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(54) Title: MAIN MAGNET BASED ON ELLIPTICAL HALBACH ARRAYS, ASSOCIATED MAGNETIC RESONANCE IMAGING SCANNER AND ASSOCIATED METHOD OF MANUFACTURE

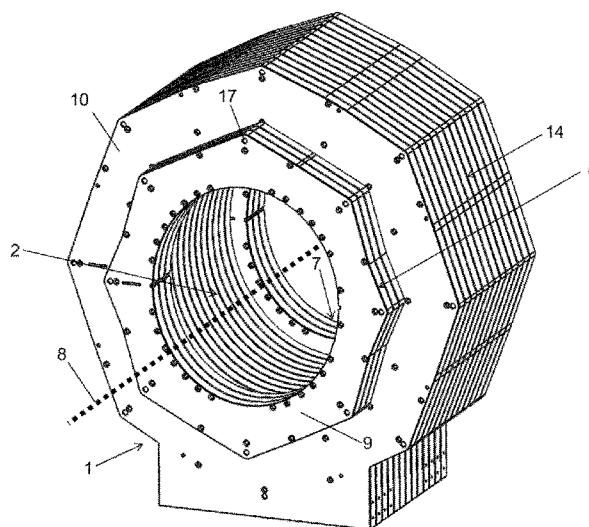


FIG. 1

(57) Abstract: The invention relates to a main magnet (1) comprising a plurality of rings (9, 10) with hollow sections (11, 12) forming a bore (2). Each ring (9, 10) comprises a plurality of blocks (19) of permanent magnetic material arranged in one or more layers (9', 9'', 10', 10''), each layer (9', 9'', 10', 10'') comprising a dipolar elliptical Halbach array. The minor axes of the ellipses of said layers (9', 9'', 10', 10'') are substantially parallel to one another. The bore (2) of the main magnet (1) is suitable for housing a magnetic gradient system (5) extending along the longitudinal axis (8), and wherein said magnetic gradient system (5) covers at least 70% of the entire length of the main magnet (1). The invention also relates to an MRI scanner (3) comprising said main magnet (1) and to the method of manufacturing same.

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DESCRIPTION

MAIN MAGNET BASED ON ELLIPTICAL HALBACH ARRAYS, ASSOCIATED MAGNETIC RESONANCE IMAGING SCANNER AND ASSOCIATED METHOD OF 5 MANUFACTURE

FIELD OF THE INVENTION

The present invention relates to a main magnet based on elliptical Halbach arrays and to a
10 method of manufacturing same. Said main magnet is preferably comprised in a magnetic
resonance imaging (MRI) scanner.

BACKGROUND OF THE INVENTION

15 A magnetic resonance imaging (MRI) scanner is a device that obtains images of a sample,
of a human or animal subject, or of a part of their body. Said images comprise information
about the structure and composition of the sample or of the subject. The imaging is based
on the excitation with radiofrequency (RF) signals of a plurality of nuclear spins (e.g.,
hydrogen nuclei) comprised in the sample or in the subject, and on the reconstruction of the
20 structure and composition thereof from the magnetic resonance signals generated by the
excitation. Generally, an MRI scanner comprises at least a main magnet, an RF system and
a magnetic gradient system. The main magnet applies a main magnetic field on the
sample/subject, setting the initial magnetisation of a plurality of nuclear spins comprised
therein. The RF system excites said nuclear spins, modifying their initial magnetisation by
25 means of applying an RF field. The magnetic gradient system applies one or more magnetic
fields that spatially encode the sample/subject and, at the same time, the RF system
receives the free induction decay (FID) signal emitted by the excited nuclear spins.

The main magnets for MRI scanners can be based on permanent magnets (i.e., magnets
30 made up of one or more permanent magnetic materials), resistive magnets, or
superconducting magnets. Most commercial MRI scanners are based on superconducting
magnets, typically with fields of 1.5-3 T. However, the superconducting magnets are more
expensive and require greater maintenance resources by requiring cryogenic temperatures
to function suitably. Moreover, resistive magnets require an electrical current for operation
35 and cooling means, which also represents an impact on costs and complexity. According to
this, main magnets based on permanent magnets are preferable, as their operating and

maintenance costs are substantially lower than those of superconducting or resistive magnets. In this sense, the lower cost of main magnets based on permanent magnets facilitates a wider availability of MRI scanners on the market, which is particularly beneficial in developing regions.

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In relation to the configuration of permanent magnets, they can be configured forming an array, where the total magnetic field generated at a given point in space is determined by the superposition of the magnetic fields of each magnet of the array. One special array is the so-called Halbach array (K. Halbach, *Strong rare earth cobalt quadrupoles*, IEEE Trans. Nucl. Sci. 26, 3882-3884 (1979), and K. Halbach, *Design of permanent multipole magnets with oriented rare earth cobalt material*, Nucl. Instrum. Meth. 169, 1–10 (1980)), where the arrangement of the permanent magnets is such that the total magnetic field is reinforced on one side of the permanent magnet array and is approximately zero on the other side of the array.

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An example of a Halbach array is the so-called dipolar elliptical Halbach array, where permanent magnets form an ellipse in space, and the characteristic magnetisation of the permanent magnets goes around said ellipse twice. With this approach, it is possible to arrange a plurality of dipolar elliptical Halbach arrays along a longitudinal axis, forming a cylinder, where each permanent magnet in each array has an angular position θ in the cylinder, and a magnetisation with an orientation equal to twice that angular position θ and perpendicular to the longitudinal axis of the cylinder. This arrangement creates, for very long cylinders, a relatively homogeneous magnetic field in the direction perpendicular to the longitudinal axis of the cylinder and a very weak field outside the cylinder.

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According to this, in the main magnets for MRI scanners based on Halbach arrays, the main magnetic field B_0 generated is restricted to the regions where the MRI scanner sample is placed, being negligible on the outside of the main magnet. Furthermore, said main magnets are typically lightweight and free of the so-called magnetic yoke. The use of main magnets for MRI scanners based on Halbach arrays was proposed for the first time in the article by H. Raich *et al.*, *Design and Construction of a Dipolar Halbach Array with a Homogeneous Field from Identical Bar Magnets: NMR Mandhalas*, Concepts in Magnetic Resonance Part B (Magnetic Resonance Engineering), Vol. 23B, 16-25 (2004). In addition, the article by T. O'Reilly *et al.*, *Three-dimensional MRI in a homogenous 27 cm diameter bore Halbach array magnet*, J. Magn. Reson. 307 (2019) relates to another example of a main magnet based on Halbach arrays and, in particular, to a main magnet comprising a

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plurality of rings, wherein each ring comprises a plurality of sockets and a hollow section in the centre thereof, and wherein each socket is configured to place a cube-shaped block of permanent magnetic material. Furthermore, the sockets in each ring are arranged such that two radially separated layers of blocks are formed, with each layer constituting a Halbach
5 array.

Patent US 5,659,250 A relates to a main magnet with a plurality of sections comprising dipolar elliptical Halbach arrays. Said sections are equivalent to the rings of T. O'Reilly *et al.*, although instead of individual blocks of permanent magnetic material, each section
10 comprises a plurality of segments, wherein each segment in turn comprises a series of blocks of permanent magnetic material. In each segment, the blocks are tightly packed together, and the magnetisation thereof has the same orientation. However, one of the problems of the main magnet of this patent is that its elliptical arrays limit the homogeneity and the amplitude of the magnetic field. Furthermore, the magnetisation is angularly
15 discretised into very large segments, which also negatively affects the homogeneity of said main magnetic field, as compared to a finer discretisation characteristic of arrays comprising individual one-piece blocks. Patent US 5,659,250 A also relates to several methods of optimising the main magnetic field in the bore of the main magnet. Namely, said methods consist of adjusting the main magnetic field by reducing the specific number of bricks of
20 permanent magnetic material in each section. However, the homogeneity resulting from the preferred method does not experience a substantial improvement. Furthermore, the elimination of permanent magnetic material entails a serious reduction of the amplitude of the main magnetic field.

25 Patent US 10,018,694 B2 relates to another example of a main magnet based on elliptical Halbach arrays, wherein the magnetisation of the blocks of permanent magnetic material is not perpendicular to the longitudinal axis of the main magnet. The problem with the main magnet in this document is that, for it to operate, it requires rings to support the blocks of magnetic material with complex shapes that are industrially difficult to manufacture. This
30 furthermore enhances the deviations in the homogeneity of the main magnetic field generated by the main magnet with respect to the theoretical design of the main magnet.

The present invention solves the problems existing in the aforementioned prior art by means of a novel main magnet based on elliptical Halbach arrays, as well as by means of a method
35 of manufacturing said main magnet.

BRIEF DESCRIPTION OF THE INVENTION

The present invention proposes an improved main magnet, an MRI scanner and an associated method of manufacture that solves the technical problems and drawbacks of the prior art described in the preceding section.

A first object of the invention relates to a main magnet according to claim 1. Said magnet is primarily based on dipolar elliptical Halbach arrays configured to generate a main magnetic field B_0 of an MRI scanner, wherein:

- 10 - said main magnet comprises a plurality of rings stacked along a longitudinal axis, from a first end of the main magnet to a second end of the main magnet, such that each end of the main magnet comprises one or more outer rings, and the central portion of the main magnet comprised between the first end and the second end thereof comprises one or more central rings;
- 15 - each outer and central ring comprises a plurality of sockets, wherein each socket houses a block of permanent magnetic material;
 - each outer and central ring comprises a hollow section, wherein the hollow sections of the outer and central rings form an inner bore of the main magnet;
 - in each outer and central ring, the blocks of permanent magnetic material are
- 20 radially arranged with respect to the centre of said ring in a set of a plurality of layers, wherein each layer describes substantially an ellipse, said ellipse having a minor axis and a major axis that is perpendicular to said minor axis and has a length longer than that of the minor axis;
 - the minor axes of the ellipses of the layers of blocks of permanent magnetic
- 25 material of the outer and central rings are substantially parallel to one another; and
 - in each layer, the blocks of permanent magnetic material are arranged in a dipolar elliptical Halbach array, such that the dipolar elliptical Halbach arrays of the outer and central rings generate the main magnetic field B_0 in the bore of the main magnet;
- 30 Advantageously in the invention, the bore is suitable for housing a magnetic gradient system extending along the longitudinal axis, and wherein said magnetic gradient system covers at least 70% of the entire length of the main magnet. The need to provide a main magnet based on dipolar elliptical Halbach arrays which considerably increases the field of view (FoV) of the MRI scanner comprising said main magnet and a magnetic gradient system is
- 35 thereby solved.

Other preferred embodiments of the main magnet of the invention are described in claims 2-10 of the present document.

A second object of the present invention relates to an MRI scanner according to claim 11.

5 Preferably, said scanner comprises a main magnet according to any of the embodiments described in the present document, as well as a magnetic gradient system and an RF system, wherein:

- the bore of the main magnet is configured to house the RF system and the magnetic gradient system;

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- the main magnet is configured to generate the main magnetic field B_0 in the bore;
- the gradient system is configured to apply at least one magnetic gradient in the bore; and

- the RF system is configured to apply an RF field in a sample located in the bore and to receive a magnetic resonance signal coming from said sample.

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A third object of the present invention relates to a method of manufacturing a main magnet according to claim 12 of the present document, wherein said method comprises performing the following steps, in any technically possible order:

- a) providing the outer and central rings;

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- b) forming the sockets of the outer rings by perforating same, such that said sockets are radially arranged with respect to the centre of each outer ring;

- c) placing blocks of permanent magnetic material inside the sockets of the outer rings, such that said blocks of permanent magnetic material are arranged in a set of a plurality of layers, wherein in each layer the blocks of permanent magnetic material are

25 arranged in a dipolar elliptical Halbach array;

- d) forming the sockets of the central rings by perforating same, such that said sockets are radially arranged with respect to the centre of each central ring;

- e) placing blocks of permanent magnetic material inside the sockets of the central rings, such that said blocks of permanent magnetic material are arranged in a set of a plurality of layers, wherein in each layer the blocks of permanent magnetic material are

30 arranged in a dipolar elliptical Halbach array; and

- f) stacking the outer and central rings along a longitudinal axis.

Advantageously in the method of the invention, after step f), the bore formed by the hollow sections of the outer and central rings is suitable for housing a magnetic gradient system

35 extending along the longitudinal axis, and wherein said magnetic gradient system covers at

least 70% of the entire length of the main magnet. The need to manufacture a main magnet based on dipolar elliptical Halbach arrays which considerably increases the field of view (FoV) of the MRI scanner comprising said main magnet and a magnetic gradient system is thereby solved.

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Other preferred embodiments of the method of the invention are described in claims 13-17 of the present document.

DESCRIPTION OF THE DRAWINGS

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To complete the description and for the purpose of helping to better understand the invention, provided herein is a set of drawings illustrating different embodiments thereof, which drawings should not be interpreted as being restrictive or limiting of the scope of protection of the application.

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Figure 1 shows a perspective view of a preferred embodiment of a main magnet according to the present invention.

Figure 2 shows a front view of an embodiment of an MRI scanner comprising the main magnet of Figure 1.

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Figure 3a shows an outer ring of the main magnet of Figure 1.

Figure 3b shows an enlarged view of the outer ring of Figure 3a.

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Figure 4 shows a central ring of the main magnet of Figure 1.

Figure 5 shows a graph of the amplitude of the main magnetic field B_0 generated in the longitudinal axis by a main magnet according to the present invention, as a function of the length $d_i^{(0)}/2$ of the semi-minor axis of the ellipses comprised in the layers closest to said longitudinal axis.

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Figure 6 shows a cross-section view of the main magnet of Figure 1, wherein said main magnet further comprises a shimming unit.

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Figures 7-8 show, respectively, a diagram of an optimisation algorithm and a diagram of an auxiliary algorithm according to the method of the present invention.

Figure 9 is a graph showing the result of an auxiliary algorithm used in the method of manufacturing the main magnet of Figure 6.

Reference numbers used in the figures:

(1)	Main magnet
(2)	Bore of the main magnet
(3)	MRI scanner
(4)	RF system of the MRI scanner
(5, 5', 5'', 5''')	Magnetic gradient system of the MRI scanner
(6)	First end of the main magnet
(7)	Second end of the main magnet
(8)	Longitudinal axis of the main magnet
(9)	Outer rings of the main magnet
(9', 9'')	Layers of blocks of magnetic material of the outer rings
(10)	Central rings of the main magnet
(10', 10'')	Layers of blocks of magnetic material of the central rings
(11)	Hollow section of the outer ring
(12)	Hollow section of the central ring
(13)	Sockets of the outer/central rings
(14)	Central portion of the main magnet
(15)	Cross-section of the magnetic gradient system
(16)	Through-hole
(17)	Rods
(18)	Shimming unit
(19)	Blocks of magnetic material of the outer/central rings
(20)	Field of view of the MRI scanner
(21)	Auxiliary rings
(22)	Blocks of permanent magnetic material of the auxiliary rings
(23)	Optimisation algorithm
(24)	Input parameters of the optimisation algorithm
(25)	Result of the optimisation algorithm

(26)	Optimisation variables of the optimisation algorithm
(27)	Optimisation function of the optimisation algorithm
(28)	Auxiliary algorithm
(29)	Input parameters of the auxiliary algorithm
(30)	Result of the auxiliary algorithm
(31)	Optimisation variables of the auxiliary algorithm
(32)	Optimisation function of the auxiliary algorithm

DETAILED DESCRIPTION OF THE INVENTION

A first object of the invention relates to a main magnet based on dipolar elliptical Halbach arrays, suitable for its preferred use in an MRI scanner. According to said object, Figure 1 shows a perspective view of a preferred embodiment of a main magnet (1) according to the invention, comprising an inner bore (2), configured to house an RF system (4) and a magnetic gradient system (5) of an MRI scanner (see Figure 2), wherein said bore (2) preferably extends from a first end (6) of the main magnet (1) to a second end (7) of the main magnet (1), along a longitudinal axis (8) thereof. Preferably, the RF system (4) and the magnetic gradient system (5) comprise, respectively, an RF coil (4), and a set of magnetic gradient coils (5', 5'', 5'''), wherein said coils (4, 5', 5'', 5''') are concentric with respect to the longitudinal axis (8) of the main magnet (1). Other types of RF systems (4) and/or magnetic gradient systems (5) compatible with the present invention (e.g., with other geometric shapes and/or not concentric with respect to the longitudinal axis (8) of the main magnet (2), etc.), can be deduced by a person skilled in the art based on the content of the present document.

The main magnet (1) comprises a plurality of rings (9, 10) stacked from the first end (6) to the second end (7), along the longitudinal axis (8), wherein said longitudinal axis (8) goes through each ring (9, 10). Similarly, each ring (9, 10) comprises a hollow section (11, 12) in its centre, such that the hollow sections (11, 12) of the stacked rings (9, 10) form the bore (2) of the main magnet (1). Said hollow sections (11, 12) are indicated in Figures 3-4. Preferably, each ring (9, 10) is made up of a non-magnetic material, such as, e.g., nylon or polyethylene, among others. Moreover, each ring (9, 10) comprises a plurality of sockets (13), wherein each socket (13) contains a block of permanent magnetic material therein (indicated in Figure 6 with reference number (19)), such that said blocks (19) of permanent magnetic material are embedded in each ring (9, 10). In this context, the superposition of the individual magnetic fields of the blocks (19) of permanent magnetic material generates

a main magnetic field B_0 in the bore (2) of the main magnet (1). The sockets (13) and the blocks (19) of the rings (9, 10) cannot be seen in the front view or in the perspective view of the main magnet (1) in Figures 1-2, since the faces of the rings (9, 10) that can be seen in said figures comprise covers made of non-magnetic material (such as, e.g., nylon, polyethylene, aluminium, among others). However, Figures 3-4 show the sockets (13) without the blocks (19) of magnetic material installed.

Figures 3-4 show a ring (9, 10) of the main magnet (1) of Figure 1, wherein the sockets (13) of the blocks (19) can be seen. More specifically, Figure 3a shows an outer ring (9) of the main magnet (1), i.e., a ring of one of the ends (6, 7) thereof. Figure 4 shows a central ring (10) of the main magnet (1), i.e., a ring of the central portion (14) of the main magnet (1), wherein said central portion (14) is comprised between the first end (6) and the second end (7). Moreover, in the embodiment of the main magnet (1) of Figure 1, each outer and central ring (9, 10) comprise a first flat face and a second flat face opposite the first one. The first flat face is the one that can be seen in Figures 3-4. The sockets (13) of each outer and central ring (9, 10) are formed on said first face. Unlike the central rings (10), the main magnetic field B_0 generated by the outer rings (9) of each end (6, 7) diverges outwardly from the main magnet (1). To that end, in the main magnets known in the prior art, the hollow sections (11) of the outer rings (9) have a smaller size than the hollow sections (12) of the central rings (10), which allows the layers (9', 9'') of blocks of permanent magnetic material to be arranged closer to the longitudinal axis (8) to correct the effects of the aforementioned divergences.

Moreover, in the invention, the sockets (13) and the blocks (19) of magnetic material are preferably arranged in a radial manner with respect to the centre of each ring (9, 10), such that said blocks (19) of permanent magnetic material form a set of a plurality of layers (9', 9'', 10', 10''). Therefore, when placing the blocks (19) of permanent magnetic material in the sockets (13), the outer ring (9) of Figure 3a and the central ring (10) of Figure 4 each have an inner layer (9', 10') and an outer layer (9'', 10'') of blocks (19) of permanent magnetic material. In other embodiments, the rings (9, 10) have an inner layer (9', 10') and more than one outer layer (9'', 10'') of blocks (19) of permanent magnetic material. In other embodiments of the invention, at least one of the outer or central ring (9, 10) has a number of layers (9', 9'', 10', 10'') of blocks (19) permanent magnetic material different from the remaining of rings (9, 10) of the main magnet (1).

Similarly, each layer (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material describes substantially an ellipse defined by a minor axis and a major axis perpendicular to said minor axis, wherein the length of the major axis is longer than the length of the minor axis.

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Similarly, in the above context, the expression “substantially an ellipse” refers to the fact that all the geometric centres of the blocks (19) of permanent magnetic material of one and the same layer (9' 9'', 10', 10'') are arranged substantially on the curve marked out by one and the same ellipse, except for deviations inherent to the manufacture of the main magnet (1), for example related to machining processes performed on the outer and central rings (9, 10), such as the formation of the sockets (13), or the polishing of the faces of the rings (9, 10) before the formation of said sockets (13), among others. These deviations are, generally, smaller than the characteristic lengths of the blocks (19) of permanent magnetic material (e.g., when a block (19) is cube-shaped, the length of one side of said cube), since they are determined by the precision of the devices performing said machining processes.

Moreover, the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of the outer and central rings (9, 10) are substantially parallel to one another. In this context, the expression “substantially parallel” refers to the fact that said minor axes are parallel to one another, except for deviations inherent to the manufacture of the main magnet (1). In addition to the deviations inherent to the manufacture of the main magnet (1) described above, in this context the deviations can also arise during the stacking of the outer and central rings (9, 10) along the longitudinal axis (8) and/or during the attachment of said rings (9, 10), for example by means of connecting bolts or rods.

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Figures 3-4 depict with a dashed line the ellipse described by the ellipses of the layers (9', 9'', 10', 10'') of each ring (9, 10) when the blocks (19) (Figure 6) are placed in the sockets (13) of said rings (9, 10). Furthermore, the length of the minor axis of the ellipse of the inner layer (9', 10') of the outer ring (9)/central ring (10) is denoted as d_i/d'_i , and the length of the major axis of that same ellipse is denoted as D_i/D'_i . Therefore, the position (y, z) of each block of permanent magnetic material of the inner layer (9', 10') in its respective ellipse is preferably determined by the expressions:

$$(y, z) = (d_i \cos(\theta), D_i \sin(\theta)), \text{ in an outer ring (9);}$$

$$(y, z) = (d'_i \cos(\theta), D'_i \sin(\theta)), \text{ in a central ring (10),}$$

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wherein θ is the angular position of the geometric centre of each block (19) of permanent magnetic material in the respective ellipse. As described above, Figures 3-4 indicate the angular position taken as an angular position of origin (i.e., $\theta=0^\circ$) in the ellipse of each layer (9', 10'). Similarly, the angular direction taken as positive in the ellipse of each inner layer (9', 10') is indicated in both figures with a dotted and curved arrow (counterclockwise direction in Figure 3a, and clockwise direction in Figure 4).

In the above context, in each layer (9', 9'', 10', 10'') of the rings (9, 10) of the main magnet (1), the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array, such that the magnetisation characteristic of the blocks (19) of permanent magnetic material goes around the ellipse of said layer twice. Therefore, if there is an angular separation $\Delta\theta$ between a first block and a second block contiguous to the first one in said ellipse, the direction of magnetisation of the second block is rotated by twice that angular separation $\Delta\theta$ with respect to the direction of magnetisation of the first block. For example, in the inner layer (9') of the outer ring (9) of Figure 3a, wherein the position (y, z) of a block of permanent magnetic material is determined by $(y, z) = (d_i \cos(\theta), D_i \sin(\theta))$, the components of the magnetisation of said block of permanent magnetic material are determined by

$$\begin{aligned} m_y &= m_0 \cos(2 \cdot \theta); \\ m_z &= m_0 \sin(2 \cdot \theta), \end{aligned}$$

wherein m_0 is the magnetisation of said block of permanent magnetic material. The dipolar elliptical Halbach arrays of the outer and central rings (9, 10) of the main magnet (1) generate the main magnetic field B_0 in the bore (2) thereof.

As described above, the MRI scanner (3) (Figure 2) is configured to introduce a sample/subject through one of the two ends (6, 7) of the main magnet (1) and place said sample/subject inside the bore (2), preferably at the height of the central portion (14). Typically, the end (6, 7) of the main magnet (1) through which the sample/subject is introduced is referred to as the front end, while the other one is referred to as the back end. Thus, without loss of generality, the first end (6)/second end (7) of Figure 2 may also be referred to as front end (6)/back end (7). The main magnet (1) generates the main magnetic field B_0 in the bore (2), such that said main magnetic field B_0 sets the initial magnetisation of a plurality of nuclear spins (e.g., hydrogen nuclei, phosphorus, fluorine, etc.) comprised in the sample or subject. In turn, the RF system (4) excites said nuclear spins by modifying the initial magnetisation by means of applying an RF field. The gradient system (5) applies at least one magnetic gradient in the bore (2), thereby spatially encoding the

sample/subject, and, in turn, the RF system (4) receives the free induction decay (FID) signal emitted by the excited nuclear spins. Information corresponding to the structure and composition of the sample/subject is obtained based on said signal FID.

5 Therefore, the main magnet (1) of the present invention is characterised by its bore (2) and is suitable for housing a magnetic gradient system (5) extending along the longitudinal axis (8), wherein said magnetic gradient system (5) covers at least 70% of the entire length of the main magnet (1). In the preferred embodiment of Figure 1, the bore (2) of the main magnet (2) is suitable for housing the magnetic gradient system (5) of Figure 2, extending
10 along the longitudinal axis (8) from the first end (6) to the second end (7) of the main magnet (1) and covering the entire length of said main magnet (1). The need to provide a main magnet (1) based on dipolar elliptical Halbach arrays which considerably increases the field of view (FoV) of the MRI scanner (3) comprising said main magnet (1) and a magnetic gradient system (5) is thereby solved. Based on the above, in the non-limiting embodiment
15 of Figure 1, the area of each of the hollow sections (11, 12) forming the bore (2) of the main magnet (1) is greater than or equal to that of the cross-section (15) of the magnetic gradient system (5) of Figure 2. Typically, the region covered by the FoV of the MRI scanner (3) in the bore (2) of the main magnet (1) (i.e., the region where an MRI image can be obtained) is limited by the region where the magnetic gradients generated by the magnetic gradient
20 system (5) are linear or where at least a sufficient difference in Larmor frequencies is generated between voxels of the sample. The expression "voxels" is understood to mean the volumetric elements into which the MRI image is divided. The size of the previous region is restricted by the limits of the magnetic gradient system (5). Namely, the length of the magnetic gradient system (5) along the longitudinal axis (8) is particularly critical when such
25 system generates a magnetic gradient in the direction of the longitudinal axis (8). In the embodiment of Figure 2, the coil (5') closest to the longitudinal axis (8) generates the magnetic gradient in the direction of the longitudinal axis (8). Said gradient comprises at least two lobes in the direction of the longitudinal axis (8), one in each end of the coil (5') closest to the longitudinal axis (8). These lobes cover part of the inside of said coil (5') and
30 each one has a centre. In this context, inside the magnetic gradient system (5) and in the proximity of the centres of said lobes, it is no longer possible to perform resonance imaging. Therefore, as a result of the bore (2) of the main magnet (1), the aforementioned lobes are as far away as possible and, accordingly, the region covered by the FoV of the MRI scanner (3) in the bore (2) is the largest possible.

As described above, in Figure 2 the outer coil (5''') of the magnetic gradient system (5) defines a cylindrical outer contour thereof with an elliptical cross-section (15). Similarly, Figure 2 shows the length D_G/d_G of the major/minor axis of the elliptical contour of the cross-section (15) of the magnetic gradient system (5), wherein the minor axis is perpendicular to said major axis. The ratio between the lengths of the minor axis d_G and of the major axis D_G is less than one. In this context, the hollow sections (11, 12) of the outer and central rings (9, 10) are also elliptical. Furthermore, the area of said hollow sections (11, 12) is greater than or equal to the cross-section (15) of the magnetic gradient system (5), such that the magnetic gradient system (5) goes through all the hollow sections (11, 12) forming the bore (2) of the main magnet (1) and, accordingly, extends along the entire length of the main magnet (1). In an example preferred embodiment, the length of the main magnet (1) and of the magnetic gradient system (5) of Figure 2 is comprised between 40-50 cm. Therefore, the FoV of the MRI scanner (3) of Figure 2 covers a spherical region with a radius of the order of 10 cm in the bore (2) and in the central portion (14). This represents an increase of around 50% in the size of the FoV with respect to the main magnets known with the same length, wherein the inner bore (2) thereof only allows a magnetic gradient system (5) covering the central portion (14) of said main magnets at most to be housed.

Moreover, in the main magnet (1) of Figure 1, the blocks (19) of permanent magnetic material are arranged in each outer and central ring (9, 10) such that the direction of the main magnetic field B_0 generated in the bore (2) by the dipolar elliptical Halbach arrays of the outer and central rings (9, 10) is substantially parallel to the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material. The expression "substantially parallel" refers to the fact that the direction of the main field B_0 is parallel to the minor axes of the ellipses of said layers (9', 9'', 10', 10''), except for deviations inherent to the manufacture of the main magnet (1). Generally, said deviations mean that, at each point of the bore (2), the value of the components not parallel to said minor axes of the main magnetic field B_0 is less than 10% of the value of the component parallel to said minor axes. In this context, the homogeneity and the amplitude of the main magnetic field B_0 in the bore (2) are advantageously increased with respect to the main magnetic field B_0 generated by other dipolar elliptical Halbach arrays, in particular with respect to the main magnets wherein the dipolar elliptical Halbach arrays are such that the main magnetic field B_0 generated in the bore (2) is perpendicular to the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10).

Preferably, the main magnetic field B_0 generated in the bore (2) by the dipolar elliptical Halbach arrays of the outer and central rings (9, 10) is substantially perpendicular to the longitudinal axis (8) of the main magnet (1). The expression "substantially perpendicular" refers to the fact that the direction of the main field B_0 is perpendicular to the longitudinal axis (8), except for deviations inherent to the manufacture of the main magnet (1). Generally, said deviations mean that, at each point of the bore (2), the value of the components not perpendicular to the longitudinal axis (8) of the main magnetic field B_0 is less than 1% of the value of the component perpendicular to said longitudinal axis (8).

More preferably, covers (not shown in the figures) of non-magnetic material are arranged in the main magnet on the face of the rings (9, 10) where the sockets (13) are formed. The placement of the covers is performed after placing the blocks (19) of permanent magnetic material in the sockets (13) of each ring (9, 10) and before stacking said rings (9, 10) along the longitudinal axis (8). The cover of each ring (9, 10) prevents the blocks (19) from being dislodged from inside the sockets (13).

Moreover, in a preferred embodiment of the invention, in at least one and the same outer or central ring (9, 10), the blocks (19) of permanent magnetic material are substantially identical, i.e., they have the same geometric shape, permanent magnetic material and size.

Similarly, preferably the blocks (19) of permanent magnetic material are blocks (19) comprising a plurality of edges. More preferably, the geometric shape of the blocks (19) of permanent magnetic material of the outer and central rings (9, 10) is cube-shaped. In a preferred embodiment, the blocks (19) of permanent magnetic material of all the outer and central rings (9, 10) are cube-shaped and identical. This facilitates the industrial manufacture of the main magnet (1), as compared to other embodiments where said blocks (19) have other geometric shapes (e.g., hexagonal, cylindrical, among others) or are not identical in all the outer and central rings (9, 10).

In another preferred embodiment, the blocks (19) of permanent magnetic material of the outer and central rings (9, 10) comprise blocks made up of a samarium-cobalt, Sm-Co, alloy, or a neodymium-iron-boron, Nd-Fe-B, alloy. In another preferred embodiment, the blocks (19) of permanent magnetic material of the outer and central rings (9, 10) comprise one-piece blocks (i.e., each block comprises a single individual piece of permanent magnetic material, instead of a plurality of stacked individual pieces). According to this embodiment, in the main magnet (1) of Figure 1, the blocks (19) of permanent magnetic material (see Figure 6) comprised in the outer and central rings (9, 10) are one-piece,

cube-shaped blocks. By way of example, the blocks (19) of permanent magnetic material comprised in all the outer and central rings (9, 10) can be made up of $\text{Nd}_2\text{Fe}_{15}\text{B}$, where said $\text{Nd}_2\text{Fe}_{15}\text{B}$ alloy is characterised by its high magnetisation m_0 and its high coercivity. Similarly, the magnetic degree of the $\text{Nd}_2\text{Fe}_{15}\text{B}$ alloy of the blocks (19) of permanent magnetic material of the magnet of Figure 1 is, for example, equal to N48. As is known, the magnetic degree of a block of Nd-Fe-B is a measurement of its maximum energy product that is represented with an integer (in this non-limiting example, "48"), such that the higher said integer, the greater the attractive force of said block is.

Moreover, since the bore (2) of the main magnet (1) of Figure 2 houses the magnetic gradient system (5) along the entire length of the main magnet (1), this means an increase in the size of the hollow section (11) of the outer rings (9), and, accordingly, a spacing of the blocks (19) of permanent magnetic material of said outer rings (9) with respect to the longitudinal axis (8) of the main magnet (1). Said spacing reduces the amplitude of the magnetic field generated by the blocks (19) of magnetic material of the outer rings (9) in the bore (2) of the main magnet (1). Furthermore, typically the divergences of the main magnetic field B_0 at the ends (6, 7) reduce the amplitude thereof in the region of the bore (2) comprised at said ends (6, 7). Therefore, preferably for each outer ring (9) and for the purpose of overcoming said limitation, the separation between the layer (9') of blocks (19) of permanent magnetic material closest to the longitudinal axis (8) and the magnetic gradient system (5) is minimised for the size and the geometric shape of each block (19) of magnetic material of said layer (9'), and the length D_G of the major axis and the length d_G of the minor axis of the contour of the cross-section (15) of the magnetic gradient system (5) (Figure 2). In such case, the blocks (19) of said layer (9') are said to be tightly packed with respect to the magnetic gradient system (5). Based on the above, for each outer ring (9), when the blocks (19) of permanent magnetic material of the layer (9') closest to the longitudinal axis (8) are tightly packed with respect to the magnetic gradient system (5), a manufacturing tolerance is set during the theoretical design of the main magnet (1), such that, after forming the sockets (13) of said layer (9') according to this manufacturing tolerance, the blocks (19) of permanent magnetic material placed in those sockets (13) are prevented from being superimposed with the magnetic gradient system (5). In this sense, the value of said manufacturing tolerance takes into account the precision of the devices forming the sockets (13) of the layer (9') closest to the longitudinal axis (8). Therefore, in each outer ring (9), the blocks (19) of permanent magnetic material of the layer (9') closest to the longitudinal axis (8) are tightly packed with respect to the magnetic gradient system (5). Therefore, in the preferred embodiment of the main magnet (1) of Figure 1, in the layer

(9') closest to the longitudinal axis (8) of the main magnet (1) of each outer ring (9), the blocks (19) of magnetic material are arranged such that the separating distance between each block (19) and the outer contour of the magnetic gradient system (5) is substantially equal to or less than 1 mm. In the above context, the expression "substantially equal to or less than 1 mm" refers to the fact that said distance is equal to 1 mm, except for deviations inherent to the manufacture of the main magnet (1). Similarly, for each block (19) of magnetic material, the previous distance is measured from the point of said block (19) closest to the outer contour of the magnetic gradient system (5).

10 In embodiments of the invention, the blocks (19) of magnetic material of at least one outer and/or central ring (9, 10) of the main magnet (1) of the layer (9', 10') closest to the longitudinal axis (8) are arranged such that the separating distance between each block (19) and the inner perimeter of said ring (9, 10) (i.e., the perimeter delimiting the start of the hollow section (11, 12) of that ring (9, 10)) is substantially equal to or less than 1 mm. At
15 the same time or alternatively, in embodiments of the invention, the blocks (19) of magnetic material of at least one outer and/or central ring (9, 10) of the main magnet (1) of the layer (9'', 10'') farthest away from the longitudinal axis (8) are arranged such that the separating distance between each block (19) and the outer perimeter of said ring (9, 10) (i.e., the perimeter opposite the one delimiting the start of the hollow section (11, 12) of that ring (9,
20 10)) is substantially equal to or less than 1 mm. In the above context, the "expression substantially equal to 1 mm" refers to the fact that the distances described in this paragraph are equal to 1 mm, except for deviations inherent to the manufacture of the main magnet (1). Similarly, for each block (19) of magnetic material, the above distances are measured from the point of each block (19) closest to its respective inner or outer contour of its ring
25 (9, 10).

Similarly, in the preferred embodiment of the main magnet (1) of Figure 1, the blocks (19) of permanent magnetic material of the outer and central rings (9, 10) of the main magnet (1) are tightly packed radially, angularly or axially, at the same time preventing contiguous
30 blocks (19) of permanent magnetic material from being superimposed on one another. The amplitude of the main magnetic field B_0 generated by the main magnet (1) in the bore (2) is thereby maximised. This is because, in such case, the blocks (19) of magnetic material are as close as possible to the longitudinal axis (8) and the amount of said blocks (19) of permanent magnetic material is the largest possible. In other embodiments of the invention,
35 the blocks (19) of permanent magnetic material of the outer and/or central rings (9, 10) are tightly packed only radially, or only angularly, or only axially, or in a combination of these

three arrangements. In other embodiments, the blocks (19) of permanent magnetic material are not tightly packed radially, angularly or axially.

In the above context, the blocks (19) of permanent magnetic material of the outer and/or central rings (9, 10) of the main magnet (1) are tightly packed angularly when, between two
5 contiguous blocks (19) of one and the same layer (9', 9'', 10', 10''), said contiguous blocks (19) are arranged at a separating distance substantially equal to or less than 1 mm. Furthermore, the blocks (19) of permanent magnetic material of the outer and/or central rings (9, 10) of the main magnet (1) are tightly packed radially when, between two
10 contiguous blocks (19) of two different and consecutive layers (9', 9'', 10', 10'') of one and the same ring (9, 10), said contiguous blocks (19) are arranged at a separating distance substantially equal to or less than 1 mm. Moreover, the blocks (19) of permanent magnetic material of the outer and/or central rings (9, 10) of the main magnet (1) are tightly packed axially when, between two contiguous blocks (19) of two different and consecutive rings (9,
15 10) along the longitudinal axis (8), said blocks (19) are arranged at a longitudinal separating distance substantially equal to or less than 4 mm. The expression "substantially equal" refers to the fact that each of the distances which determine how tightly packed the blocks (19) are is equal to the amount indicated above, except for deviations inherent to the manufacture of the main magnet (1). Furthermore, the distance between two contiguous
20 blocks (19) of magnetic material is defined in this sense as the distance between the two closest points between said contiguous blocks (19).

Figure 3b shows an enlarged view of the outer ring (9) of Figure 3a. In the same way as in Figure 3a, the blocks (19) of permanent magnetic material are not shown in Figure 3b (the
25 blocks (19) of outer and central rings (9, 10) are shown later, in Figure 6). Therefore, said Figure 3b shows with a double arrow the eventual separating distance δ_A between two contiguous blocks (19) of magnetic material in one and the same layer (9') when said contiguous blocks (19) are placed in the sockets (13) thereof. Furthermore, it also shows with another double arrow the eventual separating distance δ_R between two contiguous
30 blocks (19) of magnetic material of two different and consecutive layers (9', 9'') when said contiguous blocks (19) are placed in the sockets (13) thereof. As described above, the blocks (19) of the outer ring (9) of Figure 3b are placed in the sockets (13) such that they are tightly packed radially and axially.

35 As described above, in the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10), the length of the major axis of the ellipse

described by each layer (9', 9'', 10', 10'') is longer than the length of the minor axis. Advantageously, the amplitude of the main magnetic field B_0 generated in the bore (2) increases with it with respect to other known configurations where the layers of blocks of permanent magnetic material are circular. Moreover, also in the main magnet (1) of Figure 5 1, the ratio between the length of the minor axis and the length of the major axis is, in a preferred manner, substantially equal in all the ellipses described by the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material. The installation of the magnetic gradient system (5) with an elliptical cross-section (15) in the bore (2) is thereby facilitated. In this context, the expression "substantially equal" refers to the fact that it is equal in all the 10 ellipses, except for deviations inherent to the manufacture of the main magnet (1).

Figure 5 shows a graph representing the amplitude of the main magnetic field B_0 generated in the longitudinal axis (8) by a main magnet (1) according to the present invention, as a function of the length $d_i^{(0)}/2$ of the semi-minor axis of the ellipses comprised in the inner 15 layers (9', 10') of the outer and central rings (9, 10). In this example, each ring (9, 10) comprises two layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material. The ellipses described by the inner layers (9')/outer layers (9'') of the outer rings (9) are equal to the ellipses described by the inner layers (10')/outer layers (10'') of the central rings (10). In particular, the length $D_i^{(0)}/2$ of the semi-major axis of the ellipses of the inner layers (9', 20 10') is equal to 0.30 m. The minor axes of all the layers (9', 9'', 10', 10'') are parallel to one another. Moreover, the blocks (19) of permanent magnetic material of all the layers (9', 9'', 10', 10'') are cube-shaped, with a side having a length l equal to 1.9 cm, and are made up of a $\text{Nd}_2\text{Fe}_{15}\text{B}$ alloy and have a magnetic degree of N48. Similarly, the blocks (19) of magnetic material are tightly packed radially, angularly and axially, as explained above. In 25 this context, Figure 5 shows how the main magnetic field B_0 increases from 74 mT to 81 mT, when the length $d_i^{(0)}/2$ of the semi-minor axis of the ellipses of the inner layers (9', 10') decreases from 0.30 m to 0.20 m, i.e., the smaller the minor axis of the ellipse of each layer (9', 9'', 10', 10'') is with respect to the major axis of the same ellipse. It should be noted that in the graph, when the length $d_i^{(0)}/2$ of the semi-minor axis of the inner layers (9', 10') 30 decreases, the number of blocks (19) of each layer (9', 9'', 10', 10'') of the outer and central rings (9, 10) is modified at the same time, such that said blocks (19) of permanent magnetic material are still tightly packed radially, angularly and axially.

Similarly, in the main magnet (1) of Figure 1, the outer and central rings (9, 10) have a mirror 35 symmetry along the longitudinal axis (8) of the main magnet (1) and with respect to the centre of said longitudinal axis (8). Therefore, ordering the rings (9, 10) of the main magnet

(1) of Figure 1 from the first end (6) to the second end (7), the first ring (9) is substantially equal to the nineteenth ring (9), the second ring (9) is substantially equal to the eighteenth ring (9), etc. In particular, in the non-limiting embodiment of the main magnet (1) of Figure 1, the three outer rings (9) of each end (6, 7) of the main magnet (1) are substantially equal to the one shown in Figure 3a (with the blocks (19) of permanent magnetic material contained in the sockets (13) and with the covers not shown in said figure). With regard to the thirteen central rings (10), the first central ring (10) is substantially equal to the thirteenth central ring (10), the second central ring (10) is substantially equal to the twelfth central ring (10), etc. In the above context, the expression “substantially” refers to the fact that, in each mirror pair, the rings of said pair are equal, except for deviations inherent to the manufacture of the main magnet (1). When the outer and central rings (9, 10) follow a mirror symmetry along the longitudinal axis (8), the main magnetic field B_0 generated in the bore (2) is symmetrical along the longitudinal axis (8), except for deviations inherent to the manufacture of the main magnet (1). It should be noted that when the main magnet (1) comprises an odd number of rings (9, 10), the ring (10) of the centre of said main magnet (1) (e.g., the seventh central ring (10) in the main magnet (1) of Figure 1) does not have an associated mirror pair.

The outer and central rings (9, 10) of Figures 3-4 further comprise one or more through-holes (16), through which connecting bolts or rods (17) pass. Similarly, each cover of each outer and central ring (9, 10) also comprises one or more through-holes through which the same rods (17) pass. All the outer and central rings (9, 10) and their covers are thereby attached along the length of the main magnet (1). Optionally, it is possible to place a nut at the end of each rod (17) to fix said attachment. In alternative embodiments, other attachment means can be used to attach the outer and/or central rings (9, 10) and/or the covers thereof, if there are any.

In turn, the RF system (4) comprised in the bore (2) of the main magnet (1) (Figure 2) extends from the first end (6) to the second end (5) thereof, such that said RF system (4) is comprised inside the magnetic gradient system (5) and extends along the entire length of the main magnet (1). In this way, the interior of the RF system (4) comprises the region where the magnetic gradients generated are linear or where at least a sufficient difference in Larmor frequencies is generated between voxels of the sample/subject. In other embodiments of the invention, the length of the RF system (4) is smaller, coinciding with the distance between lobes of the magnetic gradient generated by magnetic gradient system (5) in the direction of the longitudinal axis (8). Alternatively, the length of the RF

system (4) is even smaller than that of the previous embodiment, for the purpose of optimising other characteristics of said RF system (4) (such as the quality factor, the ring-down of the RF coil (4), among others).

5 In another aspect of the invention, the main magnet (1) of Figure 1 is preferably manufactured according to a theoretical design, such that the main magnetic field B_0 theoretically generated by the main magnet (1) after stacking the outer and central rings (9, 10) along the longitudinal axis (8) is known. However, there are typically deviations between the main magnet (1) of the theoretical design and the manufactured main magnet (1). In
10 particular, generally the values of the amplitude and the homogeneity of the main magnetic field B_0 determined experimentally deviate from the values of the theoretical design. Said deviations are inherent to the actual manufacture of the main magnet (1). Therefore, in an embodiment of the invention, the bore (2) of the main magnet (1) is configured to house a shimming unit, where said shimming unit is in turn configured to correct said experimental
15 deviations.

Figure 6 shows a cross-section view of the main magnet (1) of Figure 1, wherein said main magnet (1) further comprises a shimming unit (18). The outer and central rings (9, 10) are not shown in Figure 6, but rather only the blocks (19) of permanent magnetic material
20 comprised in the layers (9', 9'', 10', 10'') of said outer and central rings (9, 10) are shown. Similarly, Figure 6 shows the region covered in the bore (2) by the spherical FoV (20) of an MRI scanner (3) when said scanner comprises the main magnet (1) of Figure 6 and the RF and magnetic gradient systems (4, 5) of Figure 2.

25 The shimming unit (18) comprises a plurality of auxiliary rings (21) stacked along a longitudinal axis (8) in the central portion (14) of the main magnet (1), such that the shimming unit (18) goes through the hollow section (12) of each central ring (10) of the main magnet (1). Said auxiliary rings (21) share some characteristics with the outer rings (9) of the ends (6, 7) of the main magnet (1). In this sense, preferably each auxiliary ring (21) is
30 made up of a non-magnetic material, such as, e.g., nylon or polyethylene, among others. Similarly, each auxiliary ring (21) comprises a hollow section in its centre and a plurality of sockets radially arranged with respect to the centre of each auxiliary ring (21). However, unlike the outer rings (9), in each auxiliary ring (21) each socket is empty or contains a block (22) of permanent magnetic material therein. In each auxiliary ring (21) the blocks (22) of
35 permanent magnetic material are radially arranged with respect to the centre of the auxiliary ring (21) in a set of one or more layers, wherein each layer describes substantially an ellipse,

said ellipse having a minor axis and a major axis that is perpendicular to said minor axis and has a length longer than that of the minor axis. In the above context, the expression “substantially an ellipse” refers to the fact that all the geometric centres of the blocks (22) of permanent magnetic material of one and the same layer are located in one and the same ellipse, except for deviations inherent to the manufacture of the main magnet (1).

It should be noted that, as described above, it is possible for there to be one or more sockets in each auxiliary ring (21) that do not comprise inside them a block (22) of permanent magnetic material. In such case, the ellipse described by each layer of an auxiliary ring (21) is considered to be the same that would be described by said layer in the event that all the sockets of said auxiliary ring (21) comprised a block (22) of permanent magnetic material. Therefore, based on the above, the blocks (22) of each layer of each auxiliary ring (21) are not arranged in a dipolar elliptical Halbach array. Indeed, the arrangement in each layer of the blocks (22) of permanent magnetic material is such that the magnetic field generated by the auxiliary rings (21) corrects the experimental deviations inherent to the manufacture of the main magnet (1). In particular, the arrangement of the blocks (22) of permanent magnetic material in the layers of the auxiliary rings (21) is such that the homogeneity of the main magnetic field B_0 in the bore (2) of the main magnet (1) is increased with respect to the homogeneity of said main magnetic field B_0 when the main magnet (1) does not comprise the shimming unit (18) in its bore (2). Therefore, in an embodiment of the invention, when a socket of an auxiliary ring (21) contains a block (22) of permanent magnetic material therein, said block (22) is placed inside the socket such that the orientation of its magnetisation can be any of the orientations allowed by the socket, even an orientation parallel to the longitudinal axis of the main magnet (1).

25

Similarly, in the shimming unit (18), the minor axes of the ellipses of the layers of blocks (22) of permanent magnetic material of the auxiliary rings (21) are substantially parallel to the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10). In this context, the expression “substantially” refers to deviations inherent to the manufacture of the main magnet (1).

30

As described above, in the embodiment of Figure 6 the blocks (22) of permanent magnetic material of the auxiliary rings (21) are arranged in a single layer in each auxiliary ring (21). In particular, said blocks (22) are identical, cube-shaped, one-piece blocks and are made up of $\text{Nd}_2\text{Fe}_{15}\text{B}$. Furthermore, the blocks (22) of permanent magnetic material are placed in

35

each layer of each auxiliary ring (21) such that in each socket of each layer, one of the following three situations arises:

5 I. Halbach magnetisation: the direction and sense of magnetisation of the block (22) of permanent magnetic material are the direction and sense that would correspond to said block (22) in said socket, if all the blocks (22) of permanent magnetic material in said layer were arranged in a dipolar elliptical Halbach array.

10 II. Anti-Halbach magnetisation: the direction of magnetisation of the block (22) of permanent magnetic material is the direction that would correspond to said block (22) in said socket, if all the blocks (22) of permanent magnetic material in said layer were arranged in a dipolar elliptical Halbach array. However, the sense of magnetisation of said block (22) of permanent magnetic material is opposite to that which would correspond to said block (22) in said socket, if all the blocks (22) of
15 permanent magnetic material in said layer were arranged in a dipolar elliptical Halbach array.

III. No-block: the socket has no block (22) of permanent magnetic material placed therein.
20

Similarly, in the embodiment of Figure 6, the ratio between the length of the minor axis and the length of the major axis is substantially equal in all the ellipses described by the layers (9', 9'', 10', 10'') of blocks (19, 22) of permanent magnetic material of all the outer, central and auxiliary rings (9, 10, 21). The expression "substantially" refers to the fact that said ratio
25 is equal in all those ellipses, except for deviations inherent to the manufacture of the main magnet (1). Thereby, the ellipticity of the ellipses of the layers (9', 9'', 10', 10'') of all the outer, central and auxiliary rings (9, 10, 21) is about the same. The manufacture of a shimming unit (18) comprising layers with said ellipticities is simpler on an industrial level and in turn facilitates said shimming unit (18) having a geometric shape that is suitable for
30 the bore (2) of the main magnet (1).

In another embodiment of the invention, the blocks (22) of magnetic material of the auxiliary rings (21) are made up of another permanent magnetic material, for example a neodymium-iron-boron, Nd-Fe-B, alloy or a samarium-cobalt, Sm-Co, alloy. Moreover, in the preferred
35 embodiment of Figure 6, the blocks (19) of the outer and central rings (9, 10) and the blocks (22) of the auxiliary rings (21) are made up of exactly the same permanent magnetic

material. This facilitates the shimming unit (18) properly correcting the experimental deviations inherent to the method of manufacture and/or to the design of the main magnet (1) and its dependence on the temperature of the blocks (19, 22). Therefore, in the above context, the expression “exactly the same permanent magnetic material” refers to the fact
5 that the blocks (19) of the outer and central rings (9, 10) and the blocks (22) of the auxiliary rings (21) of Figure 6 are made up of $\text{Nd}_2\text{Fe}_{15}\text{B}$, with a magnetic degree equal to N48.

In another embodiment of the invention, in at least one auxiliary ring (21) at least one block (22) of permanent magnetic material has a geometric shape, magnetic material and/or size
10 different from the remaining blocks (22) of said auxiliary ring (21).

In another embodiment of the invention, the blocks (22) of permanent magnetic material of at least one auxiliary ring (21) comprise blocks with other geometric shapes other than cube-shaped, wherein said blocks preferably comprise a plurality of edges. In a non-limiting
15 example, each auxiliary ring (21) comprises several layers, each one of them with blocks (22) of permanent magnetic material of the same size and geometric shape, but where in each auxiliary ring (21) the size of the blocks (22) increases from one layer to another layer farther away from the longitudinal axis (8) of the main magnet (1). The shimming unit (18) thereby corrects the deviations of the main magnetic field mentioned above in different
20 levels of shimming, the smaller the size of the blocks (22) of magnetic material of each layer the finer the shimming.

Moreover, in the shimming unit (18) of Figure 6, each auxiliary ring (21) comprises a first flat face and a second flat face opposite the first one, where the sockets of each auxiliary
25 ring (21) are formed only on said first face. Furthermore, there is a portion of non-magnetic material between the bottom of each socket and the second face of each auxiliary ring (21), such that the socket is not open at said bottom. Similarly, each auxiliary ring (21) comprises a cover made of a non-magnetic material (such as, e.g., nylon, polyethylene, aluminium, among others), similarly to the outer and central rings (9, 10). In particular, in the method of
30 manufacturing the main magnet (1) of Figure 6, a cover made of a non-magnetic material is placed on the face of each auxiliary ring (21) where the sockets are formed. The placement of said covers is performed after placing the blocks (22) of permanent magnetic material in the corresponding sockets and before stacking said auxiliary rings (21) along the longitudinal axis (8). The cover of each auxiliary ring (21) prevents the blocks (22) of
35 permanent magnetic material from being dislodged from inside the sockets.

In an embodiment of the invention, the blocks (22) of permanent magnetic material of the auxiliary rings (21) are tightly packed radially, angularly, and/or axially. In this context, the definitions of blocks (22) of permanent magnetic materials tightly packed radially, angularly, and axially are analogous to those of the blocks (19) of permanent magnetic material of the outer and central rings (9, 10). In particular, when a socket of an auxiliary ring is empty, it is considered for said definitions that said socket comprises a block (22) of magnetic material.

Moreover, in the preferred embodiment of Figure 6, and according to the present invention, the shimming unit (18) is configured to house therein the magnetic gradient system (5) of Figure 2, such that said magnetic gradient system (5) goes through the hollow section of each auxiliary ring (21) and extends along the longitudinal axis (8), substantially from the first end (6) to the second end (7) of the main magnet (1) and covering the entire length thereof. In this sense, the area of each hollow section of each auxiliary ring (21) is greater than or equal to the cross-section (15) of the magnetic gradient system (5). In particular, the hollow section of each auxiliary ring (21) of Figure 6 has the same shape as the cross-section (15) of the magnetic gradient system (5) of Figure 2, such that the auxiliary rings (21) are configured to hold said magnetic gradient system (5).

Moreover, in an embodiment of the main magnet (1) according to the present invention, the amplitude of the main magnetic field B_0 in at least one region of the bore (2) is preferably less than 1 T, and more preferably less than 0.1 T. The main magnet (1) according to said embodiment is referred to as a low field magnet. Similarly, the at least one region of the previous bore (2) is preferably the region covered by the FoV (20) of an MRI scanner (3) comprising said main magnet (1).

Another object of the invention relates to a method of manufacturing a main magnet (1) according to any of the embodiments described in the present document. Preferably, the method is performed following a theoretical design of the main magnet (1) to be manufactured and comprises the following steps, performed in any technically possible order:

- a) providing the outer and central rings (9, 10);
- b) forming the sockets (13) of the outer rings (9) by perforating same, such that said sockets (13) are radially arranged with respect to the centre of each outer ring (9);
- c) placing blocks (19) of permanent magnetic material inside the sockets (13) of the outer rings (9), such that said blocks (19) of permanent magnetic material are arranged in

a set of a plurality of layers (9', 9''), wherein in each layer (9', 9'') the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array;

d) forming the sockets (13) of the central rings (10) by perforating same, such that said sockets (13) are radially arranged with respect to the centre of each central ring (10);

5 e) placing blocks (19) of permanent magnetic material inside the sockets (13) of the central rings (10), such that said blocks (19) of permanent magnetic material are arranged in a set of a plurality of layers (10', 10''), wherein in each layer (10', 10'') the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array; and

f) stacking the outer and central rings (9, 10) along a longitudinal axis (8).

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Furthermore, advantageously in the method of the present invention, after step f), the bore (2) formed by the hollow sections (11, 12) of the outer and central rings (9, 10) is suitable for housing a magnetic gradient system (5) extending along the longitudinal axis (8), and wherein said magnetic gradient system (5) covers at least 70% of the entire length of the
15 main magnet (1).

In a preferred embodiment of the method of the present invention, after step f), the method comprises step k) of arranging the gradient system (5) in the bore (2) of the main magnet (1).

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Similarly, in embodiments of the method of the present invention, steps a), b), c), d), e), f) and/or k) of the method are performed in a manner that complies with that described above for any of the embodiments of the main magnet (1) of the present invention. For example, in the method of manufacturing the main magnet (1) of Figure 1, steps b) and d) of forming
25 the sockets (13), and steps c) and e) of placing the blocks (19) of permanent magnetic material, are performed such that the direction of the main magnetic field B_0 generated in the bore (2) by the dipolar elliptical Halbach arrays of the rings (9, 10) is substantially parallel to the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material.

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At the same time, in the embodiment of the method of manufacturing the main magnet (1) of Figure 1, after step f), the bore (2) formed by the hollow sections (11, 12) of the outer and central rings (9, 10) is suitable for housing the magnetic gradient system (5) of Figure 2, extending along the longitudinal axis (8) from the first end (6) to the second end (7) of the
35 main magnet (1), and covers the entire length of said main magnet (1).

Furthermore, the embodiment of the method of manufacturing the main magnet (1) of Figure 1, the sockets (13) are formed in each outer and central ring (9, 10) on one of the two flat faces of said ring (9, 10) and, after placing the blocks (19) of permanent magnetic material inside the sockets (13), a cover made of a non-magnetic material is placed on said face.

5 The cover of each ring (9, 10) prevents the blocks (19) of permanent magnetic material from being dislodged from inside the sockets (13). In other embodiments of the invention, instead of using covers, adhesive means or other suitable fixing means can be used to prevent the blocks (19) from being dislodged from inside the sockets (13).

10 More preferably, the method of the invention further comprises the following steps, performed in any technically possible order:

g1) determining the amplitude and/or the homogeneity of the main magnetic field B_0 in a region of the bore (2);

15 g2) determining one or more characteristics of each auxiliary ring (21) of the shimming unit (18) of the theoretical design of the main magnet (1) comprising same, which increase or maximise the homogeneity of the main magnetic field B_0 in said region of the bore (2), to a desired value of homogeneity.

In a preferred embodiment of the invention, the orientation of magnetisation of each block
20 (22) of permanent magnetic material of each auxiliary ring (21), and/or the geometric shape and/or size of each block (22) of permanent magnetic material of each auxiliary ring (21) is determined in above step g2).

In turn, the theoretical design of the main magnet (1) (see, for example, Figure 1) is
25 additionally based on the result of an optimisation algorithm (23) (see Figure 7). Said design optimisation algorithm at least partially determines the configuration of each central ring (10), such that the homogeneity of the main magnetic field B_0 is maximised in the region of the bore (2) covered by the FoV (20) of the MRI scanner (3) (see, for example, according to Figure 2, when the MRI scanner (3) comprises the main magnet (1) of Figure 1).

30

Therefore, in a preferred embodiment of the present invention, at least before step d) of forming the sockets (13) of the central rings (10), the method of manufacturing the main magnet (1) comprises the following step:

h) determining, by means of an optimisation algorithm (23), one or more
35 characteristics of each central ring (10) of the theoretical design of the main magnet (1) which maximise or optimise the homogeneity of the main magnetic field B_0 in a region of

the bore (2); such that the sockets (13) are formed in step d) and/or blocks (19) of permanent magnetic material are placed in step e) according to the information determined by the optimisation algorithm (23) in step h).

- 5 More specifically, in the method of manufacturing the main magnet (1) of Figure 1, the optimisation algorithm (23) determines in step h) the distances to the longitudinal axis (8) of the main magnet (1) of each layer (10', 10'') of blocks (19) of permanent magnetic material of each central ring (10), such that the sockets (13) are formed in step d) according to the information determined in step h) by said optimisation algorithm (23). The optimisation
10 algorithm (23) can also be applied in an alternative or complementary manner to the blocks (22) of permanent magnetic material of the auxiliary rings (21).

In other embodiments of the method of the invention, the optimisation algorithm (23) determines the geometric shape, size, and/or composition of each block (19) of permanent
15 magnetic material of each central ring (10), and/or another or other characteristics of each central ring (10), such that the sockets (13) are formed in step d) and/or blocks (19) of permanent magnetic material are placed in step e) according to the information determined by the optimisation algorithm (23) in step h).

- 20 Figure 7 shows a diagram of a non-limiting example of an optimisation algorithm (23) according to the present invention. The optimisation algorithm (23) is supplied with a set of one or more input parameters (24). Similarly, the optimisation algorithm (23) obtains a result (25). Said result (25) comprises the values of one or more optimisation variables (26) which optimise at least one optimisation function (27). Preferably, the input parameters (24) and
25 the optimisation variables (26) are parameters comprising information about the theoretical design of the main magnet (1) and, therefore, comprise information about the dimensions of said main magnet (1) and of the bore (2) thereof, about the amount and the spatial distribution of the permanent magnetic material comprised in the outer and central rings (9, 10) of said main magnet (1), and about the dimensions of the region covered by the FoV
30 (20) in the bore (2) when an MRI scanner (3) comprises said main magnet (1). In this sense, the difference between the input parameters (24) and the optimisation variables (26) is that the input parameters (24) are set parameters, whereas the optimisation variables (26) are parameters that the optimisation algorithm (23) varies while carrying out a method of optimisation. Therefore, in an embodiment of the invention, a particular parameter of the
35 design of the main magnet (1) is an input parameter (24), while in another different embodiment of the invention that same parameter is an optimisation variable (26).

In a preferred embodiment of the invention, the maximum dimensions of the main magnet (1) of the theoretical design, the minimum dimensions of the bore (2), and/or the size and shape of the FoV (20) are input parameters (24), or design parameters of the main magnet (1) derived from one or more input parameters (24). Typically, the length of the main magnet (1) and the dimensions of its bore (2) are particularly relevant parameters. Their relevance is generally due to the fact that the theoretical design of the main magnet (1) is conceived for a specific type of sample (e.g., a patient's head or leg), such that the main magnet (1) is configured to position the sample in the region covered by the FoV (20) in the bore (2) and in the central portion (14). Furthermore, in different embodiments of the invention, the length and dimensions of the bore (2) of the main magnet (1) delimit the size of the FoV (20) of the MRI scanner (3) comprising same, as explained above in the description of the embodiment of Figure 2. Moreover, in an embodiment of the invention, the input parameters (24) comprise the amplitude range of the main magnetic field B_0 expected to be generated in the region covered by the FoV (20), the expected total weight of the main magnet (1), the manufacturing tolerances of the outer and central rings (9, 10), and/or the ratio between the length of the minor axis and the length of the major axis of the ellipse of each layer (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of each outer and/or central ring (9, 10).

In another preferred embodiment of the invention, the optimisation variables (26) comprise the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring (10). In the above context, the input parameters (24) generally restrict the value of the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring (10). Therefore, the value of the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring (10) determines the total number of blocks (19) of said central ring (10), as well as the distances to the longitudinal axis (8) of the main magnet (1) of each layer (10', 10'') of blocks (19) of permanent magnetic material of said central ring (10). In another embodiment of the invention, the optimisation variables (26) comprise the geometric shape and/or size of each block (19) of permanent magnetic material of each layer (10', 10'') of each central ring (10). In another embodiment of the invention, the optimisation variables (26) comprise the composition of each block (19) of permanent magnetic material of each layer (10', 10'') of each central ring (10). In a non-limiting example, in the theoretical design of the main magnet (1) each block (19) of permanent magnetic material is made up of an Nd-Fe-B alloy, and one of the optimisation

variables (26) of the optimisation algorithm (23) is the magnetic degree of each block (19) comprised in each central ring (10).

Similarly, when the theoretical design refers to a main magnet (1) having a mirror symmetry
5 along the longitudinal axis (8) of the main magnet (1) and with respect to the centre of said longitudinal axis (8), the number of optimisation variables (23) is advantageously reduced. For example, if said theoretical design refers to a main magnet (1) comprising five central rings (10), and the optimisation variables (23) are the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring
10 (10), said optimisation variables (23) would then comprise three different numbers N_1 , N_2 , N_3 of blocks (19) of permanent magnetic material. In this way, the distribution of the number N_i of blocks (19) of permanent magnetic material of the inner layer (10') of each central ring (10) along the longitudinal axis (8) would be [N_1 , N_2 , N_3 , N_2 , N_1].

15 Based on the above, the optimisation algorithm (23) of Figure 7 is configured to simulate, from the input parameters (24) and the optimisation variables (26), the main magnetic field B_0 generated in at least one region of the bore (2) of the main magnet (1) of the theoretical design. Preferably, said region is the region in the bore (2) covered by the FoV (20) of an eventual MRI scanner (1) comprising the main magnet (1) of the theoretical design.
20 Similarly, said optimisation algorithm (23) considers that the arrangement of the blocks (19) of permanent magnetic material of each layer (9', 9'', 10', 10'') of each outer and central ring (9, 10) is such that the direction of the simulated main magnetic field B_0 in the bore (2) is parallel to the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of said outer and central ring (9, 10).

25 In different embodiments of the invention, the optimisation function (27) comprises one or more linear functions. Linear programming is advantageously simpler and more efficient than non-linear programming. In these embodiments, typically one or more upper and/or lower bounds are imposed during the actual optimisation. Preferably, said bounds and/or
30 one or more parameters which determine same are supplied to the optimisation algorithm (23) together with the input parameters (24). In a non-limiting example, the linear optimisation function (27) is the actual number of blocks (19) of permanent magnetic material of each central ring (10). In this context, the optimisation algorithm (23) minimises the number of blocks (19) of the central rings (10), such that the simulated main magnetic
35 field B_0 is less than the sum of a target value B_{tar} and a range ϵ , and greater than the difference between said target value B_{tar} and said range ϵ . Preferably, the target value B_{tar}

and the range ε are supplied to the optimisation algorithm (23) together with the input parameters (24). The target value B_{tar} and the range ε impose bounds during optimisation, and said range ε furthermore restricts the homogeneity of the main magnetic field B_0 simulated by the optimisation algorithm (23).

5

In other embodiments of the invention, the optimisation function (27) comprises one or more non-linear functions. In a non-limiting example, the non-linear optimisation function (27) is the inhomogeneity function, I , of the simulated main magnetic field B_0 , determined, for example, by the expression $I = (B_{0,max} - B_{0,min})/B_{0,mean}$, wherein $B_{0,max}$, $B_{0,min}$ and $B_{0,mean}$ are, respectively, simulated values of the maximum, minimum and average main magnetic field B_0 in the region covered by a FoV (20) in the bore (2) of the main magnet (1) of the theoretical design. In this context, the optimisation algorithm (23) obtains as a result (25) the optimisation variables (26) which minimise said inhomogeneity (I).

10

15 Additionally, the optimisation algorithm (23) can use different methods of optimisation. In a preferred embodiment of the invention, the optimisation algorithm (23) comprises a genetic algorithm, which is executed in an evolutionary manner. In said embodiment, the optimisation algorithm (23) generates a starting population of main magnets (1), wherein each population comprises a plurality of individuals. In this context, the expression
20 “individual” refers to the parameters defining the theoretical design of a main magnet (1), wherein said parameters comprise the input parameters (24) and random values generated by the optimisation algorithm (23) of the optimisation variables (26) (e.g., the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring (10)). Typically, said random values are integers and discrete.
25 Therefore, each individual is associated with its corresponding homogeneity of the main magnetic field B_0 simulated by the optimisation algorithm (23). After generating the starting population, the optimisation algorithm (23) selects a first subset of said population of main magnets (1), where said subset comprises the most successful individuals (i.e., with higher values of homogeneity of the simulated main magnetic field B_0). Next, the optimisation
30 algorithm (23) mixes the values of the optimisation variables (26) of the individuals comprised in the first subset, forming a second population of main magnets (1). In this context, said second population is referred to as offspring. Therefore, the optimisation algorithm (23) progressively generates new offspring, selecting the most successful individuals and mixing the values of the optimisation variables (26) of said individuals, until
35 a convergence criterion is achieved. In a non-limiting example, the generation of new offspring ends when the inhomogeneity, I , of an individual of one of the populations of the

last offspring generated is less than a target value. In said example, the result (25) of the optimisation algorithm (23) comprises the value of the optimisation variables (27) of said individual of the last offspring generated. In preferred embodiments, before or after mixing the values of the optimisation variables (26) of the most successful individuals, the
5 optimisation algorithm (23) generates random mutations, i.e., randomly modifies the value of one or more optimisation variables (26) in one or more individuals.

In another embodiment of the invention, the optimisation algorithm (23) comprises a differential evolution algorithm. Unlike genetic algorithms, in the starting population
10 generated by the differential evolution algorithm, the random values of the optimisation variables (26) are real, non-discrete values and not necessarily integers. Furthermore, typically the optimisation algorithm (23) arranges the individuals of the starting population and of the offspring in vectors. Therefore, from the starting population, the optimisation algorithm (23) progressively generates offspring using directional information, until a
15 convergence criterion is achieved in an individual of the last offspring generated (e.g., when the inhomogeneity, I , of said individual is less than a pre-set value). In an embodiment of the invention, when the convergence criterion is achieved, the optimisation algorithm (23) transforms each non-discrete value of the optimisation variables (26) of said individual of the last offspring generated, in the integer value closest to said non-discrete value (e.g., in
20 non-limiting embodiments in which the optimisation variables (26) comprise the number N_i of blocks (19) of permanent magnetic material of the layer (10') closest to the longitudinal axis (8) of each central ring (10)).

In another embodiment of the invention, the optimisation algorithm (23) comprises
25 modifying one or more input parameters (24) (e.g., the number of layers (10', 10''), the number of blocks (19) of permanent magnetic material of each layer (10', 10''), the separation between contiguous blocks (19) of each layer (10', 10''), and/or the ratio between the length of the minor axis and the length of the major axis of the ellipse of each layer (10', 10'') of each central ring (10)), for the purpose of obtaining a new result (25) which increases
30 the homogeneity of the simulated main magnetic field B_0 and/or improves another or other characteristic of the main magnet (1) of the theoretical design, with respect to the result (25) previously obtained by the optimisation algorithm (23). Non-limiting examples of other characteristics are the total weight of the main magnet (1) of the theoretical design or the amplitude of the simulated main magnetic field B_0 . In another embodiment of the invention,
35 the optimisation algorithm (23) is configured to vary the size and/or geometric shape of each block (19) of permanent magnetic material of each outer and/or central ring (9, 10), by

means of a loop running through different values of size and/or geometric shapes. In said embodiment, the optimisation algorithm (23) selects the number of outer and central rings (9, 10) compatible with a length of the main magnet (1) and with an amplitude range of the simulated main field B_0 that are pre-set. Similarly, for each size of block (19) of permanent
5 magnetic material, the algorithm can preferably determine how many layers (10', 10'') of each central ring (10) are needed to achieve said amplitude range.

In another embodiment of the invention, the optimisation algorithm (23) imposes, for each central ring (10), at least one lower bound on the distances to the longitudinal axis (8) of the
10 main magnet (1) of the layer (10') of blocks (19) closest to said longitudinal axis (8). For example, when the theoretical design of the main magnet (1) refers to a main magnet (1) configured to house in its bore (2) a magnetic gradient system (5), a RF system (4) and a shimming unit (18), the optimisation algorithm (23) imposes limits on the distances to the longitudinal axis (8) of the main magnet (1) of the layer (10') of blocks (19) of permanent
15 magnetic material closest to said longitudinal axis (8), such that they are compatible with the main magnet (1) housing said magnetic gradient system (5), RF system (3, 4) and shimming unit (18).

In another embodiment of the invention, the optimisation algorithm (23) imposes, for each
20 central ring (10), at least one higher bound on the distances to the longitudinal axis (8) of the main magnet (1) of the layer (10'') of blocks (19) of permanent magnetic material farthest away from said longitudinal axis (8). For example, in a non-limiting embodiment, the input parameters (24) further comprise a maximum height and/or a maximum width of the main magnet (1). In said embodiment, from said maximum height and/or a maximum width of the
25 main magnet (1) and for each central ring (10), the optimisation algorithm (23) bounds the maximum distance to the longitudinal axis (8) of the layer (10'') of blocks (19) of permanent magnetic material farthest away from said longitudinal axis (8).

In another embodiment of the method of the invention, after forming the sockets (13) of
30 each central ring (10), the outer and central rings (9, 10) are stacked along a longitudinal axis (8). After applying said rings (9, 10), typically the homogeneity of the main magnetic field B_0 generated in the bore (2) of the main magnet (1) undergoes deviations with respect to the value of said homogeneity determined in the theoretical design. Said deviations are inherent to the actual manufacture of a main magnet (1). This explains that the design of
35 the main magnet (1) of Figure 1 would refer to a main magnet configured to house a

shimming unit (18), where said shimming unit (18) increases the homogeneity of the main magnetic field B_0 in the bore (2).

Therefore, based on the above, a preferred embodiment of the invention relates to a method
5 of manufacturing a main magnet (1) comprising a shimming unit (18) according to any of the embodiments described in the present document, wherein, in addition to the steps described above, before or after step f), the method comprises the following steps, performed in any technically possible order:

- i1) providing the auxiliary rings (21) of the shimming unit (18);
- 10 i2) forming the sockets of the auxiliary rings (21) by perforating same, such that said sockets are radially arranged with respect to the centre of each auxiliary ring (21); and
- i3) placing blocks (22) of permanent magnetic material inside the sockets of the auxiliary rings (21), such that each socket is empty or contains a block (22) of permanent magnetic material therein.

15

Additionally, the previous embodiment of the method comprises the following step after step f):

- i4) arranging the auxiliary rings (21) along a longitudinal axis (8) and placing them in the central portion (14) of the main magnet (1), such that the shimming unit (18) goes
20 through the hollow section (12) of each central ring (10) of the main magnet (1).

Figure 8 shows a diagram of a non-limiting example of an auxiliary algorithm (28) for optimising the shimming unit (18), according to a preferred embodiment of the present invention. The auxiliary algorithm (28) is an optimisation algorithm that is supplied with a
25 set of one or more input parameters (29). Similarly, the auxiliary algorithm (28) obtains a result (30). Said result (30) comprises the values of one or more optimisation variables (31) which optimise at least one optimisation function (32).

The input parameters (29) and the optimisation variables (31) of the auxiliary algorithm (28)
30 are parameters comprising information about the theoretical design of a main magnet (1) comprising the shimming unit (18), and about the main magnetic field B_0 generated, after stacking the outer and central rings (9, 10), by the main magnet (1) in its bore (20) and in the absence of the shimming unit (18). Preferably, the input parameters (29) and the optimisation variables (31) of the auxiliary algorithm (28) are parameters comprising
35 information about dimensions of the shimming unit (18) and about the amount and the spatial distribution of the permanent magnetic material comprised in the auxiliary rings (21)

of said shimming unit (18). The input parameters (29) of the auxiliary algorithm (28) are set parameters, whereas the optimisation variables (31) of the auxiliary algorithm (28) are parameters that the auxiliary algorithm (28) varies while carrying out a method of optimisation. In an embodiment of the invention, a particular parameter is an input
5 parameter (29) of the auxiliary algorithm (28), while in another different embodiment of the invention that same parameter is an optimisation variable (31).

In an embodiment of the invention, the input parameters (29) of the auxiliary algorithm (28) comprise one or more manufacturing tolerances of each auxiliary ring (21). In another
10 embodiment of the invention, said input parameters (29) comprise information about the design of the main magnet (1), about the dimensions occupied by eventual RF and/or magnetic gradient systems (4, 5) in the bore (2) thereof. In an embodiment of the invention, said input parameters (29) comprise the size and shape of the FoV (20) of an MRI scanner (3) comprising the main magnet (1) which houses the shimming unit (18) in its bore (2),
15 and/or the amplitude of the main magnetic field B_0 in said FoV (20) measured experimentally and in the absence of the shimming unit (18).

In an embodiment of the invention, the optimisation variables (31) of the auxiliary algorithm (28) comprise the orientation of magnetisation of each block (22) of permanent magnetic
20 material of each auxiliary ring (21), and/or the geometric shape and/or size of each block (22) of permanent magnetic material of each auxiliary ring (21). In an embodiment of the invention, the optimisation variables (31) of the auxiliary algorithm (28) comprise the geometric shape and/or size of each block (22) of permanent magnetic material of each auxiliary ring (21), and the auxiliary algorithm (28) is configured to iteratively vary the value
25 of each geometric shape and/or size. Said values can be supplied together with the input parameters (29) (corresponding, for example, to the values of the geometric shapes and/or sizes of the blocks (22) of permanent magnetic material available on the market).

Based on the above, the auxiliary algorithm (28) of Figure 8 is configured to simulate, from
30 the input parameters (29) and the optimisation variables (31), the main magnetic field B_0 generated in at least one region of the bore (2) of the main magnet (1) comprising the shimming unit (18), according to a theoretical design. Preferably, said region is the region in the bore (2) covered by the FoV (20) of an eventual MRI scanner (3) comprising said main magnet (1). Furthermore, the auxiliary algorithm (28) is configured to optimise at least
35 one optimisation function (32) which depends on the input parameters (29) and the optimisation variables (31). Said optimisation function (32) determines the homogeneity of

the main magnetic field B_0 simulated by the auxiliary algorithm (28). As a result (30) of the optimisation of the optimisation function (32), the auxiliary algorithm (28) obtains the values of the optimisation variables (31) which maximise the homogeneity of the main magnetic field B_0 simulated by the auxiliary algorithm (28). In this context, the result (30) of the auxiliary algorithm (28) is the information determined in step g2) of an embodiment of the method of manufacturing the main magnet (1). Therefore, in an embodiment of the method of the invention, the sockets of each auxiliary ring (21) are formed in step i2) and/or blocks (22) of permanent magnetic material are placed in step i3) in each auxiliary ring (21), according to said result (30).

In a preferred embodiment of the invention, the optimisation function (32) optimised by the auxiliary algorithm (28) is a linear or non-linear function (such as, e.g., the inhomogeneity, I , of the main magnetic field B_0 in at least one region of the bore (2) simulated by the auxiliary algorithm (28)). The auxiliary algorithm (28) can use different methods of optimisation of the function (32). In an embodiment of the invention, the auxiliary algorithm (28) is a genetic algorithm or a differential evolution algorithm.

In another preferred embodiment of the invention, the optimisation algorithm (23) used for optimising the homogeneity of the main magnetic field B_0 in the absence of a shimming unit (18) is configured to determine the information of step g2) described above. In this sense, said optimisation algorithm (23) is supplied with the set of the one or more input parameters (29) and obtains the result (30) comprising the values of the one or more optimisation variables (31) which optimise the at least one previous optimisation function (32), in a similar way to what has been described about the auxiliary algorithm (28).

Figure 9 is a graph showing a result (30) of the auxiliary algorithm (28) used in the method of manufacturing the main magnet (1) according to Figure 6. On the horizontal axis of the graph, the numbers 1-23 correspond with the position along the longitudinal axis (8) of each auxiliary ring (21) of Figure 6, from right to left. On the vertical axis, the numbers 1-87 correspond with the position of each of the 87 sockets comprised in each auxiliary ring (21). Moreover, the graph indicates with three types of boxes whether or not there is a block (22) of magnetic material placed in each socket of each auxiliary ring (21) and, if there is, the direction and sense of magnetisation of said block (22). As explained above, white boxes correspond with the "Halbach magnetisation" situation, black boxes correspond with the "Anti-Halbach magnetisation" situation, and the boxes with an "X" correspond with the "No-block" situation.

Therefore, some steps of a non-limiting embodiment of the method of manufacturing the main magnet (1) of Figure 6 are described below. After stacking the outer and central rings (9, 10) along a longitudinal axis (8) in step f) and before arranging the gradient system (5) in step k), the homogeneity of the main magnetic field B_0 in a region of the bore (2) is determined in step g1). In particular, the amplitude of the main magnetic field B_0 is measured experimentally in a region of the bore (2), namely in the region of the bore (2) that will eventually be covered by the FoV (20) of the MRI scanner (3) of Figure 2. The homogeneity of the main magnetic field B_0 in the region of the bore (2) that will eventually be covered by the FoV (20) is determined from the previous measurement. Said homogeneity deviates from the theoretically expected value due to deviations inherent to the manufacture of the main magnet (1).

Next, in step g2), the orientation of magnetisation of each block (22) of permanent magnetic material of the auxiliary rings (21) is determined so as to increase the homogeneity determined in step g1) to a desired value of homogeneity, such that blocks (22) of permanent magnetic material are placed in step i3) in the sockets of the auxiliary rings (21), according to the information determined in step g2). In particular, in the method of manufacturing the main magnet (1) of Figure 6, the information determined in step g2) is the result (30) of Figure 9, determined by an auxiliary algorithm (28). Next, the auxiliary rings (21) are arranged in step i4) along a longitudinal axis (8) and are placed in the central portion (14) of the main magnet (1), such that the shimming unit (18) goes through the hollow section (12) of each central ring (10) of the main magnet (1). In this particular embodiment, before performing step i4), the outer rings (9) of the main magnet (1) are removed from one of the ends, since the size of the hollow sections (11) of said outer rings (9) prevent insertion of the shimming unit (18) inside the bore (2).

After performing step i4) the outer rings (9) that had been removed previously are stacked again. Finally, after arranging the shimming unit (18) of Figure 6 in the bore (2) of the main magnet (1), the magnetic gradient system (5) of Figure 2 is arranged in step k), such that said magnetic gradient system (5) covers the entire length of the main magnet (1).

CLAIMS

1. A main magnet (1) based on dipolar elliptical Halbach arrays, configured to generate the main magnetic field B_0 of an MRI scanner (3), wherein:

5 - said main magnet (1) comprises a plurality of rings (9, 10) stacked along a longitudinal axis (8), from a first end (6) of the main magnet (1) to a second end (7) of the main magnet (1), such that each end (6, 7) of the main magnet (1) comprises one or more outer rings (9), and the central portion (14) of the main magnet (1) comprised between the first end (6) and the second end (7) thereof comprises one or more central rings (10);

10 - each outer and central ring (9, 10) comprises a plurality of sockets (13), wherein each socket (13) houses a block (19) of permanent magnetic material;

 - each outer and central ring (9, 10) comprises a hollow section (11, 12), wherein the hollow sections (11, 12) of the outer and central rings (9, 10) form an inner bore (2) of the main magnet (1);

15 - in each outer and central ring (9, 10), the blocks (19) of permanent magnetic material are radially arranged with respect to the centre of said ring (9, 10) in a set of a plurality of layers (9', 9'', 10', 10''), wherein each layer (9', 9'', 10', 10'') describes substantially an ellipse, said ellipse having a minor axis and a major axis that is perpendicular to said minor axis and has a length longer than that of the minor axis;

20 - the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10) are substantially parallel to one another; and

 - in each layer (9', 9'', 10', 10''), the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array, such that the dipolar elliptical Halbach arrays
25 of the outer and central rings (9, 10) generate the main magnetic field B_0 in the bore (2) of the main magnet (1);

 the main magnet (1) being **characterised in that:**

 the bore (2) is suitable for housing a magnetic gradient system (5) extending along the longitudinal axis (8), and wherein said magnetic gradient system (5) covers at least 70%
30 of the entire length of the main magnet (1).

2. The main magnet (1) according to the preceding claim, wherein the magnetic gradient system (5) extends from the first end (6) of the main magnet (1) to the second end (7) of the main magnet (1), and wherein said magnetic gradient system (5) covers the entire
35 length of the main magnet (1).

3. The main magnet (1) according to any of the preceding claims, wherein the blocks (19) of permanent magnetic material are arranged, in each outer and central ring (9, 10), such that the direction of the main magnetic field B_0 generated in the bore (2) by the dipolar elliptical Halbach arrays of the outer and central rings (9, 10) is substantially parallel to the
5 minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of said rings (9, 10).

4. The main magnet (1) according to any of the preceding claims, further comprising a shimming unit (18) configured to homogenise the main magnetic field B_0 in the bore (2),
10 wherein:

- the shimming unit (18) comprises a plurality of auxiliary rings (21), stacked along a longitudinal axis (8) in the central portion (14) of the main magnet (1), such that the shimming unit (18) goes through the hollow section (12) of each central ring (10) of the main magnet (1);
- 15 - each auxiliary ring (21) comprises a plurality of sockets, wherein each socket is empty or contains a block (22) of permanent magnetic material therein;
- each auxiliary ring (21) comprises a hollow section;
- in each auxiliary ring (21), the blocks (22) of permanent magnetic material are radially arranged with respect to the centre of the auxiliary ring (21) in an array of one or
20 more layers, wherein each layer describes substantially an ellipse, said ellipse having a minor axis and a major axis that is perpendicular to said minor axis and has a length longer than that of the minor axis; and
- the minor axes of the ellipses of the layers of blocks (22) of permanent magnetic material of the auxiliary rings (21) are substantially parallel to the minor axes of the ellipses
25 of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10).

5. The main magnet (1) according to the preceding claim, wherein the blocks (19) of the outer and central rings (9, 10) and the blocks (22) of the auxiliary rings (21) are made
30 up of exactly the same permanent magnetic material.

6. The main magnet (1) according to any of the preceding claims, wherein the direction of magnetisation of each block (19) of permanent magnetic material of the outer and central rings (9, 10) is substantially perpendicular to the longitudinal axis (8) of the main
35 magnet (1).

7. The main magnet (1) according to any of the preceding claims, wherein:

- the blocks (19, 22) of permanent magnetic material of the outer and central rings (9, 10) and/or of the auxiliary rings (21) are made up of a samarium-cobalt, Sm-Co alloy or of a neodymium-iron-boron, Nd-Fe-B alloy; and/or are one-piece blocks (19, 22) of permanent magnetic material;

- at least in one and the same outer or central ring (9, 10), the blocks (19) of permanent magnetic material have the same geometric shape, permanent magnetic material and size;

- the minor axes of the ellipses of the layers (9', 9'', 10', 10'') of blocks (19) of permanent magnetic material of the outer and central rings (9, 10) are substantially parallel or substantially perpendicular to a surface in which the main magnet (1) is located;

- in the layers (9', 9'', 10', 10'') of blocks (19, 22) of permanent magnetic material of the outer and central rings (9, 10) and/or of the auxiliary rings (21), the length of the major axis of the ellipse described by each layer (9', 9'', 10', 10'') is longer than the length of the minor axis; and/or

- the ratio between the length of the minor axis and the length of the major axis is substantially equal in all the ellipses described by the layers (9', 9'', 10', 10'') of blocks (19, 22) of permanent magnetic material of all the outer and central rings (9, 10) and/or of all the auxiliary rings (21).

8. The main magnet (1) according to any of the preceding claims, wherein the geometric shape of the blocks (19, 22) of permanent magnetic material of the outer and central rings (9, 10) and/or of the auxiliary rings (21) is cube-shaped.

9. The main magnet (1) according to any of the preceding claims, wherein

- in at least one outer ring (9) and in the layer (9') closest to the longitudinal axis (8) of the main magnet (1) of said outer ring (9), the blocks (19) of magnetic material of said layer (9') are arranged such that the separating distance between each block (19) and the outer contour of the magnetic gradient system (5) is substantially equal to or less than 1 mm;

- the blocks (19) of permanent magnetic material of at least one outer and/or central ring (9, 10) of the main magnet (1) of the layer (9', 10') closest to the longitudinal axis (8), are arranged such that the separating distance between each block (19) and the inner perimeter of said ring (9, 10) is substantially equal to or less than 1 mm;

- the blocks (19) of permanent magnetic material of at least one outer and/or central ring (9, 10) of the main magnet (1) of the layer (9'', 10'') farthest away from the longitudinal

axis (8), are arranged such that the separating distance between each block (19) and the outer perimeter of said ring (9, 10) is substantially equal to or less than 1 mm;

- in the outer and/or central rings (9, 10) of the main magnet (1), the contiguous blocks (19) of permanent magnetic material of one and the same layer (9', 9'', 10', 10''), are
5 arranged at a separating distance substantially equal to or less than 1 mm;

- in the outer and/or central rings (9, 10) of the main magnet (1), the contiguous blocks (19) of permanent magnetic material of two different and consecutive layers (9', 9'', 10', 10'') of one and the same ring (9, 10) are arranged at a separating distance substantially equal to or less than 1 mm; and/or

10 - in the outer and/or central rings (9, 10) of the main magnet (1), the contiguous blocks (19) of permanent magnetic material of two different and consecutive rings (9, 10) along the longitudinal axis (8) are arranged at a longitudinal separating distance substantially equal to or less than 4 mm.

15 10. The main magnet (1) according to any of the preceding claims, wherein the amplitude of the main magnetic field B_0 in at least one region of the bore (2) is less than 0.1 T.

20 11. An MRI scanner (3) comprising the main magnet (1) according to any of the preceding claims, a magnetic gradient system (5) and an RF system (4), wherein:

- the bore (2) of the main magnet (1) is configured to house the RF system (4) and the magnetic gradient system (5);

- the main magnet (1) is configured to generate the main magnetic field B_0 in the bore (2);

25 - the gradient system (5) is configured to apply at least one magnetic gradient in the bore (2); and

- the RF system (4) is configured to apply an RF field in a sample located in the bore (2) and to receive a magnetic resonance signal coming from said sample.

30 12. A method of manufacturing the main magnet (1) according to any of claims 1-10, wherein the method comprises the following steps, performed in any technically possible order:

a) providing the outer and central rings (9, 10);

35 b) forming the sockets (13) of the outer rings (9) by perforating same, such that said sockets (13) are radially arranged with respect to the centre of each outer ring (9);

c) placing blocks (19) of permanent magnetic material inside the sockets (13) of the outer rings (9), such that said blocks (19) of permanent magnetic material are arranged in a set of one or more layers (9', 9''), wherein in each layer (9', 9'') the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array;

5 d) forming the sockets (13) of the central rings (10) by perforating same, such that said sockets (13) are radially arranged with respect to the centre of each central ring (10);

e) placing blocks (19) of permanent magnetic material inside the sockets (13) of the central rings (10), such that said blocks (19) of permanent magnetic material are arranged in a set of one or more layers (10', 10''), wherein in each layer (10', 10'') the blocks (19) of permanent magnetic material are arranged in a dipolar elliptical Halbach array; and

10 f) stacking the outer and central rings (9, 10) along a longitudinal axis (8),
the method being **characterised in that**, after step f), the bore (2) formed by the hollow sections (11, 12) of the outer and central rings (9, 10) is suitable for housing a magnetic gradient system (5) extending along the longitudinal axis (8), and wherein said
15 magnetic gradient system (5) covers at least 70% of the entire length of the main magnet (1).

13. The method according to the preceding claim, wherein, after step f), the method comprises step k) of arranging the gradient system (5) in the bore (2) of the main magnet
20 (1).

14. The method according to any of claims 12-13, comprising, before or after step f), the following steps performed in any technically possible order:

i1) providing a plurality of auxiliary rings (21) of a shimming unit (18);

25 i2) forming sockets of the auxiliary rings (21) by perforating same, such that said sockets are radially arranged with respect to the centre of each auxiliary ring (21); and

i3) placing blocks (22) of permanent magnetic material inside the sockets of the auxiliary rings (21), such that each socket is empty or contains a block (22) of permanent magnetic material therein;

30 wherein the method further comprises the following step after step f):

i4) arranging the auxiliary rings (21) along a longitudinal axis (8) and placing them in the central portion (14) of the main magnet (1), such that the shimming unit (18) goes through the hollow section (12) of each central ring (10) of the main magnet (1).

15. The method according to the preceding claim, wherein after step f) and before steps i2) and/or i3), the method comprises the following steps, performed in any technically possible order:

5 g1) determining the homogeneity of the main magnetic field B_0 in a region of the bore (2);

g2) determining the orientation of magnetisation of each block (22) of permanent magnetic material of the auxiliary rings (21), and/or the geometric shape and/or size of each block (22) of permanent magnetic material of the auxiliary rings (21), which increase the homogeneity of the main magnetic field B_0 determined in step g1) to a desired value of
10 homogeneity;

such that the sockets of the auxiliary rings (21) are formed in step i2) and/or blocks (22) of permanent magnetic material are placed in step i3) according to the information determined in step g2).

16. The method according to any of claims 12-15 wherein, before forming the sockets (13) of the central rings (10) in step d), the method comprises the step of:

h) determining, by means of an optimisation algorithm (23), the geometric shape, the size and/or the composition of the blocks (19) of permanent magnetic material of the central rings (10), and/or the distances to the longitudinal axis (8) of the main magnet (1) of
20 each layer (10', 10'') of blocks (19) of permanent magnetic material of the central rings (10), which maximise the homogeneity of the main magnetic field B_0 in a region of the bore (2);

such that the sockets (13) are formed in step d) and/or blocks (19) of permanent magnetic material are placed in step e) according to the information determined by the optimisation algorithm (23) in step h).

25

17. The method according to the preceding claim, wherein:

- in the determination of step h), the optimisation algorithm (23) optimises at least one non-linear optimisation function (27);

30 - the optimisation algorithm (23) is a differential evolution algorithm or a genetic algorithm;

- for each central ring (10), the optimisation algorithm (23) imposes at least one lower bound on the distances to the longitudinal axis (8) of the main magnet (1) of the layer (10') of blocks (19) of permanent magnetic material closest to said longitudinal axis (8); and/or

35 - for each central ring (10), the optimisation algorithm (23) imposes at least one higher bound on the distances to the longitudinal axis (8) of the main magnet (1) of the layer

(10'') of blocks (19) of permanent magnetic material farthest away from said longitudinal axis (8).

DRAWINGS

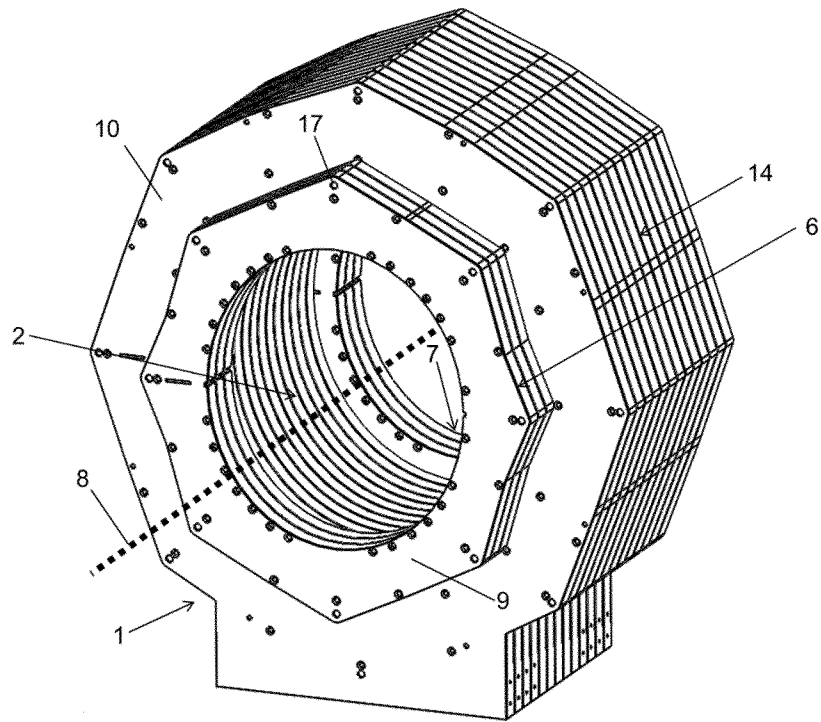


FIG. 1

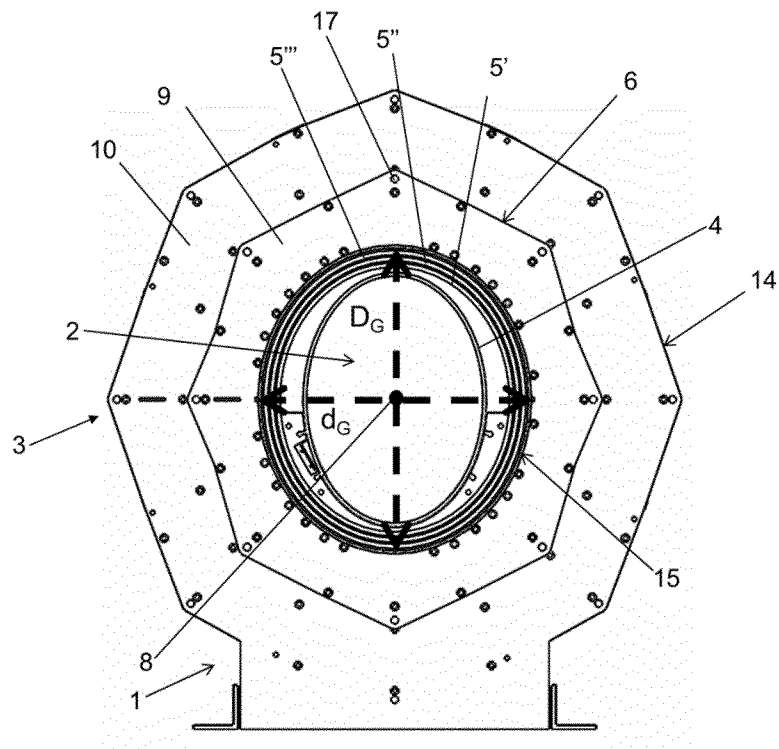


FIG. 2

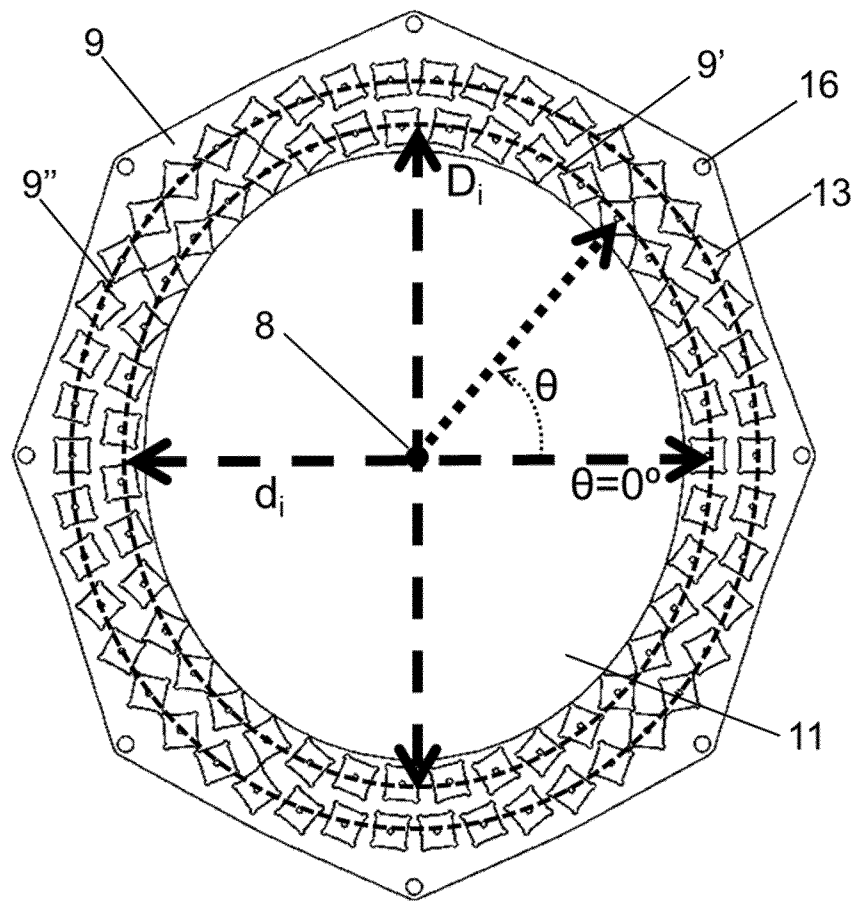


FIG. 3a

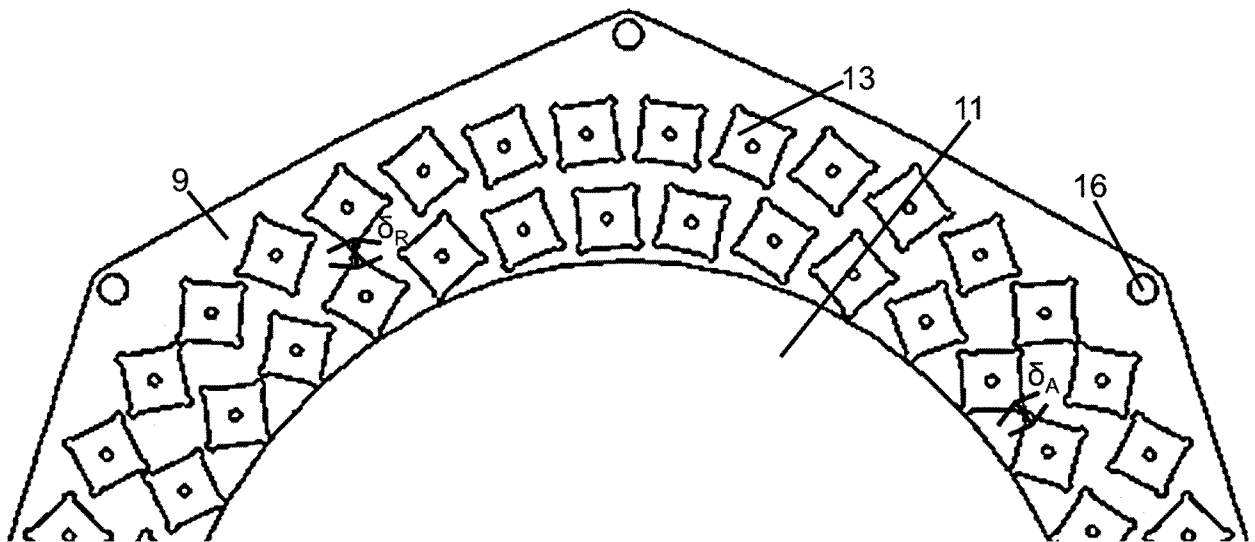


FIG. 3b

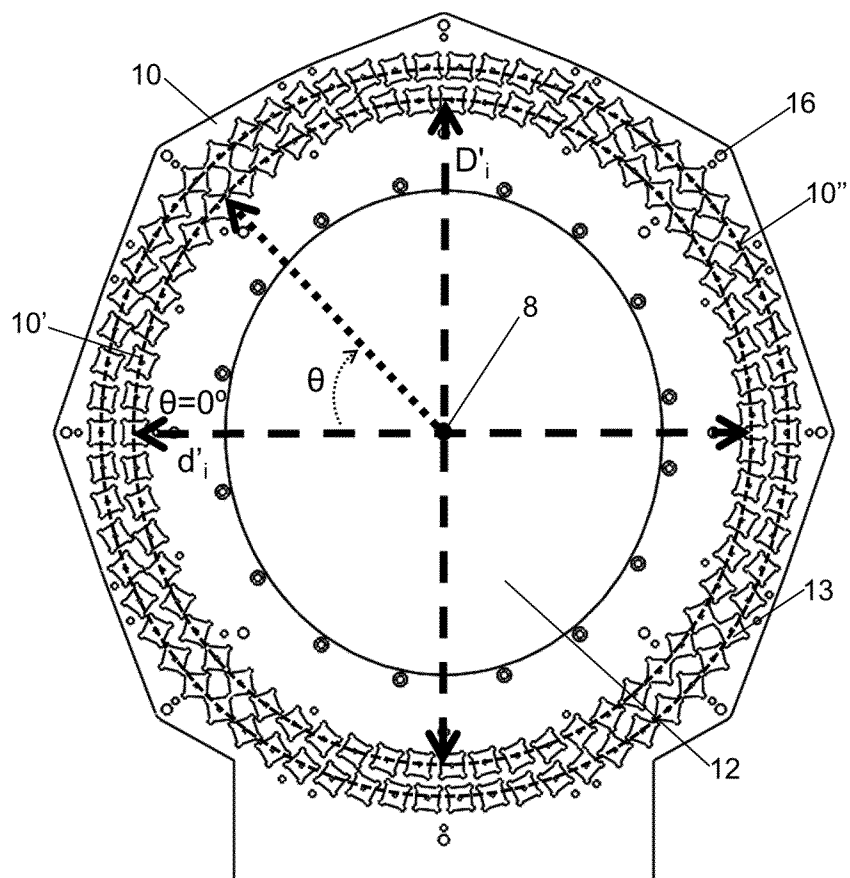


FIG. 4

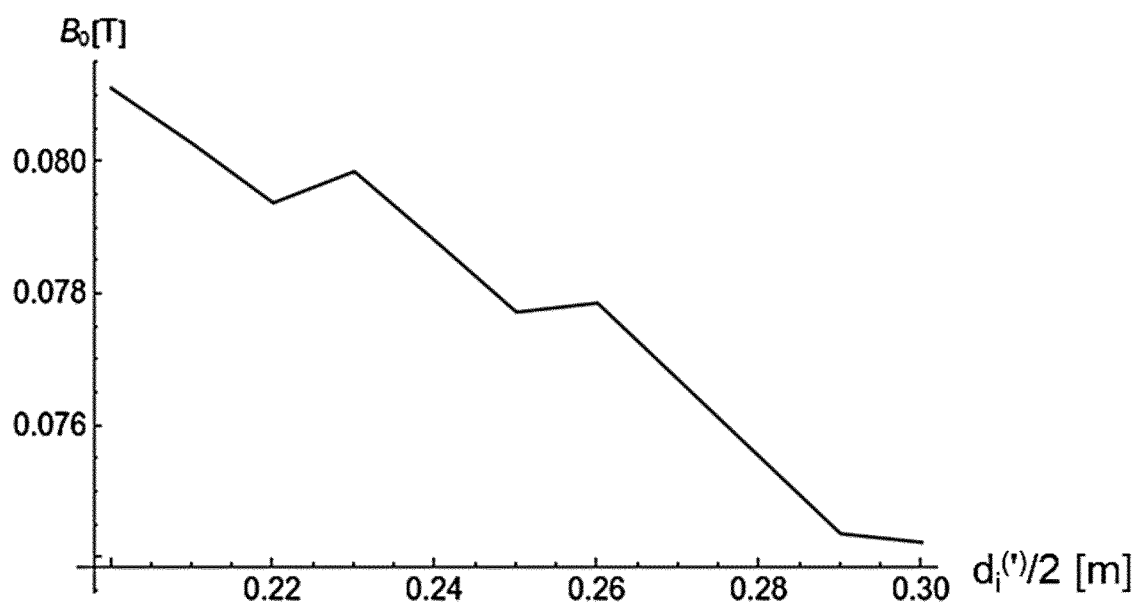


FIG. 5

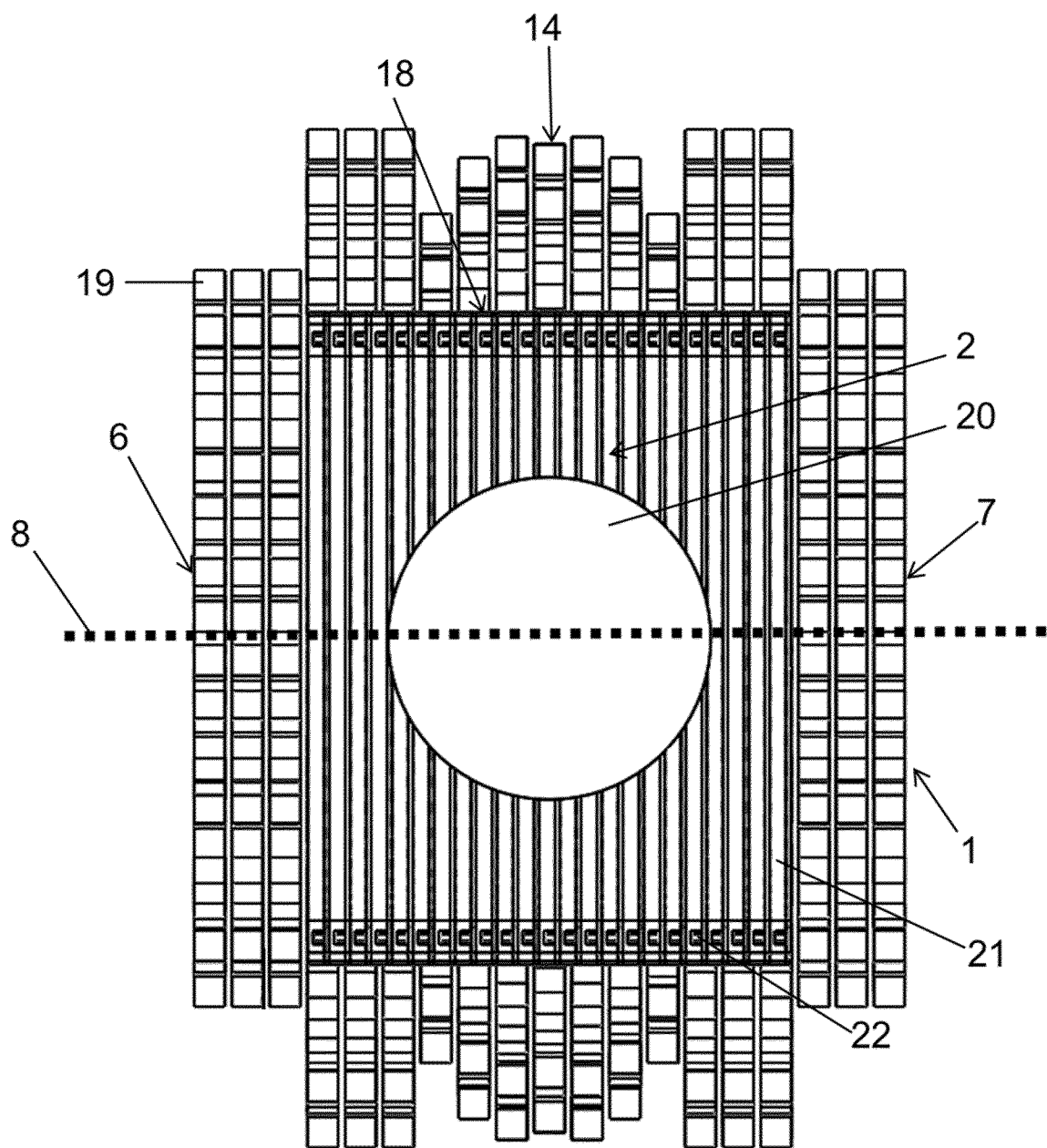


FIG. 6

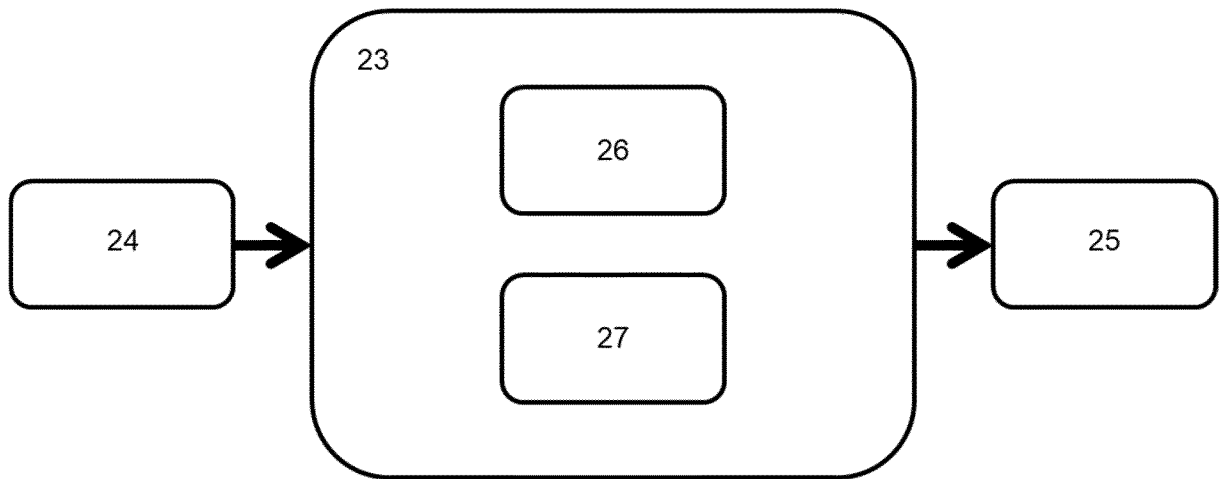


FIG. 7

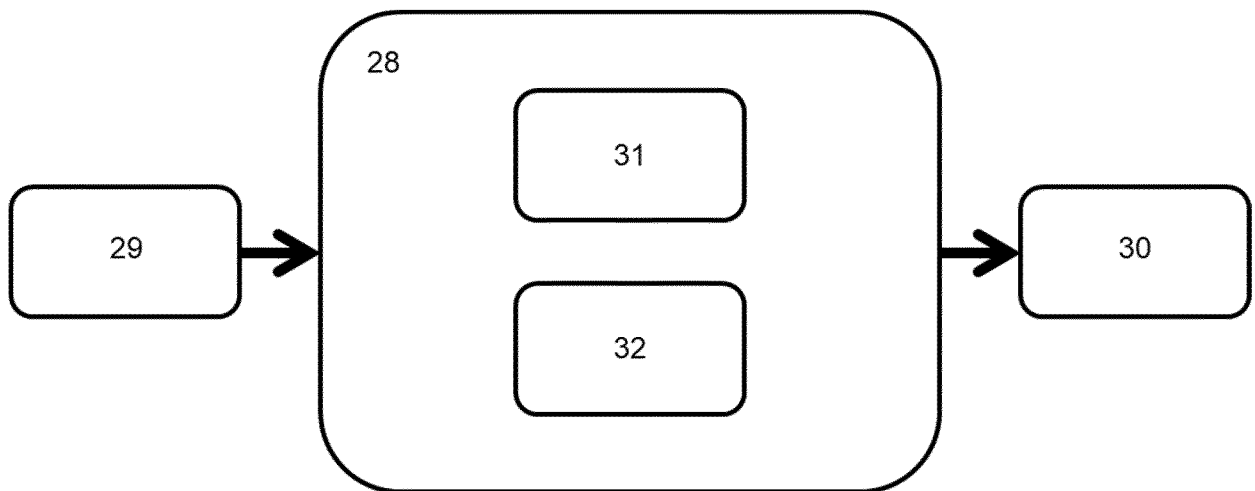
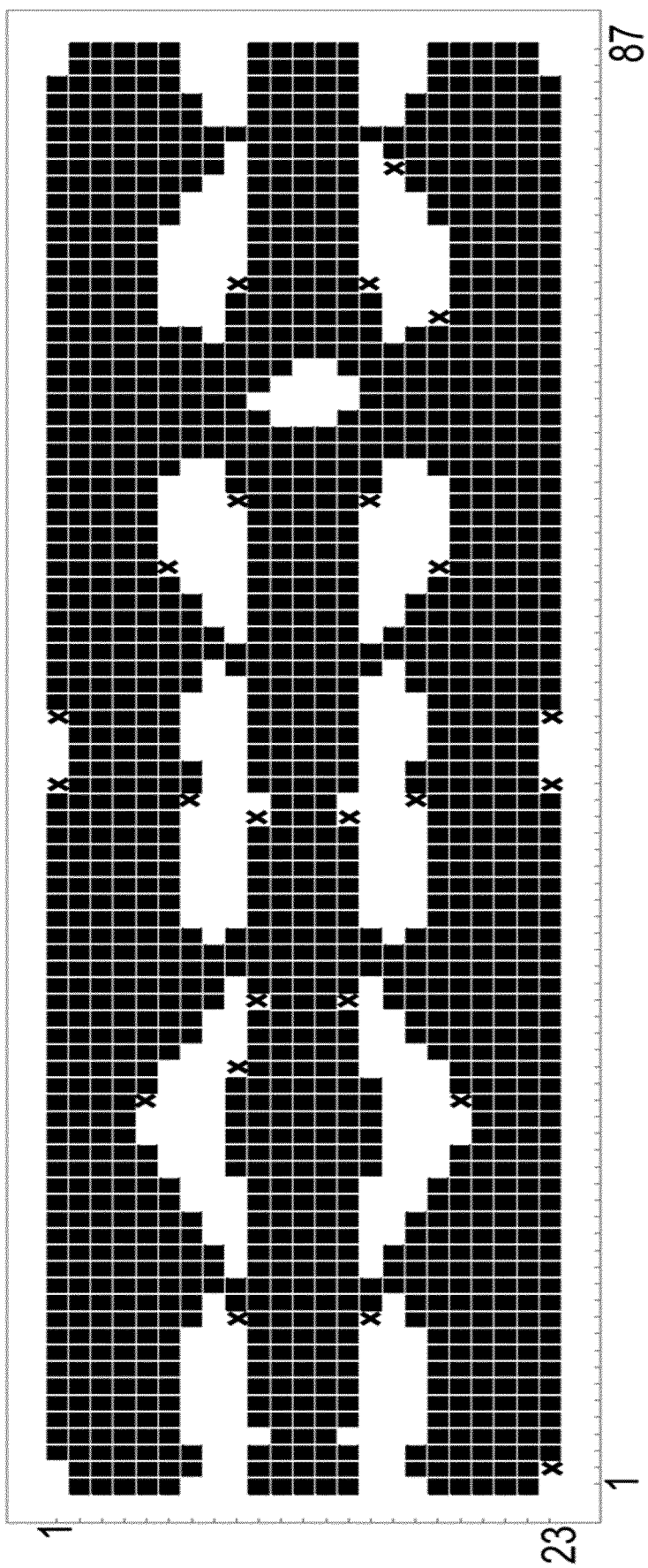


FIG. 8



INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2024/074964

A. CLASSIFICATION OF SUBJECT MATTER INV. G01R33/38 G01R33/383 G01R33/3873 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 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, IBM-TDB, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	FERNANDO GALVE ET AL: "Elliptical Halbach magnet and gradient modules for low-field portable MRI", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 12 March 2024 (2024-03-12), XP091698322, the whole document ----- -/-	1-17
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "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 "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 8 November 2024		Date of mailing of the international search report 20/11/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Streif, Jörg Ulrich

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/074964

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	GUALLART-NAVAL TERESA ET AL: "Benchmarking the performance of a low-cost magnetic resonance control system at multiple sites in the open MarCoS community", NMR IN BIOMEDICINE., vol. 36, no. 1, 29 September 2022 (2022-09-29), XP093222501, GB ISSN: 0952-3480, DOI: 10.1002/nbm.4825 section 2.2 figures 3, 4 -----	1 - 17
L	GUALLART-NAVAL TERESA ET AL: "Portable magnetic resonance imaging of patients indoors, outdoors and at home", SCIENTIFIC REPORTS, vol. 12, no. 1, 30 July 2022 (2022-07-30), XP093222505, US ISSN: 2045-2322, DOI: 10.1038/s41598-022-17472-w This document was cited in section 2.2.3 of the preceding document as reference (16) and completes the disclosure of the preceding document with respect to the portable MRI system referred to in section 2.2.3. section "Methods", subsection "Scanner" figure 1 -----	1 - 17
Y	CN 116 580 917 A (UNIV HONG KONG) 11 August 2023 (2023-08-11) figure 6 -----	1 - 17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2024/074964

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 116580917	A	11-08-2023	NONE
