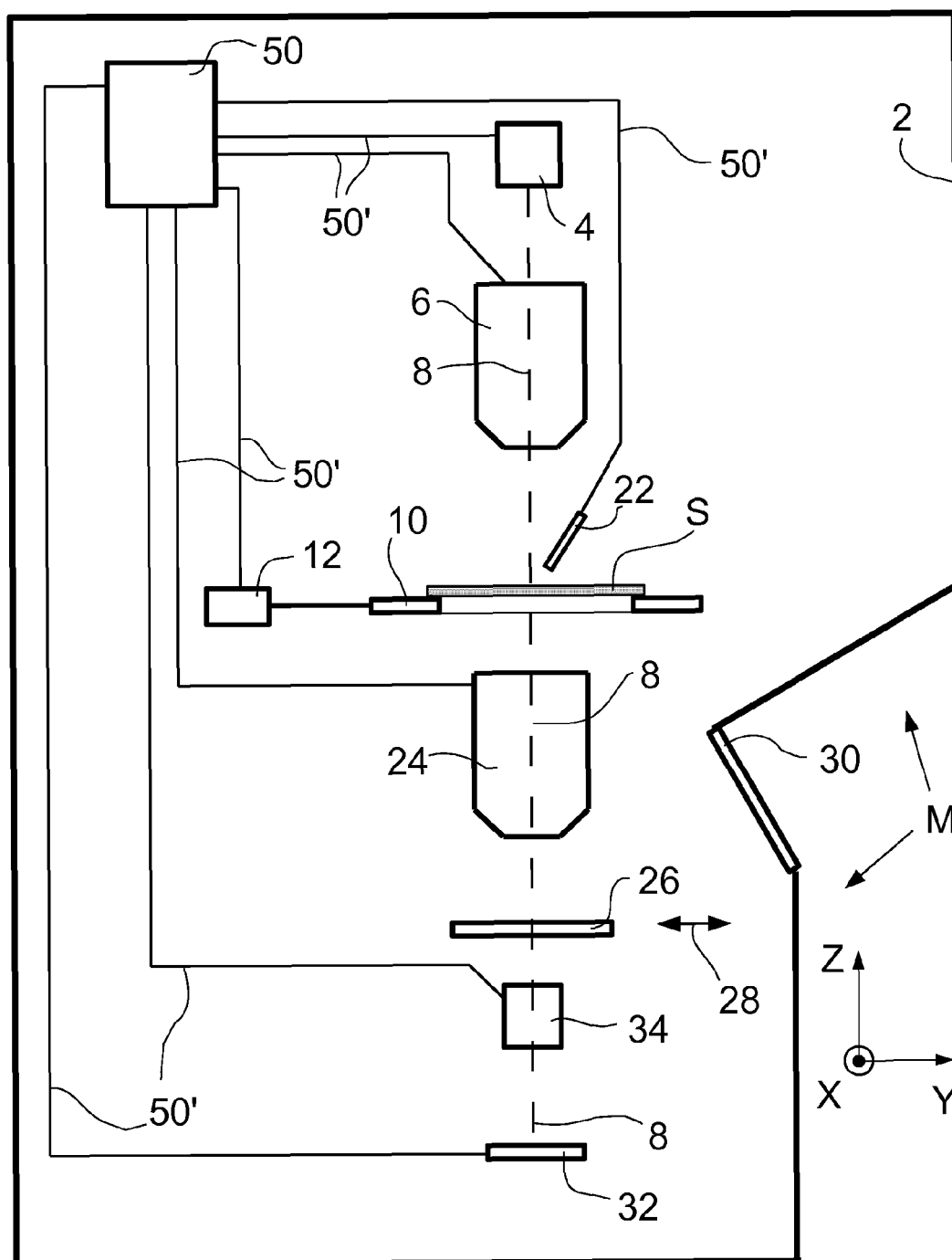


Fig. 8



EUROPEAN SEARCH REPORT

Application Number
EP 13 18 4564

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	WO 2011/042614 A1 (SALOMAEKI JARKKO [FI]) 14 April 2011 (2011-04-14)	1-6	INV. H01F27/28
Y	* page 1, line 21 - page 2, line 3 * * page 5, line 21 - page 6, line 4 * * page 6, lines 22 - 27 * * page 17, lines 20, 21 * * figures 4, 27 *	7	
X	US 7 508 289 B1 (WERNICKI PAUL F [US]) 24 March 2009 (2009-03-24)	1-6	
Y	* column 3, lines 12 - 15 * * column 4, lines 16 - 38 * * column 8, lines 37 - 43 * * column 9, lines 4 - 25 and 39 - 54 * * column 9, line 65 - column 10, line 17; figure 15A *	7	
Y	US 5 008 549 A (CREWE ALBERT V [US]) 16 April 1991 (1991-04-16)	7	
A	* column 1, lines 6 - 8 * * column 2, lines 14 - 17 * * claim 1 * * figures 1, 2 *	1-6	TECHNICAL FIELDS SEARCHED (IPC)
			H01F H01J
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 27 January 2014	Examiner Van den Berg, G
CATEGORY OF CITED DOCUMENTS		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	
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**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 13 18 4564

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27-01-2014

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2011042614 A1	14-04-2011	CN 102648503 A	22-08-2012
		EP 2486576 A1	15-08-2012
		FI 20096045 A	10-04-2011
		KR 20120099673 A	11-09-2012
		US 2012242442 A1	27-09-2012
		WO 2011042614 A1	14-04-2011

US 7508289 B1	24-03-2009	US 7508289 B1	24-03-2009
		US 2009179721 A1	16-07-2009
		WO 2009089452 A1	16-07-2009

US 5008549 A	16-04-1991	US 5008549 A	16-04-1991
		WO 9115870 A1	17-10-1991

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Non-patent literature cited in the description

- **MAX JAKOB.** *Transactions of the American Society of Mechanical Engineers*, August 1943, vol. 65, 593-605 [0010]