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(54) **Title**: DYNAMIC BACKGROUND CORRECTION IN MPI

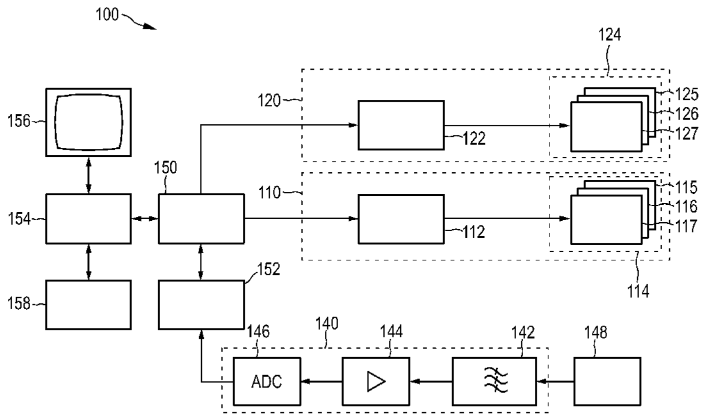

FIG. 5

(57) **Abstract**: The present invention relates to an apparatus (100) for detecting magnetic particles in a field of view (28), which apparatus comprises selection means, drive means, receiving means for acquiring detection signals, and reconstruction means (152) for reconstructing an image of the field of view (28) from detection signals. Said reconstruction means is adapted to identify in the detection signals one or more background time periods (tb1, tb2, tb3, tb4) at which no magnetic particles were present in the field of view (28), wherein signal time periods (ts1, ts2, ts1) at which magnetic particles were present in the field of view (28) are interspersed with at least one (tb2, tb3) of said one or more background time periods (tb1, tb2, tb3, tb4), using the detection signals obtained at said background time periods (tb1, tb2, tb3, tb4) to correct detection signals obtained at said signal time periods (ts1, ts2, ts1), and reconstructing the image from said corrected detection signals obtained at said signal time periods (ts1, ts2, ts1).

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DYNAMIC BACKGROUND CORRECTION IN MPI

FIELD OF THE INVENTION

The present invention relates to an apparatus and a method for detecting magnetic particles in a field of view which enable the removal of background signals. The present invention relates particularly to the field of magnetic particle imaging.

BACKGROUND OF THE INVENTION

Magnetic Particle Imaging (MPI) is an emerging medical imaging modality. The first versions of MPI were two-dimensional in that they produced two-dimensional images. Newer versions are three-dimensional (3D). A four-dimensional image of a non-static object can be created by combining a temporal sequence of 3D images to a movie, provided the object does not significantly change during the data acquisition for a single 3D image.

MPI is a reconstructive imaging method, like Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). Accordingly, an MP image of an object's volume of interest is generated in two steps. The first step, referred to as data acquisition, is performed using an MPI scanner. The MPI scanner has means to generate a static magnetic gradient field, called the "selection field", which has a (single) field-free point (FFP) or a field-free line (FFL) at the isocenter of the scanner. Moreover, this FFP (or the FFL; mentioning "FFP" in the following shall generally be understood as meaning FFP or FFL) is surrounded by a first sub-zone with a low magnetic field strength, which is in turn surrounded by a second sub-zone with a higher magnetic field strength. In addition, the scanner has means to generate a time-dependent, spatially nearly homogeneous magnetic field. Actually, this field is obtained by superposing a rapidly changing field with a small amplitude, called the "drive field", and a slowly varying field with a large amplitude, called the "focus field". By adding the time-dependent drive and focus fields to the static selection field, the FFP may be moved along a predetermined FFP trajectory throughout a "volume of scanning" surrounding the isocenter. The scanner also has an arrangement of one or more, e.g. three, receive coils and can record any voltages induced in these coils. For the data acquisition, the object to be imaged is placed in the scanner such that the object's volume of interest is enclosed by the scanner's field of view, which is a subset of the volume of scanning.

The object must contain magnetic nanoparticles or other magnetic non-linear materials; if the object is an animal or a patient, a contrast agent containing such particles is administered to the animal or patient prior to the scan. During the data acquisition, the MPI scanner moves the FFP along a deliberately chosen trajectory that traces out / covers the volume of scanning, or at least the field of view. The magnetic nanoparticles within the object experience a changing magnetic field and respond by changing their magnetization. The changing magnetization of the nanoparticles induces a time-dependent voltage in each of the receive coils. This voltage is sampled in a receiver associated with the receive coil. The samples output by the receivers are recorded and constitute the acquired data. The parameters that control the details of the data acquisition make up the “scan protocol”.

In the second step of the image generation, referred to as image reconstruction, the image is computed, or reconstructed, from the data acquired in the first step. The image is a discrete 3D array of data that represents a sampled approximation to the position-dependent concentration of the magnetic nanoparticles in the field of view. The reconstruction is generally performed by a computer, which executes a suitable computer program. Computer and computer program realize a reconstruction algorithm. The reconstruction algorithm is based on a mathematical model of the data acquisition. As with all reconstructive imaging methods, this model can be formulated as an integral operator that acts on the acquired data; the reconstruction algorithm tries to undo, to the extent possible, the action of the model.

Such an MPI apparatus and method have the advantage that they can be used to examine arbitrary examination objects – e.g. human bodies – in a non-destructive manner and with a high spatial resolution, both close to the surface and remote from the surface of the examination object. Such an apparatus and method are generally known and have been first described in DE 101 51 778 A1 and in Gleich, B. and Weizenecker, J. (2005), “Tomographic imaging using the nonlinear response of magnetic particles” in Nature, vol. 435, pp. 1214-1217, in which also the reconstruction principle is generally described. The apparatus and method for magnetic particle imaging (MPI) described in that publication take advantage of the non-linear magnetization curve of small magnetic particles.

Background signal variations and spurious signals, which occur both in MPI calibration scans and object scans, can strongly compromise image quality. Different sources of background signal exhibit different spectral behavior, so that background signal contributions are not homogeneously spread over the measured bandwidth, but vary in intensity and temporal pattern between different frequency components.

Further, the design of the MPI apparatus and methods described so far are not yet optimal for human beings.

In particular, background signals are either generated by scanner components (i.e. components of the MPI apparatus) or are coupled from the outside into the shielded cabin and then picked up by the detection system. To achieve good image quality, the signal background should be removed from the measured data. Time-constant components of the background can be easily subtracted using one background measurement. However, time-varying background components that change during an object or patient scan are hard to remove with existing strategies.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an apparatus and method for detecting magnetic particles in a field of view that enable the examination of such larger subjects (human beings, animals), in particular for adult human beings, and that allow the removal of background signals.

In a first aspect of the present invention an apparatus for influencing and/or detecting magnetic particles in a field of view is presented, which apparatus comprises:

- selection means comprising a selection field signal generator unit and selection field elements for generating a magnetic selection field having a pattern in space of its magnetic field strength such that a first sub-zone having a low magnetic field strength where the magnetization of the magnetic particles is not saturated and a second sub-zone having a higher magnetic field strength where the magnetization of the magnetic particles is saturated are formed in the field of view,
- drive means comprising a drive field signal generator unit and drive field coils for changing the position in space of the two sub-zones in the field of view by means of a magnetic drive field so that the magnetization of the magnetic material changes locally,
- receiving means comprising at least one signal receiving unit and at least one receiving coil for acquiring detection signals, which detection signals depend on the magnetization in the field of view, which magnetization is influenced by the change in the position in space of the first and second sub-zone, and
- reconstruction means for reconstructing an image of the field of view from detection signals, wherein said reconstruction means is adapted to

  - identify in the detection signals one or more background time periods (tb1, tb2, tb3, tb4) at which no magnetic particles were present in the field of view (28), wherein signal time periods at which magnetic particles were present in the field of view are interspersed with at least one of said one or more background time periods,

- using the detection signals obtained at said background time periods to correct detection signals obtained at said signal time periods, and

- reconstructing the image from said corrected detection signals obtained at said signal time periods.

In another aspect of the present invention an apparatus for influencing and/or detecting magnetic particles in a field of view is presented, which apparatus comprises:

i) selection-and-focus means for generating a magnetic selection-and-focus field having a pattern in space of its magnetic field strength such that a first sub-zone having a low magnetic field strength where the magnetization of the magnetic particles is not saturated and a second sub-zone having a higher magnetic field strength where the magnetization of the magnetic particles is saturated are formed in the field of view and for changing the position in space of the field of view within an examination area, said selection-and-focus means comprising at least one set of selection-and-focus field coils, and a selection-and-focus field generator unit for generating selection-and-focus field currents to be provided to said at least one set of selection-and-focus field coils for controlling the generation of said magnetic selection-and-focus field,

wherein said at least one set of selection-and-focus field coils comprises

- at least one inner selection-and-focus field coil being formed as a closed loop about an inner coil axis, and

- a group of at least two outer selection-and-focus field coils arranged at a larger distance from said inner coil axis than said at least one inner selection-and-focus field coil and at different angular positions, each being formed as a closed loop about an associated outer coil axis, and

ii) drive means comprising a drive field signal generator unit and drive field coils for changing the position in space and/or size of the two sub-zones in the field of view by means of a magnetic drive field so that the magnetization of the magnetic material changes locally,

ii) receiving means comprising at least one signal receiving unit and at least one receiving coil for acquiring detection signals, which detection signals depend on the magnetization in the field of view, which magnetization is influenced by the change in the position in space of the first and second sub-zone, and

iv) reconstruction means for reconstructing an image of the field of view from detection signals, wherein said reconstruction means is adapted to

- identify in the detection signals one or more background time periods (tb1, tb2, tb3, tb4) at which no magnetic particles were present in the field of view (28), wherein signal time periods at which magnetic particles were present in the field of view are interspersed with at least one of said one or more background time periods,

- using the detection signals obtained at said background time periods to correct detection signals obtained at said signal time periods, and

- reconstructing the image from said corrected detection signals obtained at said signal time periods.

In an embodiment a computer program is presented comprising program code means for causing a computer to control an apparatus according to the present invention to carry out the steps of the method according to the present invention when said computer program is carried out on the computer.

Preferred embodiments of the invention are defined in the dependent claims. It shall be understood that the claimed method and computer program have similar and/or identical preferred embodiments as the claimed coil arrangement and as defined in the dependent claims.

The present invention aims to obtain pure background spectra at several points in time during an object or patient scan. To this end, time periods are identified during which no tracer material (i.e. the magnetic particles or a material containing magnetic particles) is present in the field of view (i.e. the imaging volume, from which detection signals are obtained and for which an image shall be reconstructed) and which thus represent the pure background signal. The spectrum of harmonics acquired during one repetition of the field-free-point trajectory, i.e. the trajectory along which the first sub-zone is moved, is a useful tool to discriminate between signal changes which are due to variations in the signal background and those changes which are due to tracer material entering the imaging volume.

Time-varying components that change slowly and rather linearly can generally be removed by using two background measurements, one before and one after the object scan. Using a linear interpolation between the two measurements data suitable for background subtraction can be generated. However, if the background signal changes in more complex ways (e.g. jumps, non-monotonic variations, etc.), the linear two-point interpolation fails. It is therefore proposed to obtain several background measurements interspersed with an object measurement.

The present invention thus suggests identification of time periods during which no tracer is detected by analysis of one or more frequency components of the signal spectrum. These time periods occur when the object or patient is in the scanner, but no tracer material is yet injected into the object or patient, or when the object or the imaging volume is moved such that no tracer is in the active imaging volume. During these time periods, the signal directly represents the background signal and can be used for background removal.

This approach has the advantage that generally a number of background measurements are available that are temporally very close to the object measurements, thus enabling the best possible background correction. Since the background sometimes changes abruptly in the middle of a scan, an approach that uses a linear interpolation between background scans before and after the object scan often fails, while the proposed approach leads to much more accurate results.

In a preferred embodiment focus fields are used to move the imaging volume after a fixed time interval to a region where no tracer material is located and only background signal is detected. This however requires brief interruptions of the scan.

In a more flexible embodiment the signal is monitored at different harmonics in order to identify time periods during which no tracer material is in the imaging volume. These time periods can then be used as additional background measurements, yielding more points for the background interpolation. As a side effect, using this information long time periods where no tracer is in the imaging volume can be discarded and thus save storage space and reconstruction time.

As mentioned above, in an embodiment said reconstruction means is adapted to identify in the detection signals said one or more background time periods by analyzing one or more frequency components over time. Preferably, one or more frequency components which are harmonics or mix frequencies of harmonics of drive field frequencies of the magnetic drive field are analyzed for this purpose since those harmonics do most likely show changes if magnetic particles enter the field of view.

In another embodiment changes in said one or more frequency components and/or in one or more derived functions that are derived from said one or more frequency components are identified which changes are used as an indicator that from that moment on magnetic particles are present in the field of view or are no longer present in the field of view, respectively. It is preferably identified if and when changes of the amplitude exist in said one or more frequency components and/or in one or more derived functions that are derived from said one or more frequency components.

In still another embodiment detection signals obtained at said background time periods are removed or subtracted, per frequency component, from detection signals obtained at said signal time periods. In this way a good correction of the detection signal is achieved.

In an embodiment it is preferred to calculate, per frequency component, an interpolated or average background signal and to subtract said interpolated or average background signal from the detection signals obtained at said signal time periods. A further improvement of background signal correction, which may be used for real time signal correction, can be achieved by an embodiment according to which a background signal or average thereof is calculated per frequency component and per background time period and said background signal or average thereof is subtracted from the detection signals obtained at neighboring signal time periods. In the real-time scenario, the background measurement is not yet available after the object signal window, so that the previous (possibly averaged) background value is used.

Preferably, said reconstruction means is adapted to correlate said identified changes with additional information indicating when and/or where in the field of view magnetic particles are present. This provides for a further improvement of the background signal detection. Said additional information, for instance, indicates the time when magnetic particles have been introduced into an object present in the field of view and/or the positional relationship between the object and the field of view.

The preferably proposed MPI apparatus employing combined selection-and-focus field coils is based on the idea to combine the focus field coils and the selection field coils that are generally provided as separate coils in the known MPI apparatus into a combined set of selection-and-focus field coils. Hence, a single current is provided to each of said coils rather than separate currents as conventionally provided to each focus field coil and each selection field coil. The single currents can thus be regarded as two superposed currents for focus field generation and selection field generation. The desired location and movement of the field of view within the examination area can be easily changed by controlling the currents to the various coils. Not all selection-and-focus field coils must, however, always be provided with control currents, but some coils are only needed for certain movements of the field of view.

The proposed apparatus further provides more freedom of how and where to arrange the coils with respect to the examination area in which the subject is place. It is particularly possible with this arrangement to build an open scanner that is easily accessible both by the patient and by doctors or medical personnel, e.g. a surgeon during an intervention.

With such an apparatus the magnetic gradient field (i.e. the magnetic selection field) is generated with a spatial distribution of the magnetic field strength such that the field of view comprises a first sub-area with lower magnetic field strength (e.g. the FFP), the lower magnetic field strength being adapted such that the magnetization of the magnetic particles located in the first sub-area is not saturated, and a second sub-area with a higher magnetic field strength, the higher magnetic field strength being adapted such that the magnetization of the magnetic particles located in the second sub-area is saturated. Due to the non-linearity of the magnetization characteristic curve of the magnetic particles the magnetization and thereby the magnetic field generated by the magnetic particles shows higher harmonics, which, for example, can be detected by a detection coil. The evaluated signals (the higher harmonics of the signals) contain information about the spatial distribution of the magnetic particles, which again can be used e.g. for medical imaging, for the visualization of the spatial distribution of the magnetic particles and/or for other applications.

The MPI apparatus according to the present invention are based on a new physical principle (i.e. the principle referred to as MPI) that is different from other known conventional medical imaging techniques, as for example nuclear magnetic resonance (NMR). In particular, this new MPI-principle, does, in contrast to NMR, not exploit the influence of the material on the magnetic resonance characteristics of protons, but rather directly detects the magnetization of the magnetic material by exploiting the non-linearity of the magnetization characteristic curve. In particular, the MPI-technique exploits the higher harmonics of the generated magnetic signals which result from the non-linearity of the magnetization characteristic curve in the area where the magnetization changes from the non-saturated to the saturated state.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiment(s) described hereinafter. In the following drawings

Fig. 1 shows a first embodiment of an MPI apparatus,

Fig. 2 shows an example of the selection field pattern produced by an apparatus as shown in Fig. 1,

Fig. 3 shows a second embodiment of an MPI apparatus,

Fig. 4 shows a third and a fourth embodiment of an MPI apparatus,

Fig. 5 shows a block diagram of an MPI apparatus according to the present invention,

Fig. 6 shows two perpendicular cross sections through an embodiment of a selection-and-focus field coil arrangement for the third and fourth embodiments of the MPI apparatus,

Fig. 7 shows two perpendicular cross sections through an embodiment of a pole shoe arrangement for the third and fourth embodiments of the MPI apparatus,

Fig. 8 shows a perspective view of the embodiment of a pole shoe arrangement shown in Fig. 7,

Fig. 9 shows two perpendicular cross sections through an embodiment of a selection-and-focus field coil arrangement for the third and fourth embodiments of the MPI apparatus,

Fig. 10 shows an enlarged of one of the cross sections through an embodiment of one set of selection-and-focus field coils of the selection-and-focus field coil arrangement shown in Fig. 9,

Fig. 11 illustrates background signal measurements according to a preferred embodiment, and

Fig. 12 illustrates background interpolation, smoothing and correction.

DETAILED DESCRIPTION OF THE INVENTION

Before the details of the present invention shall be explained, basics of magnetic particle imaging shall be explained in detail with reference to Figs. 1 to 4. In particular, four embodiments of an MPI scanner for medical diagnostics will be described. An informal description of the data acquisition will also be given. The similarities and differences between the different embodiments will be pointed out. Generally, the present invention can be used in all these different embodiments of an MPI apparatus.

The first embodiment 10 of an MPI scanner shown in Fig. 1 has three pairs 12, 14, 16 of coaxial parallel circular coils, these coil pairs being arranged as illustrated in Fig. 1. These coil pairs 12, 14, 16 serve to generate the selection field as well as the drive and focus fields. The axes 18, 20, 22 of the three coil pairs 12, 14, 16 are mutually orthogonal and meet in a single point, designated the isocenter 24 of the MPI scanner 10. In addition, these axes 18, 20, 22 serve as the axes of a 3D Cartesian x-y-z coordinate system attached to the isocenter 24. The vertical axis 20 is nominated the y-axis, so that the x- and z-axes are horizontal. The coil pairs 12, 14, 16 are named after their axes. For example, the y-coil pair

14 is formed by the coils at the top and the bottom of the scanner. Moreover, the coil with the positive (negative) y-coordinate is called the y^+-coil (y^--coil), and similarly for the remaining coils. When more convenient, the coordinate axes and the coils shall be labelled with x_1, x_2, and x_3, rather than with x, y, and z.

The scanner 10 can be set to direct a predetermined, time-dependent electric current through each of these coils 12, 14, 16, and in either direction. If the current flows clockwise around a coil when seen along this coil's axis, it will be taken as positive, otherwise as negative. To generate the static selection field, a constant positive current I^S is made to flow through the z^+-coil, and the current $-I^S$ is made to flow through the z^--coil. The z-coil pair 16 then acts as an anti-parallel circular coil pair.

It should be noted here that the arrangement of the axes and the nomenclature given to the axes in this embodiment is just an example and might also be different in other embodiments. For instance, in practical embodiments the vertical axis is often considered as the z-axis rather than the y-axis as in the present embodiment. This, however, does not generally change the function and operation of the device and the effect of the present invention.

The magnetic selection field, which is generally a magnetic gradient field, is represented in Fig. 2 by the field lines 50. It has a substantially constant gradient in the direction of the (e.g. horizontal) z-axis 22 of the z-coil pair 16 generating the selection field and reaches the value zero in the isocenter 24 on this axis 22. Starting from this field-free point (not individually shown in Fig. 2), the field strength of the magnetic selection field 50 increases in all three spatial directions as the distance increases from the field-free point. In a first sub-zone or region 52 which is denoted by a dashed line around the isocenter 24 the field strength is so small that the magnetization of particles present in that first sub-zone 52 is not saturated, whereas the magnetization of particles present in a second sub-zone 54 (outside the region 52) is in a state of saturation. In the second sub-zone 54 (i.e. in the residual part of the scanner's field of view 28 outside of the first sub-zone 52) the magnetic field strength of the selection field is sufficiently strong to keep the magnetic particles in a state of saturation.

By changing the position of the two sub-zones 52, 54 (including the field-free point) within the field of view 28 the (overall) magnetization in the field of view 28 changes. By determining the magnetization in the field of view 28 or physical parameters influenced by the magnetization, information about the spatial distribution of the magnetic particles in the field of view 28 can be obtained. In order to change the relative spatial position of the two sub-zones 52, 54 (including the field-free point) in the field of view 28, further magnetic fields, i.e. the magnetic drive field, and, if applicable, the magnetic focus field, are superposed to the selection field 50.

To generate the drive field, a time dependent current $I^D{}_1$ is made to flow through both x-coils 12, a time dependent current $I^D{}_2$ through both y-coils 14, and a time dependent current $I^D{}_3$ through both z-coils 16. Thus, each of the three coil pairs acts as a parallel circular coil pair. Similarly, to generate the focus field, a time dependent current $I^F{}_1$ is made to flow through both x-coils 12, a current $I^F{}_2$ through both y-coils 14, and a current $I^F{}_3$ through both z-coils 16.

It should be noted that the z-coil pair 16 is special: It generates not only its share of the drive and focus fields, but also the selection field (of course, in other embodiments, separate coils may be provided). The current flowing through the $z^{\pm}$-coil is $I^D{}_3 + I^F{}_3 \pm I^S$. The current flowing through the remaining two coil pairs 12, 14 is $I^D{}_k + I^F{}_k$, $k = 1, 2$. Because of their geometry and symmetry, the three coil pairs 12, 14, 16 are well decoupled. This is wanted.

Being generated by an anti-parallel circular coil pair, the selection field is rotationally symmetric about the z-axis, and its z-component is nearly linear in z and independent of x and y in a sizeable volume around the isocenter 24. In particular, the selection field has a single field-free point (FFP) at the isocenter. In contrast, the contributions to the drive and focus fields, which are generated by parallel circular coil pairs, are spatially nearly homogeneous in a sizeable volume around the isocenter 24 and parallel to the axis of the respective coil pair. The drive and focus fields jointly generated by all three parallel circular coil pairs are spatially nearly homogeneous and can be given any direction and strength, up to some maximum strength. The drive and focus fields are also time-dependent. The difference between the focus field and the drive field is that the focus field varies slowly in time and may have a large amplitude, while the drive field varies rapidly and has a small amplitude. There are physical and biomedical reasons to treat these fields differently. A rapidly varying field with a large amplitude would be difficult to generate and potentially hazardous to a patient.

In a practical embodiment the FFP can be considered as a mathematical point, at which the magnetic field is assumed to be zero. The magnetic field strength increases with increasing distance from the FFP, wherein the increase rate might be different for different directions (depending e.g. on the particular layout of the device). As long as the magnetic field strength is below the field strength required for bringing magnetic particles into the state of saturation, the particle actively contributes to the signal generation of the signal measured by the device; otherwise, the particles are saturated and do not generate any signal.

The embodiment 10 of the MPI scanner has at least one further pair, preferably three further pairs, of parallel circular coils, again oriented along the x-, y-, and z-axes. These coil pairs, which are not shown in Fig. 1, serve as receive coils. As with the coil pairs 12, 14, 16 for the drive and focus fields, the magnetic field generated by a constant current flowing through one of these receive coil pairs is spatially nearly homogeneous within the field of view and parallel to the axis of the respective coil pair. The receive coils are supposed to be well decoupled. The time-dependent voltage induced in a receive coil is amplified and sampled by a receiver attached to this coil. More precisely, to cope with the enormous dynamic range of this signal, the receiver samples the difference between the received signal and a reference signal. The transfer function of the receiver is non-zero from zero Hertz ("DC") up to the frequency where the expected signal level drops below the noise level. Alternatively, the MPI scanner has no dedicated receive coils. Instead the drive field transmit coils are used as receive coils.

The embodiment 10 of the MPI scanner shown in Fig. 1 has a cylindrical bore 26 along the z-axis 22, i.e. along the axis of the selection field. All coils are placed outside this bore 26. For the data acquisition, the patient (or object) to be imaged is placed in the bore 26 such that the patient's volume of interest – that volume of the patient (or object) that shall be imaged – is enclosed by the scanner's field of view 28 – that volume of the scanner whose contents the scanner can image. The patient (or object) is, for instance, placed on a patient table. The field of view 28 is a geometrically simple, isocentric volume in the interior of the bore 26, such as a cube, a ball, a cylinder or an arbitrary shape. A cubical field of view 28 is illustrated in Fig. 1.

The size of the first sub-zone 52 is dependent on the strength of the gradient of the magnetic selection field and on the field strength of the magnetic field required for saturation, which in turn depends on the magnetic particles. For a sufficient saturation of typical magnetic particles at a magnetic field strength of 80 A/m and a gradient (in a given space direction) of the field strength of the magnetic selection field amounting to 50×10^3 A/m^2, the first sub-zone 52 in which the magnetization of the particles is not saturated has dimensions of about 1 mm (in the given space direction).

The patient's volume of interest is supposed to contain magnetic nanoparticles. Prior to the diagnostic imaging of, for example, a tumor, the magnetic particles are brought to the volume of interest, e.g. by means of a liquid comprising the magnetic particles which is injected into the body of the patient (object) or otherwise administered, e.g. orally, to the patient.

Generally, various ways for bringing the magnetic particles into the field of view exist. In particular, in case of a patient into whose body the magnetic particles are to be introduced, the magnetic particles can be administered by use of surgical and non-surgical methods, and there are both methods which require an expert (like a medical practitioner) and methods which do not require an expert, e.g. can be carried out by laypersons or persons of ordinary skill or the patient himself / herself. Among the surgical methods there are potentially non-risky and/or safe routine interventions, e.g. involving an invasive step like an injection of a contrast agent into a blood vessel (if such an injection is at all to be considered as a surgical method), i.e. interventions which do not require considerable professional medical expertise to be carried out and which do not involve serious health risks. Further, non-surgical methods like swallowing or inhalation can be applied.

Generally, the magnetic particles are pre-delivered or pre-administered before the actual steps of data acquisition are carried out. In embodiments, it is, however, also possible that further magnetic particles are delivered / administered into the field of view.

An embodiment of magnetic particles comprises, for example, a spherical substrate, for example, of glass which is provided with a soft-magnetic layer which has a thickness of, for example, 5 nm and consists, for example, of an iron-nickel alloy (for example, Permalloy). This layer may be covered, for example, by means of a coating layer which protects the particle against chemically and/or physically aggressive environments, e.g. acids. The magnetic field strength of the magnetic selection field 50 required for the saturation of the magnetization of such particles is dependent on various parameters, e.g. the diameter of the particles, the used magnetic material for the magnetic layer and other parameters.

In the case of e.g. a diameter of 10 μm with such magnetic particles, a magnetic field of approximately 800 A/m (corresponding approximately to a flux density of 1 mT) is then required, whereas in the case of a diameter of 100 μm a magnetic field of 80 A/m suffices. Even smaller values are obtained when a coating of a material having a lower saturation magnetization is chosen or when the thickness of the layer is reduced.

In practice, magnetic particles commercially available under the trade name Resovist (or similar magnetic particles) are often used, which have a core of magnetic material or are formed as a massive sphere and which have a diameter in the range of nanometers, e.g. 40 or 60 nm.

For further details of the generally usable magnetic particles and particle compositions, the corresponding parts of EP 1304542, WO 2004/091386, WO 2004/091390, WO 2004/091394, WO 2004/091395, WO 2004/091396, WO 2004/091397, WO 2004/091398, WO 2004/091408 are herewith referred to, which are herein incorporated by reference. In these documents more details of the MPI method in general can be found as well.

During the data acquisition, the x-, y-, and z-coil pairs 12, 14, 16 generate a position- and time-dependent magnetic field, the applied field. This is achieved by directing suitable currents through the field generating coils. In effect, the drive and focus fields push the selection field around such that the FFP moves along a preselected FFP trajectory that traces out the volume of scanning – a superset of the field of view. The applied field orientates the magnetic nanoparticles in the patient. As the applied field changes, the resulting magnetization changes too, though it responds nonlinearly to the applied field. The sum of the changing applied field and the changing magnetization induces a time-dependent voltage V_k across the terminals of the receive coil pair along the x_k-axis. The associated receiver converts this voltage to a signal S_k, which it processes further.

Like the first embodiment 10 shown in Fig. 1, the second embodiment 30 of the MPI scanner shown in Fig. 3 has three circular and mutually orthogonal coil pairs 32, 34, 36, but these coil pairs 32, 34, 36 generate the selection field and the focus field only. The z-coils 36, which again generate the selection field, are filled with ferromagnetic material 37. The z-axis 42 of this embodiment 30 is oriented vertically, while the x- and y-axes 38, 40 are oriented horizontally. The bore 46 of the scanner is parallel to the x-axis 38 and, thus, perpendicular to the axis 42 of the selection field. The drive field is generated by a solenoid (not shown) along the x-axis 38 and by pairs of saddle coils (not shown) along the two remaining axes 40, 42. These coils are wound around a tube which forms the bore. The drive field coils also serve as receive coils.

To give a few typical parameters of such an embodiment: The z-gradient of the selection field, G, has a strength of $G/\mu_0 = 2.5$ T/m, where μ_0 is the vacuum permeability. The temporal frequency spectrum of the drive field is concentrated in a narrow band around 25 kHz (up to approximately 150 kHz). The useful frequency spectrum of the received signals lies between 50 kHz and 1 MHz (eventually up to approximately 15 MHz). The bore has a diameter of 120 mm. The biggest cube 28 that fits into the bore 46 has an edge length of 120 mm/$\sqrt{2} \approx$ 84 mm.

Since the construction of field generating coils is generally known in the art, e.g. from the field of magnetic resonance imaging, this subject need not be further elaborated herein.

In an alternative embodiment for the generation of the selection field, permanent magnets (not shown) can be used. In the space between two poles of such (opposing) permanent magnets (not shown) there is formed a magnetic field which is similar to that shown in Fig. 2, that is, when the opposing poles have the same polarity. In another alternative embodiment, the selection field can be generated by a mixture of at least one permanent magnet and at least one coil.

Fig. 4 shows two embodiments of the general outer layout of an MPI apparatus 200, 300. Fig. 4A shows an embodiment of the proposed MPI apparatus 200 comprising two selection-and-focus field coil units 210, 220 which are basically identical and arranged on opposite sides of the examination area 230 formed between them. Further, a drive field coil unit 240 is arranged between the selection-and-focus field coil units 210, 220, which are placed around the area of interest of the patient (not shown). The selection-and-focus field coil units 210, 220 comprise several selection-and-focus field coils for generating a combined magnetic field representing the above-explained magnetic selection field and magnetic focus field. In particular, each selection-and-focus field coil unit 210, 220 comprises a, preferably identical, set of selection-and-focus field coils. Details of said selection-and-focus field coils will be explained below.

The drive field coil unit 240 comprises a number of drive field coils for generating a magnetic drive field. These drive field coils may comprise several pairs of drive field coils, in particular one pair of drive field coils for generating a magnetic field in each of the three directions in space. In an embodiment the drive field coil unit 240 comprises two pairs of saddle coils for two different directions in space and one solenoid coil for generating a magnetic field in the longitudinal axis of the patient.

The selection-and-focus field coil units 210, 220 are generally mounted to a holding unit (not shown) or the wall of room. Preferably, in case the selection-and-focus field coil units 210, 220 comprise pole shoes for carrying the respective coils, the holding unit does not only mechanically hold the selection-and-focus field coil unit 210, 220 but also provides a path for the magnetic flux that connects the pole shoes of the two selection-and-focus field coil units 210, 220.

As shown in Fig. 4a, the two selection-and-focus field coil units 210, 220 each include a shielding layer 211, 221 for shielding the selection-and-focus field coils from magnetic fields generated by the drive field coils of the drive field coil unit 240.

In the embodiment of the MPI apparatus 201 shown in Fig. 4B only a single selection-and-focus field coil unit 220 is provided as well as the drive field coil unit 240. Generally, a single selection-and-focus field coil unit is sufficient for generating the required combined magnetic selection and focus field. Said single selection-and-focus field coil unit 220 may thus be integrated into a (not shown) patient table on which a patient is placed for the examination. Preferably, the drive field coils of the drive field coil unit 240 may be arranged around the patient's body already in advance, e.g. as flexible coil elements. In another implementation, the drive field coil unit 240 can be opened, e.g. separable into two subunits 241, 242 as indicated by the separation lines 243, 244 shown in Fig. 4b in axial direction, so that the patient can be placed in between and the drive field coil subunits 241, 242 can then be coupled together.

In still further embodiments of the MPI apparatus, even more selection-and-focus field coil units may be provided which are preferably arranged according to a uniform distribution around the examination area 230. However, the more selection-and-focus field coil units are used, the more will the accessibility of the examination area for placing a patient therein and for accessing the patient itself during an examination by medical assistance or doctors be limited.

Fig. 5 shows a general block diagram of an MPI apparatus 100 according to the present invention. The general principles of magnetic particle imaging explained above are valid and applicable to this embodiment as well, unless otherwise specified.

The embodiment of the apparatus 100 shown in Fig. 5 comprises various coils for generating the desired magnetic fields. First, the coils and their functions in MPI shall be explained.

For generating the combined magnetic selection-and-focus field, selection-and-focus means 110 are provided. The magnetic selection-and-focus field has a pattern in space of its magnetic field strength such that the first sub-zone (52 in Fig. 2) having a low magnetic field strength where the magnetization of the magnetic particles is not saturated and a second sub-zone (54 in Fig. 4) having a higher magnetic field strength where the magnetization of the magnetic particles is saturated are formed in the field of view 28, which is a small part of the examination area 230, which is conventionally achieved by use of the magnetic selection field. Further, by use the magnetic selection-and-focus field the position in space of the field of view 28 within the examination area 230 can be changed, as conventionally done by use of the magnetic focus field.

The selection-and-focus means 110 comprises at least one set of selection-and-focus field coils 114 and a selection-and-focus field generator unit 112 for generating selection-and-focus field currents to be provided to said at least one set of selection-and-focus field coils 114 (representing one of the selection-and-focus field coil units 210, 220 shown in Figs. 4A, 4B) for controlling the generation of said magnetic selection-and-focus field. Preferably, a separate generator subunit is provided for each coil element (or each pair of coil elements) of the at least one set of selection-and-focus field coils 114. Said selection-and-focus field generator unit 112 comprises a controllable current source (generally including an amplifier) and a filter unit which provide the respective coil element with the field current to individually set the gradient strength and field strength of the contribution of each coil to the magnetic selection-and-focus field. It shall be noted that the filter unit 114 can also be omitted.

For generating the magnetic drive field the apparatus 100 further comprises drive means 120 comprising a drive field signal generator unit 122 and a set of drive field coils 124 (representing the drive coil unit 240 shown in Figs. 4A, 4B) for changing the position in space and/or size of the two sub-zones in the field of view by means of a magnetic drive field so that the magnetization of the magnetic material changes locally. As mentioned above said drive field coils 124 preferably comprise two pairs 125, 126 of oppositely arranged saddle coils and one solenoid coil 127. Other implementations, e.g. three pairs of coil elements, are also possible.

The drive field signal generator unit 122 preferably comprises a separate drive field signal generation subunit for each coil element (or at least each pair of coil elements) of said set of drive field coils 124. Said drive field signal generator unit 122 preferably comprises a drive field current source (preferably including a current amplifier) and a filter unit (which may also be omitted with the present invention) for providing a time-dependent drive field current to the respective drive field coil.

The selection-and-focus field signal generator unit 112 and the drive field signal generator unit 122 are preferably controlled by a control unit 150, which preferably controls the selection-and-focus field signal generator unit 112 such that the sum of the field strengths and the sum of the gradient strengths of all spatial points of the selection field is set at a predefined level. For this purpose the control unit 150 can also be provided with control instructions by a user according to the desired application of the MPI apparatus, which, however, is preferably omitted according to the present invention.

For using the MPI apparatus 100 for determining the spatial distribution of the magnetic particles in the examination area (or a region of interest in the examination area), particularly to obtain images of said region of interest, signal detection receiving means 148, in particular a receiving coil, and a signal receiving unit 140, which receives signals detected by said receiving means 148, are provided. Preferably, three receiving coils 148 and three receiving units 140 – one per receiving coil – are provided in practice, but more than three receiving coils and receiving units can be also used, in which case the acquired detection signals are not 3-dimensional but K-dimensional, with K being the number of receiving coils.

Said signal receiving unit 140 comprises a filter unit 142 for filtering the received detection signals. The aim of this filtering is to separate measured values, which are caused by the magnetization in the examination area which is influenced by the change in position of the two part-regions (52, 54), from other, interfering signals. To this end, the filter unit 142 may be designed for example such that signals which have temporal frequencies that are smaller than the temporal frequencies with which the receiving coil 148 is operated, or smaller than twice these temporal frequencies, do not pass the filter unit 142. The signals are then transmitted via an amplifier unit 144 to an analog/digital converter 146 (ADC).

The digitalized signals produced by the analog/digital converter 146 are fed to an image processing unit (also called reconstruction means) 152, which reconstructs the spatial distribution of the magnetic particles from these signals and the respective position which the first part-region 52 of the first magnetic field in the examination area assumed during receipt of the respective signal and which the image processing unit 152 obtains from the control unit 150. The reconstructed spatial distribution of the magnetic particles is finally transmitted via the control means 150 to a computer 154, which displays it on a monitor 156. Thus, an image can be displayed showing the distribution of magnetic particles in the field of view of the examination area.

In other applications of the MPI apparatus 100, e.g. for influencing the magnetic particles (for instance for a hyperthermia treatment) or for moving the magnetic particles (e.g. attached to a catheter for moving the catheter or attached to a medicament for moving the medicament to a certain location) the receiving means may also be omitted or simply not used.

Further, an input unit 158 may optionally be provided, for example a keyboard. A user may therefore be able to set the desired direction of the highest resolution and in turn receives the respective image of the region of action on the monitor 156. If the critical direction, in which the highest resolution is needed, deviates from the direction set first by the user, the user can still vary the direction manually in order to produce a further image with an improved imaging resolution. This resolution improvement process can also be operated automatically by the control unit 150 and the computer 154. The control unit 150 in this embodiment sets the gradient field in a first direction which is automatically estimated or set as start value by the user. The direction of the gradient field is then varied stepwise until the resolution of the thereby received images, which are compared by the computer 154, is maximal, respectively not improved anymore. The most critical direction can therefore be found respectively adapted automatically in order to receive the highest possible resolution.

While generally selection field coils and focus field coils are implemented as separate elements according to the present invention, according to a preferred embodiment of the present invention said selection-and-focus field coils 114 comprise at least one inner selection-and-focus field coil 115 being formed as a closed loop about an inner coil axis 115a, and a group of at least two outer selection-and-focus field coils 116, 117 arranged at a larger distance from said inner coil axis 115a than said at least one inner selection-and-focus field coil 115 and at different angular positions, each being formed as a closed loop about an associated outer coil axis 116a, 117a as shown in Figs. 6A and 6B showing perpendicular cross sections. Preferably, two additional outer selection-and-focus field coils 118, 119, each being formed as a closed loop about an associated outer coil axis 118a, 119a are provided as indicated by the dashed lines in Fig. 6B.

It is generally possible according to the present invention that the selection-and-focus field means only comprises various coils as shown in Fig. 6. However, it is preferred according to the present invention that the selection-and-focus field means are a combination of magnetic material in the form of one or more pole shoes, particularly soft-magnetic material, and electromagnetic coils. The at least one pole shoe serves for conducting the magnetic flux and, thus, for increasing the generation of the required magnetic fields.

An embodiment of a pole shoe arrangement is shown in Figs. 7 and 8, wherein Figs. 7A and 7B show two perpendicular cross sections through the pole shoe arrangement 300 and Fig. 8 shows a perspective view of the pole shoe arrangement 300. In this embodiment of the pole shoe arrangement 300 two pole shoes 310, 320 are provided which are connected via a pole shoe bearing 330 mechanically carrying and magnetically coupling the two pole shoes 310, 320. While the pole shoes 310, 320 shown in these figures will, in this embodiment, have the geometrical properties shown here, the particular shape of the pole shoe bearing 330 is only shown here as a simple example, while the particular shape for a practical application will be determined by construction parameters like the required stability.

As shown in Figs. 7 and 8 each pole shoe 310, 320 comprises at least one, here in this embodiment two, inner pole shoe segments 311, 312 and 321, 322, respectively, and at least two, here in this embodiment four, outer pole shoe segments 313-316 and 323-326, respectively. Further, each pole shoe 310, 320 comprises a pole shoe yoke 317 and 327, respectively, that connects the various pole shoe segments of the same pole shoe.

All pole shoe segments of a common pole shoe are coaxially arranged about the common inner coil axis 115a wherein the second inner pole shoe segments 312, 322 are arranged as rings around the respective inner pole shoe segment 311, 321. The outer pole shoe segments 313-316 and 323-326, respectively, are each designed in form of a ring segment arranged at the same distance around the inner coil axis 115a but have different angular positions as shown in Fig. 7B.

Such an arrangement of pole shoes, on which the various coils of the selection-and-focus field coils are arranged as will be shown and explained below, is advantageous for achieving the desired movement of the selection-and-focus field coil (the first sub-zone 52). The segmentation of the outer pole shoe segments, here in two to four segments (generally at least two segments, but also more segments are possible), is particularly advantageous for movement of the FFP along the x- and y-direction.

In a practical implementation, the distance d_i between the inner pole shoe segments 311, 321 (in z-direction) is at least so large that a patient as well as drive field coils can be arranged there between. This means that the distance d_i should be at least 40 cm, preferably at least 45 cm. The distance d_o between the outer pole shoe segments b can be slightly smaller since there between no drive field coils are generally arranged. Hence, the distance d_o should be at least 25 cm, preferably at least 40 cm.

The pole shoes are generally made of soft-magnetic material. Preferably, the two inner pole shoe segments 311, 312 and 321, 322, respectively, and head portions 313h-314h and 323h-324h (see Fig. 7A; the head portions of the other outer pole shoe segments are not explicitly shown in this figure) are made from a soft-magnetic material and have a high saturation induction, in particular FeCo, Fe, Dy, Gd or an alloy thereof such as $Fe_{49}V_{1.9}Co_{49}$ (such as the material known under the trade name Vacoflux48). Alternatively, FeNi may be used, but this material has a lower saturation induction. Preferably, the tail portions 313t, 314t and 323t, 324t of the outer pole shoe segments (the tail portions of the outer pole shoe segments 315 or 316, 325, 326 are not explicitly shown) facing away from the examination area and the pole shoe yoke are made from the same material. However, for cost reasons it is possible to make them from a soft-magnetic material having a lower saturation induction than the material of the inner head pole shoe segments, in particular FeSi, FeNi, Permalloy or an alloy thereof such as $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ (commonly known as Nanoperm).

Fig. 9 shows two perpendicular cross sections through an embodiment of a selection-and-focus field coil arrangement 400 in which the various selection-and-focus field coils are mounted on a pole shoe arrangement 300 as shown in Figs. 7 and 8.

Fig. 10 shows an enlarged view of a single selection-and-focus field coil sub-unit 410 which will be used to explain further details thereof. The first inner pole shoe segment 311 carries the first inner selection-and-focus field coil 115 which is formed as a ring around said first inner pole shoe segment 311. A second inner selection-and-focus field coil 113 is formed as another ring coil which is carried by the second inner pole shoe segment 312, which itself is formed as a ring around said first inner selection-and-focus field coil 115. Four outer selection-and-focus field coils 116, 117 (only two outer selection-and-focus field coils are shown in Figs. 9 and 10; the other two outer selection-and-focus field coils are not shown in Figs. 9 and 10) are carried by respective outer pole shoe segments 313, 314, 315, 316. Each of said outer selection-and-focus field coils 116, 117 is wound around its associated outer pole shoe segment 313, 314, 315, 316 so that the current flows around the respective outer pole show segment. Each outer pole shoe segment 313, 314, 315, 316 has the form of a ring segment arranged at different angular positions around the inner coil axis 115a.

Thus, the selection-and-focus field coil arrangement 400 shown in Fig. 9A comprises in total twelve selection-and-focus field coils, six coils (the coils 113, 115-119) in the upper selection-and-focus field coil sub-unit 410 and six coils (the coils 133, 135, 136; the remaining two coils are not visible in Fig. 9A) in the lower selection-and-focus field coil sub-unit 420. This number shall, however, only be understood as an exemplary number. Other numbers are possible as well. Generally, at least six, preferably at least eight, selection-and-focus field coil units are desired.

Preferably, for each selection-and-focus field coil a single selection-and-focus field generator sub-unit is provided so that each selection-and-focus field coil can be individually controlled by providing an individual current to the selection-and-focus field coil. However, it is also possible to couple selection-and-focus field coils together and provide them with a common current so that the number of selection-and-focus field generator sub-units can be reduced. For instance, in an embodiment the two outer selection-and-focus field coils 116 and 117 are provided by a common current. Similarly, the other two outer selection-and-focus field coils are coupled together. This means that for such an selection-and-focus field coil arrangement in total eight selection-and-focus field generator sub-units are required.

In another embodiment, the two oppositely arranged selection-and-focus field coils of two different selection-and-focus field coil sub-units 410, 420 are coupled together and provided with a common current. For instance, the two (in Fig. 9) outer selection-and-focus field coils on the right-hand side may be coupled together and be provided with the identical current. The same holds for the other outer selection-and-focus field coils.

Preferably, according to an embodiment one or more of the selection-and-focus field coils are split into at least two, in particular at least four, coil segments, wherein coil segments of a coil are arranged adjacent to each other in the direction of the associated coil axis (which means, in the direction of the inner coil axis 115a if all coil axes are parallel as in the depicted embodiment) and wherein adjacent coil segments are electrically connected. Preferably, as shown in Figs. 9 and 10, all selection-and-focus field coils are split into several coil segments as indicated by multiple coil sample division lines in Figs. 9A and 10.

For instance, the first inner selection-and-focus field coil 115 is split into four coil segments indicated by letters A, B, C, D in Fig. 10. Similarly, the second inner selection-and-focus field coil 113 and the various outer selection-and-focus field coils 116, 117 are split into a plurality of coil segments indicated by letters A, B, C, etc.

This splitting of the selection-and-focus field coils into several segments enables the realization of different current densities along the respective selection-and-focus field coil. The following table summarizes, as an exemplary embodiment, the maximum current densities for each coil segment. These exemplary values for the current densities are obtained from simulation runs taking into account that different locations of the selection-and-focus field coil require large currents in different coils. Over all, the total of electrical power was at -100 kW. The maximum power in the first inner selection-and-focus field coil was 49 kW, while no more than 38 kW was used for the currents in the second inner selection-and-focus field coil. In each of the outer selection-and-focus field coils no more than 20 kW dissipated.

	curd [A/m²]	curd [A/mm²]
113A	**3,9104E+07**	**39,1042**
113B	**3,0290E+07**	**30,2900**
113C	**1,4279E+07**	**14,2788**
113D	**1,2366E+07**	**12,3658**
115A	**1,4485E+07**	**14,4853**
115B	**1,3682E+07**	**13,6820**
115C	**1,2966E+07**	**12,9664**
115D	**1,2250E+07**	**12,2499**
115E	**1,1529E+07**	**11,5291**
115F	**1,0699E+07**	**10,6994**
115G	**9,9520E+06**	**9,9520**
115H	**8,9570E+06**	**8,9570**
115I	**1,0142E+07**	**10,1418**
115J	**7,8558E+06**	**7,8558**
115K	**4,5355E+06**	**4,5355**
115L	**4,7809E+06**	**4,7809**
117A	**7,0403E+06**	**7,0403**
117B	**7,0148E+06**	**7,0148**
117C	**6,9895E+06**	**6,9895**
117D	**6,9645E+06**	**6,9645**
117E	**6,9398E+06**	**6,9398**
117F	**6,9153E+06**	**6,9153**
117G	**6,8911E+06**	**6,8911**
117H	**6,8671E+06**	**6,8671**
117I	**6,8434E+06**	**6,8434**
117J	**6,8199E+06**	**6,8199**

Preferably, the coil segments are arranged such that in the direction of the associated coil axis in the obtained current density increases with decreasing distance from the examination area. Various embodiments accessed are to obtain this. Preferred embodiments include that one or more coil segments of the coil arranged closer to the examination area are, compared to one or more coil segments of the same coil arranged further away from the examination area, made of a different material, have thicker windings, are more compact and/or have a higher thickness in the direction of the associated coil axis. For instance, the ratios of the current densities of the different coil segments are used to determine how the wire cross sections should be varied within each coil. In practice, however, deviations from the theoretical values are certainly required since manufacturers of wires generally provide only a limited number of cross section values.

It can further be observed from Figs. 9 and 10 that in this preferred embodiment a cross section perpendicular to the inner coil axis 115a through a head portion 312h of the second inner pole shoe segment 312 facing the examination area, i.e. a cross section along line X shown in Fig. 10, covers a smaller area than the parallel cross section through a tail portion 312t of said second inner pole shoe segment 312 facing away from said examination area, i.e. along line Y shown in Fig. 10.

Preferably, the outer diameter of said head portion 312h of the second inner pole shoe segment 312 decreases in the direction of the inner coil axis 315a with decreasing distance from the examination area 230. In other words, the outer edges of the head portion 312h are inclined in the direction of the inner coil axis 315a.

Still further, a cross section perpendicular to the inner coil axis 315a through a head portion 313h, 314h of the outer pole shoe segments 313, 314 (the same holds for the other outer pole shoe segments not explicitly shown in Fig. 10) facing said examination area, i.e. along line X, covers a larger area than a parallel cross section through the tail portion 313t, 314t of said outer pole shoe segments 313, 314 facing away from the examination area, i.e. a cross section along line Y.

Still further, the distance of the inner diameter of said head portions 313h, 314h of the outer pole shoe segments 313, 314 (the same holds for the other, not shown outer pole shoe segments) from the inner coil axis 315a decreases in the direction of the inner coil axis 115a with decreasing distance from the examination area 330. In other words, the inner edges of the head portions 313h, 314h are inclined in the direction of the inner coil axis 115a.

As shown, the second inner selection-and-focus field coil 113 and the outer selection-and-focus field coils 116, 117 (the same holds for the other not shown outer selection-and-focus field coils) are moved around the respective pole shoe segment assembling the same outer shape than the corresponding pole shoe segment, which is, however, not necessarily required.

These measures provide for the highest flux density on the surface of the inner pole shoe segments 311, 312 and the inner selection-and-focus field coils 113, 115 facing the examination area, particularly to obtain a high gradient of the magnetic field. It shall be noted, that also the outer edges of the outer pole shoe segments can be inclined into the direction of the inner coil axis 115a to further increase this effect.

For moving the field of view 28 through the examination area, which is conventionally achieved by use of the magnetic focus field, it is generally not required to provide all selection-and-focus field coils with currents. In particular, for moving the field of view 28 in the upper or lower direction, i.e. along the inner direction of the inner coil axis 115a, mainly the two inner selection-and-focus field coils 115, 113 are used. For instance, if a movement of the field of view 28 is desired from the upper selection-and-focus field coil sub-unit 410 in the direction of the lower selection-and-focus field coil sub-unit 420 a current provided to the first inner selection-and-focus field coil of the lower selection-and-focus field coil sub-unit 420 and to the current provided to the second inner selection-and-focus field coil of the upper selection-and-focus field coil sub-unit 410 are increased. Alternatively or in addition the current provided to the first inner selection-and-focus field coil of the upper selection-and-focus field coil sub-unit 410 and the current provided to the second inner selection-and-focus field coil of the lower selection-and-focus field coil sub-unit 420 are decreased. The outer selection-and-focus field coils need not necessarily be used for such a movement.

If a movement of the field of view 28 is desired in a direction perpendicular to the inner coil axis 115a, the outer selection-and-focus field coils are additionally provided with currents. In particular, by said outer selection-and-focus field coils an additional magnetic field is generated in a direction along the desired direction of movement and perpendicular to the inner coil axis 115a. For instance, if a movement from left to right is desired in Fig. 9A a magnetic field is additionally generated having a north pole on the left side and a south pole on the right side (or vice versa). By the amplitude of the current provided to the outer selection-and-focus field coils it can than be controlled how far the field of view 28 shall be moved in this direction.

The above explanation only provides a brief general idea how movement of the field of view can generally be achieved. In practice, of course, the currents need to be controlled precisely which is, however, only a matter of implementation which strongly depends on the exact layout of the overall arrangement.

With respect to the pole shoes it shall be noted that they are preferably made from magnetically conductive sheets, wherein sheets forming the inner pole shoe segments 311, 312 and an adjacent head portion 317h of the pole shoe yoke 317 of the pole shoe 310 (the same holds for the inner pole shoe segments and the pole shoe yoke of the other pole shoe 320) are arranged along a direction parallel to the inner coil axis 315a. Sheets forming the tail portion 317t of the pole shoe yoke 317 (the same holds for the other pole shoe yoke 327) are preferably arranged in a direction substantially perpendicular to the inner coil axis 315a. This provides for an optimum connectivity of the magnetic flux.

In case of using two or more pole shoes that are connected by a pole shoe bearing 330, as shown in Fig. 8, it is preferred that also the pole shoe bearing 330 is made from magnetically conductive sheets that are arranged adjacent to each other in the same direction as sheets forming the portion of the pole shoe to which the pole shoe bearing is connected. For instance, if the pole shoe bearing connects to the head portions of the pole shoe yokes, the sheets of the pole shoe bearing are preferably arranged in a direction perpendicular to the inner coil axis. The sheets forming the pole shoe bearing are also arranged in a direction perpendicular to the inner coil axis 315a at least at the connection to the pole shoe yokes. Generally, the sheets should be arranged such that the best magnetic flux connectivity is achieved.

It shall be noted that in addition to the various selection-and-focus field coils additionally a permanent material in each selection-and-focus field coil sub-unit may be provided to further strengthen the generation of the magnetic selection field for generating the selection-and-focus field coil. This permanent magnet would preferably be located close to the examination zone substituting parts of the soft-magnetic material.

Further, it shall be noted that the cooling means are preferably provided for cooling some or all of the coils. The cooling means may use a cooling fluid like water or oil. The coils may be made from copper or aluminum, but it is also possible to make them from superconductive material, which would then be cooled by use of an appropriate cooling material such as helium. In case of high temperature superconductive conductors the cooling can be achieved by use of gaseous helium. In case of low temperature superconductive conductors the cooling can be achieved by use of liquid helium.

For certain applications (MR) it is desirable to generate a magnetic field which does not have an FFP but is rather homogeneous. Simulations were therefore performed in which the current direction in one of the inner pole-shoes was reversed. Using all coils and different distributions of the available power (100 kW) the maximum observed field strength at the origin was 0.45 T. The field strength increases along z and decreases along x/y.

To compute the energy stored in the magnetic field the integral

$$E = \frac{1}{2}\int_V B \cdot H \, dV$$

is evaluated over volume V. Within our simulations the maximum observed energy stored in the magnetic field was below 40 kJ. The maximum was seen in a simulation trying to obtain a homogeneous (MR) field.

In the following the process of reconstruction as proposed according to the present invention and as performed by the reconstruction unit 152 shall be explained in more detail. As explained above, background signal variations and spurious signals, which occur in object scans, can strongly compromise image quality. Different sources of background signal exhibit different spectral behavior, so that background signal contributions are not homogeneously spread over the measured bandwidth, but vary in intensity and temporal pattern between different frequency components. To achieve good image quality, the signal background should be removed from the measured data. This is done according to the present invention by an appropriate design of the reconstruction means 152. The proposed solution is illustrated by use of Figs. 11 and 12.

Fig. 11 shows a plot of a spectral signal evolution during a scan. The abscissa displays the frequency components of a spectrum measured on a channel (e.g. the x channel) during one repetition of the field-free-point sequence (i.e. one run along the trajectory). The ordinate relates to the evolution of the spectrum during sequential FFP sequences, each of which encodes a full volume. Fig. 12 shows the temporal signal variation of selected harmonics of the x channel signal.

The reconstruction means 152 are configured to identify in the detection signals one or more background time periods tb1, tb2, tb3, tb4 at which no magnetic particles were present in the field of view, wherein signal time periods ts1, ts2, ts1 at which magnetic particles were present in the field of view are interspersed with at least one tb2, tb3 of said one or more background time periods tb1, tb2, tb3, tb4. The detection signals obtained at said background time periods tb1, tb2, tb3, tb4 are then used to correct detection signals obtained at said signal time periods ts1, ts2, ts1. Finally, the desired image is reconstructed from said corrected detection signals obtained at said signal time periods ts1, ts2, ts1.

Thus, in the signal time periods ts1, ts2, ts1 the object (or part thereof) filled with tracer material was in the imaging volume, giving rise to signal in many frequency components. In the background time periods tb1, tb2, tb3, tb4 no object was in the imaging volume and thus the observed signal represents the signal background. Due to changing spurious signals or thermal effects, the signal background can change over time, not only smoothly, but also abruptly, as indicated by the arrow. For successful background correction, these effects increase the need to use background signal which is temporally very close to the object measurement. The optimal time windows can be determined using a plot as shown in Fig. 11, or a selection of signal-containing harmonics as indicated in Fig. 16.

Using the plot shown in Fig. 12, background time periods, during which no tracer material is in the imaging volume, can be identified and thus signal suitable for background correction can be selected with high accuracy. As shown in Figs. 11 and 12, not only an initial background time period tb1(e.g. before a bolus of tracer material is introduced into the object or before the bolus reaches the imaging volume) and a final background time period tb4 (e.g. after the bolus has left the imaging volume) are used, but at least one background time period (here two background time periods tb2, tb3) is detected in between signal time periods. The exact amplitudes of the detection signal of the object generally depend on the shape of the object. The displayed (exemplary) harmonics are chosen to be multiples of the x excitation frequency (n*528, with n = 2, 3, 4), since these typically contain most signal.

The decision, which data can be used as background data, can be based on visual inspection of the temporal signal evolution of a selection of harmonics and mix frequencies of the excitation frequencies, or a combination or weighted function of these frequency components. The signal evolution or the derived function can be visualized over time as e.g. be depicted in Fig. 12. Assuming that no tracer is in the imaging volume at a known point in time, the user can observe harmonic signal changes when tracer is entering the imaging volume. Using this visualization, it is rather easy for the user to assign time periods suitable for background subtraction, e.g. by defining these regions on the time axis using the computer mouse or other input devices.

In an embodiment one or more, possibly pre-selected frequency components or a function thereof (e.g. the average, the norm, or the variance of selected frequency components or of the time-derivative of selected frequency components are evaluated automatically. Starting, for instance, from a tracer-free imaging volume, any substantial change (that is preferably larger than a predetermined threshold, e.g. more than the typical noise variation) in one or, preferably, several frequency components or a function thereof indicates that tracer material has entered the imaging volume and that the now obtained detection signals cannot be used for background correction.

If in doubt whether signal changes are really due to tracer material, or to further improve the detection of background time periods, it is proposed to furthermore correlate signal changes with additional information, e.g. the time when the bolus of tracer material was injected and/of the position of the imaging volume with the respect to the object or patient.

In the further course of the scan, it is monitored, when the spectral components or function values go back to the typical background pattern in order to find the next time period during which tracer is in the imaging volume. Depending on the typical variations that are found in the background spectrum of a scanner, this monitoring and evaluation of the signal evolution has to allow for some change in the background signal over time. However, as can be seen in Fig. 12, the regions with tracer material in the imaging volume are usually clearly delineated. In this context typical variations are signal variations occurring in the absence of magnetic particles, e.g. due to heating or spurious signals. They exhibit certain patterns, e.g. only occur in low harmonics or affect the background level of all frequency components at the same time.

In still another embodiment frequency components exhibit a rapid variation during the time windows tb, so that an interpolation over the windows ts is not feasible. This is achieved by discarding or suppressing (e.g. adding low weight) to these frequency components in the reconstruction process.

Since MPI scans produce very much data, the proposed solution may advantageously be used to only store data that can be related to tracer material and not store long stretches of data corresponding to an empty imaging volume. Furthermore, the start of an image reconstruction can be triggered by the observed change in one or more frequency components, e.g. the amplitudes of harmonics of the drive frequency of the magnetic drive field, to avoid spending computer power on the reconstruction of empty images.

In summary, any real MPI scanner produces background signals that can change non-linearly in time. The presented approach ensures constant and reproducible image quality by making additional data available for a dynamic background correction during an object or patient scan.

Background subtraction is a crucial feature in MPI to ensure decent image quality in view of scanner imperfections and spurious signals picked up by the receive system. The present invention provides a solution for efficient background measurement and subtraction.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims.

In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single element or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

Any reference signs in the claims should not be construed as limiting the scope.

CLAIMS:

1. An apparatus (100) for detecting magnetic particles in a field of view (28), which apparatus comprises:

- selection means comprising a selection field signal generator unit (110) and selection field elements (116) for generating a magnetic selection field (50) having a pattern in space of its magnetic field strength such that a first sub-zone (52) having a low magnetic field strength where the magnetization of the magnetic particles is not saturated and a second sub-zone (54) having a higher magnetic field strength where the magnetization of the magnetic particles is saturated are formed in the field of view (28),

- drive means (120) comprising a drive field signal generator unit (122) and drive field coils (124; 125, 126, 127) for changing the position in space of the two sub-zones (52, 54) in the field of view (28) by means of a magnetic drive field so that the magnetization of the magnetic material changes locally,

- receiving means comprising at least one signal receiving unit (140) and at least one receiving coil (148) for acquiring detection signals, which detection signals depend on the magnetization in the field of view (28), which magnetization is influenced by the change in the position in space of the first and second sub-zone (52, 54), and

- reconstruction means (152) for reconstructing an image of the field of view (28) from detection signals, wherein said reconstruction means is adapted to

- identify in the detection signals one or more background time periods (tb1, tb2, tb3, tb4) at which no magnetic particles were present in the field of view (28), wherein signal time periods (ts1, ts2, ts1) at which magnetic particles were present in the field of view (28) are interspersed with at least one (tb2, tb3) of said one or more background time periods (tb1, tb2, tb3, tb4),

- using the detection signals obtained at said background time periods (tb1, tb2, tb3, tb4) to correct detection signals obtained at said signal time periods (ts1, ts2, ts1), and

- reconstructing the image from said corrected detection signals obtained at said signal time periods (ts1, ts2, ts1).

2. The apparatus as claimed in claim 1,
wherein said reconstruction means (152) is adapted to identify in the detection signals said one or more background time periods (tb1, tb2, tb3, tb4) by analyzing one or more frequency components over time.

3. The apparatus as claimed in claim 2,
wherein said reconstruction means (152) is adapted analyze one or more frequency components which are harmonics or mix frequencies of harmonics of drive field frequencies of the magnetic drive field.

4. The apparatus as claimed in claim 1,
wherein said reconstruction means (152) is adapted to identify changes in said one or more frequency components and/or in one or more derived functions that are derived from said one or more frequency components.

5. The apparatus as claimed in claim 4,
wherein said reconstruction means (152) is adapted to identify if and when changes of the amplitude exist in said one or more frequency components and/or in one or more derived functions that are derived from said one or more frequency components.

6. The apparatus as claimed in claim 1,
wherein said reconstruction means (152) is adapted to remove or subtract, per frequency component, detection signals obtained at said background time periods (tb1, tb2, tb3, tb4) from detection signals obtained at said signal time periods (ts1, ts2, ts1).

7. The apparatus as claimed in claim 1,
wherein said reconstruction means (152) is adapted to suppress or remove frequency components that exhibit a rapid irregular variation in the background measurements from detection signals obtained at said signal time periods (ts1, ts2, ts1).

7. The apparatus as claimed in claim 6,
wherein said reconstruction means (152) is adapted to calculate, per frequency component, an interpolated or average background signal and to subtract said interpolated or average

background signal from the detection signals obtained at said signal time periods (ts1, ts2, ts1).

8. The apparatus as claimed in claim 6,
wherein said reconstruction means (152) is adapted to calculate, per frequency component and per background time period, a background signal or average thereof and to subtract said background signal or average thereof from the detection signals obtained at neighboring signal time periods (ts1, ts2, ts1).

9. The apparatus as claimed in claim 1,
wherein said reconstruction means (152) is adapted to suppress or remove frequency components that exhibit a rapid irregular variation in the background measurements from detection signals obtained at said signal time periods (ts1, ts2, ts1).

10. The apparatus as claimed in claim 4,
wherein said reconstruction means (152) is adapted to correlate said identified changes with additional information indicating when and/or where in the field of view magnetic particles are present.

11. The apparatus as claimed in claim 10,
wherein said additional information indicates the time when magnetic particles have been introduced into an object present in the field of view and/or the positional relationship between the object and the field of view.

12. The apparatus (100) as claimed in claim 1 comprising
selection-and-focus means (120) including said selection means for generating a magnetic selection-and-focus field (50) having a pattern in space of its magnetic field strength such that the first sub-zone (52) and the second sub-zone (54) are formed in the field of view (28) and for changing the position in space of the field of view (28) within an examination area (230), said selection-and-focus means comprising at least one set of selection-and-focus field coils (114; 113, 115-119) and a selection-and-focus field generator unit (112) for generating selection-and-focus field currents to be provided to said at least one set of selection-and-focus field coils (114; 113, 115-119) for controlling the generation of said magnetic selection-and-focus field,

wherein said at least one set of selection-and-focus field coils comprises

- at least one inner selection-and-focus field coil (113, 115) being formed as a closed loop about an inner coil axis (115a), first inner selection-and-focus field coil (115) and
- a group of at least two outer selection-and-focus field coils (116-119) arranged at a larger distance from said inner coil axis (115a) than said at least one inner selection-and-focus field coil (113, 115) and at different angular positions, each being formed as a closed loop about an associated outer coil axis (116a-119a).

13. A method for detecting magnetic particles in a field of view (28), which method comprises:

- generating a magnetic selection field (50) having a pattern in space of its magnetic field strength such that a first sub-zone (52) having a low magnetic field strength where the magnetization of the magnetic particles is not saturated and a second sub-zone (54) having a higher magnetic field strength where the magnetization of the magnetic particles is saturated are formed in the field of view (28),
- changing the position in space of the two sub-zones (52, 54) in the field of view (28) by means of a magnetic drive field so that the magnetization of the magnetic material changes locally,
- acquiring detection signals, which detection signals depend on the magnetization in the field of view (28), which magnetization is influenced by the change in the position in space of the first and second sub-zone (52, 54),
- identifying in the detection signals one or more background time periods (tb1, tb2, tb3, tb4) at which no magnetic particles were present in the field of view (28), wherein signal time periods (ts1, ts2, ts1) at which magnetic particles were present in the field of view (28) are interspersed with at least one (tb2, tb3) of said one or more background time periods (tb1, tb2, tb3, tb4),
- using the detection signals obtained at said background time periods (tb1, tb2, tb3, tb4) to correct detection signals obtained at said signal time periods (ts1, ts2, ts1), and
- reconstructing an image from said corrected detection signals obtained at said signal time periods (ts1, ts2, ts1).

14. Computer program comprising program code means for causing a computer to control an apparatus as claimed in claim 1 to carry out the steps of the method as claimed in claim 13 when said computer program is carried out on the computer.

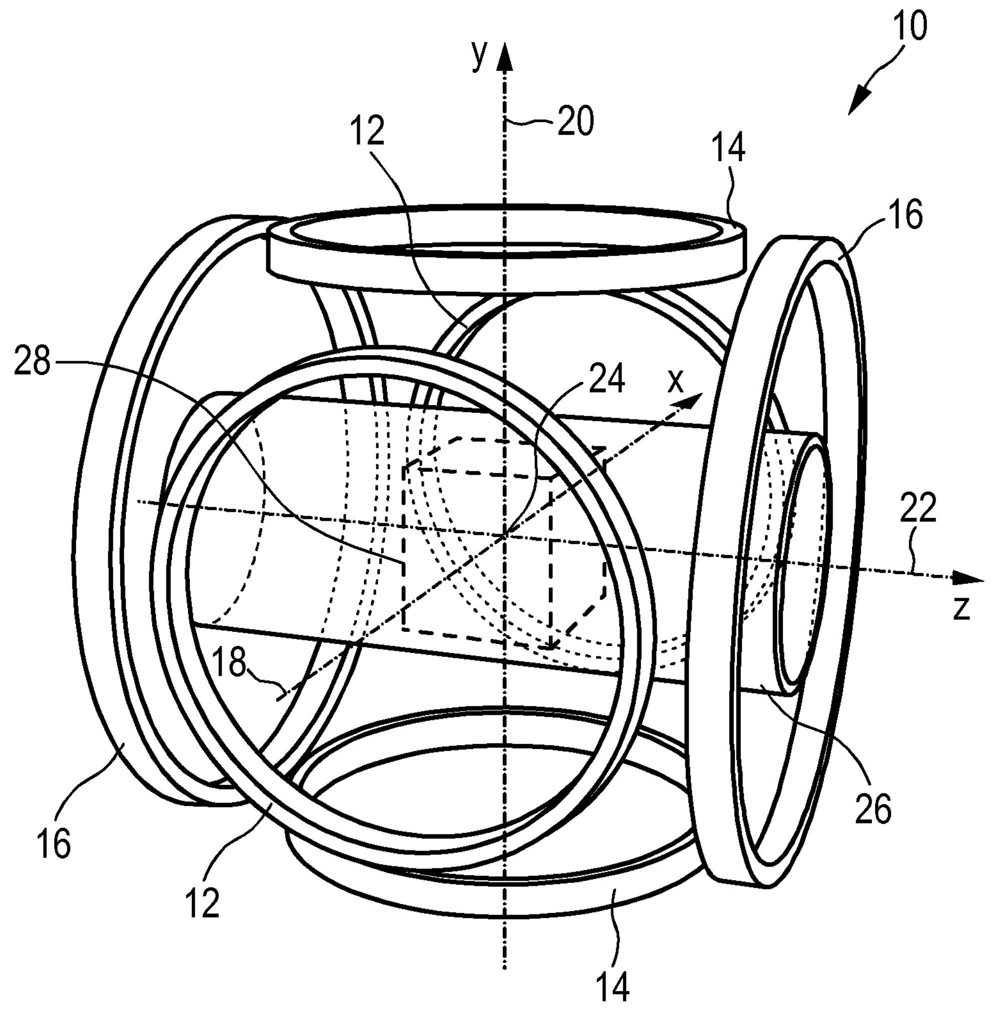


FIG. 1

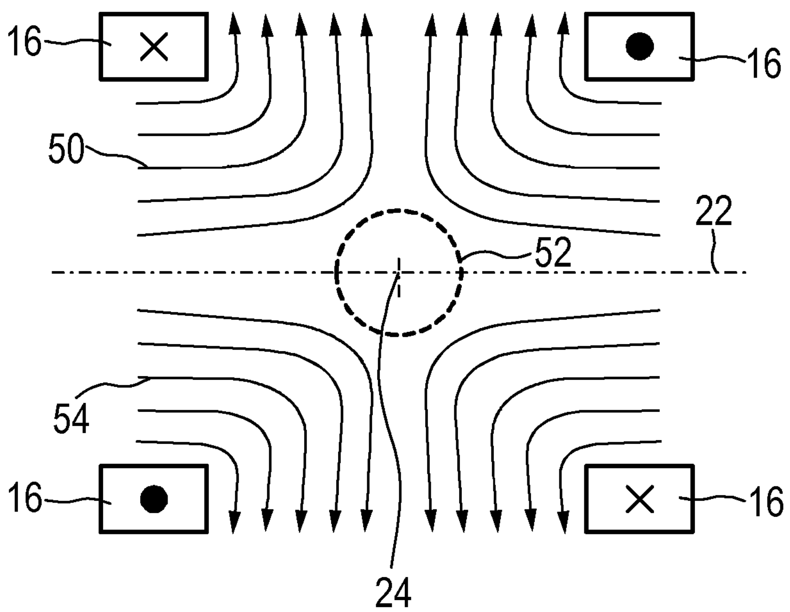


FIG. 2

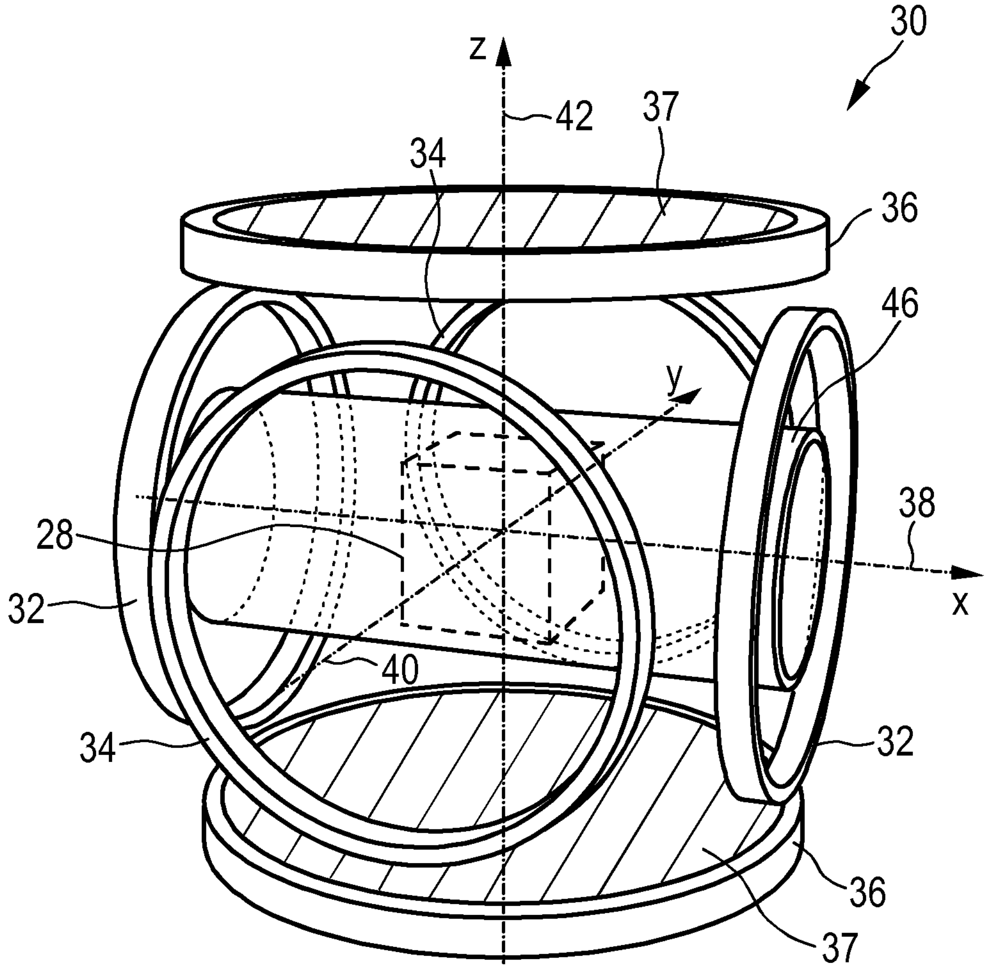


FIG. 3

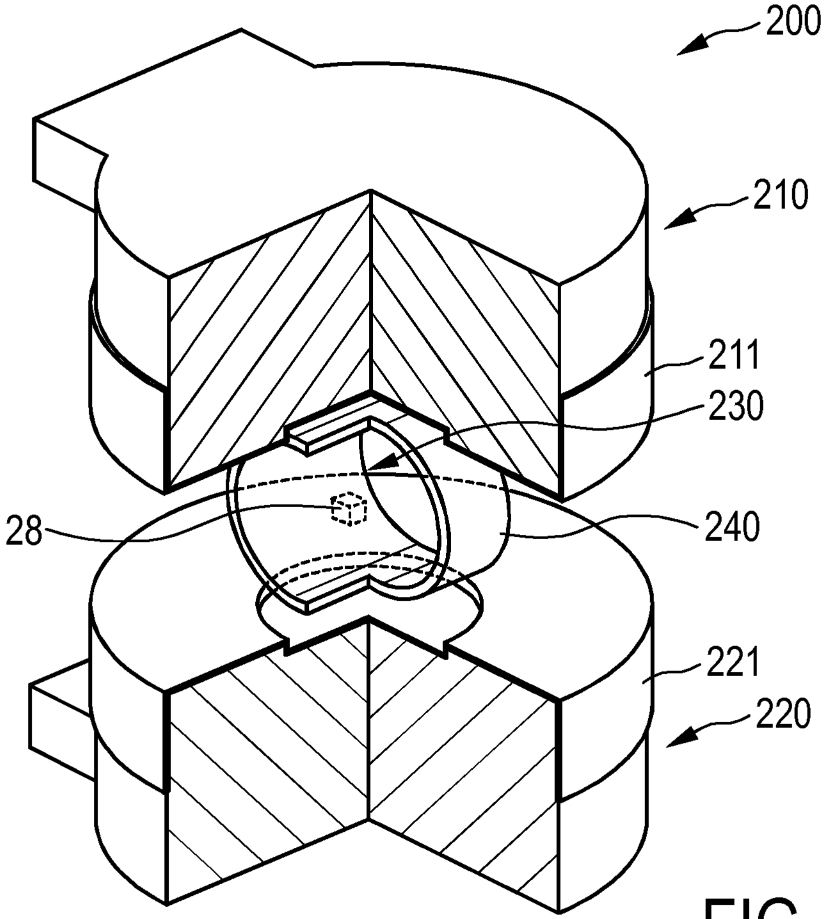


FIG. 4A

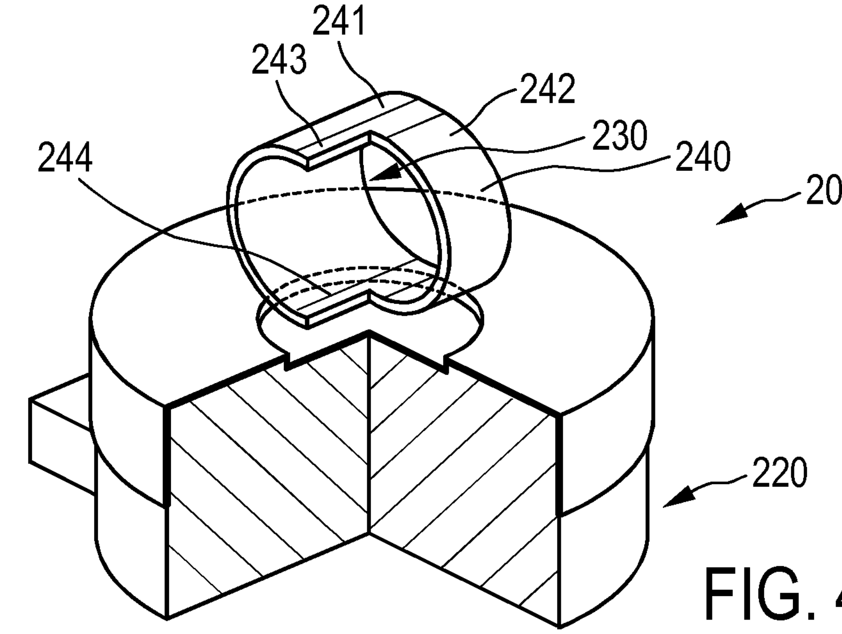
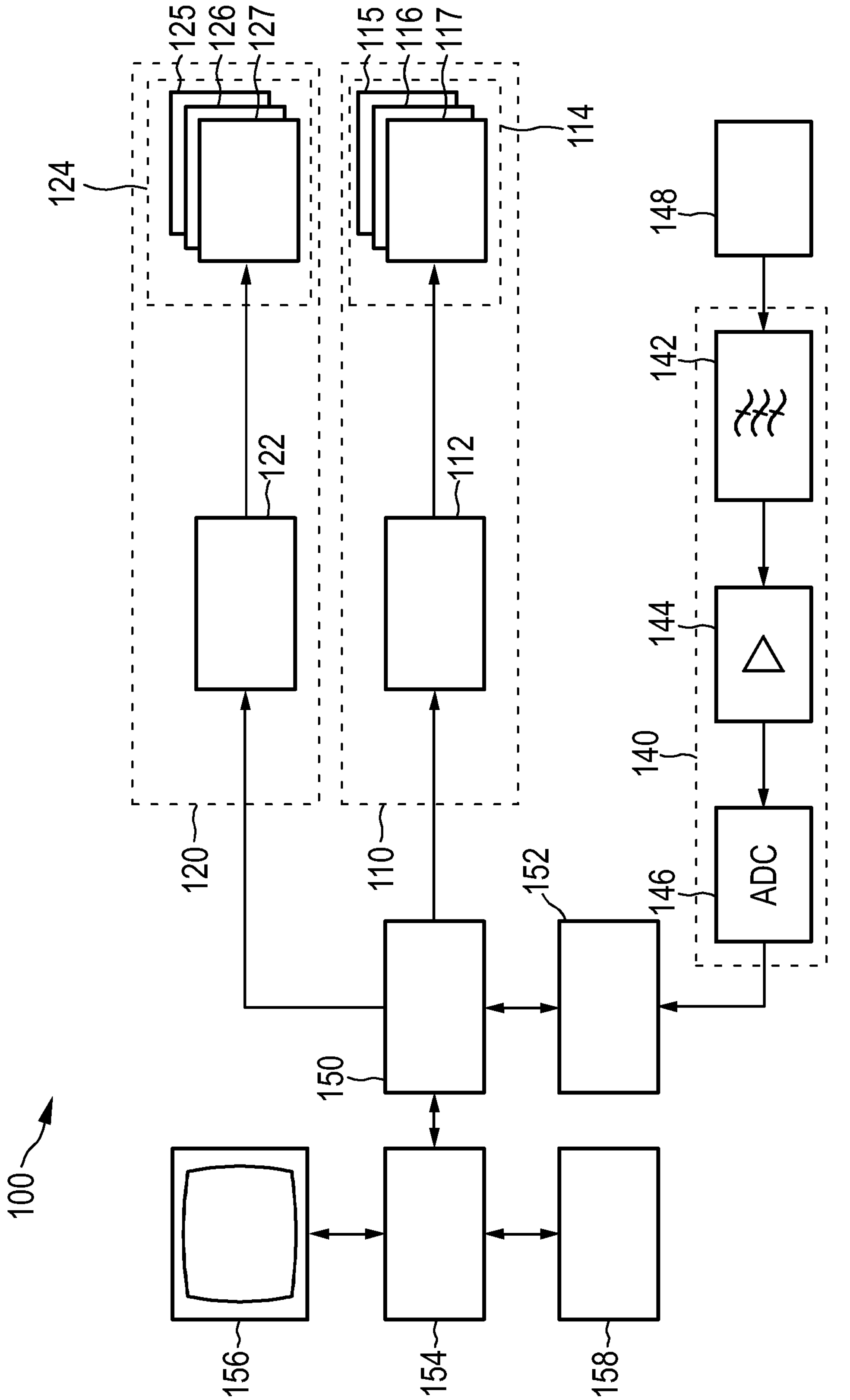


FIG. 4B


100
110
112
114
115
116
117
120
122
124
125
126
127
140
142
144
146
ADC
148
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152
154
156
158

FIG. 5

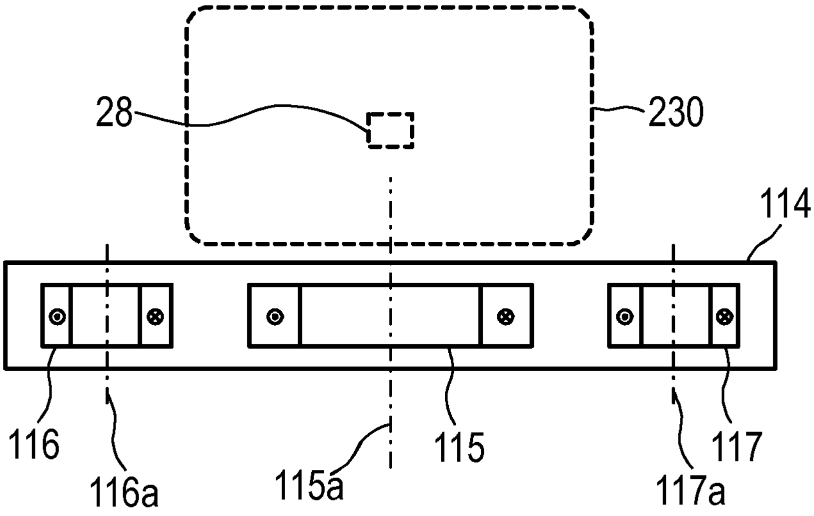

28
230
114
116
116a
115a
115
117
117a

FIG. 6A

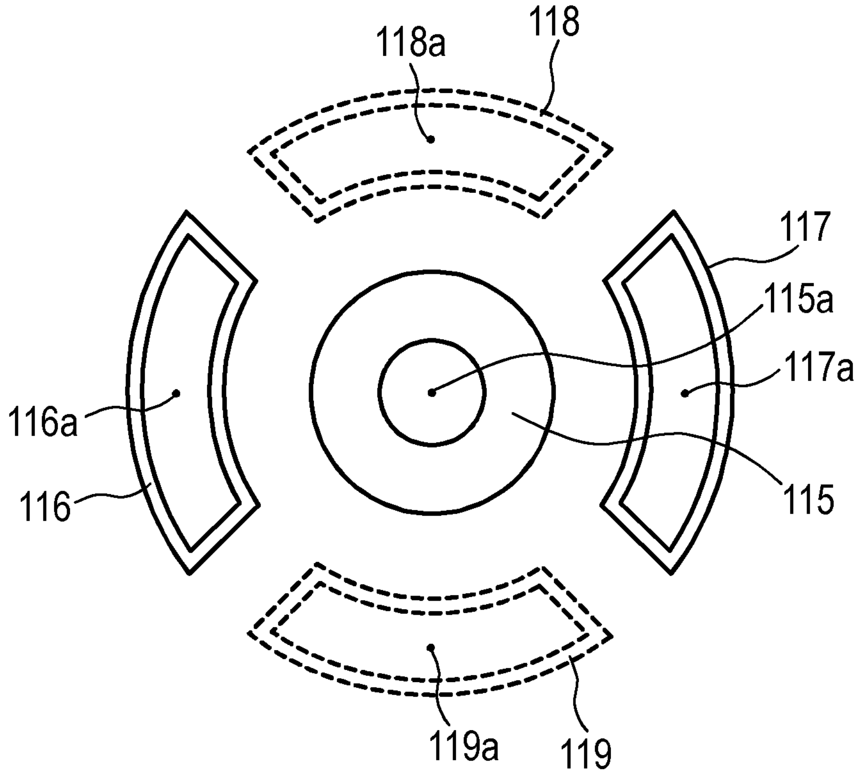

118a
118
117
115a
117a
116a
116
115
119a
119

FIG. 6B

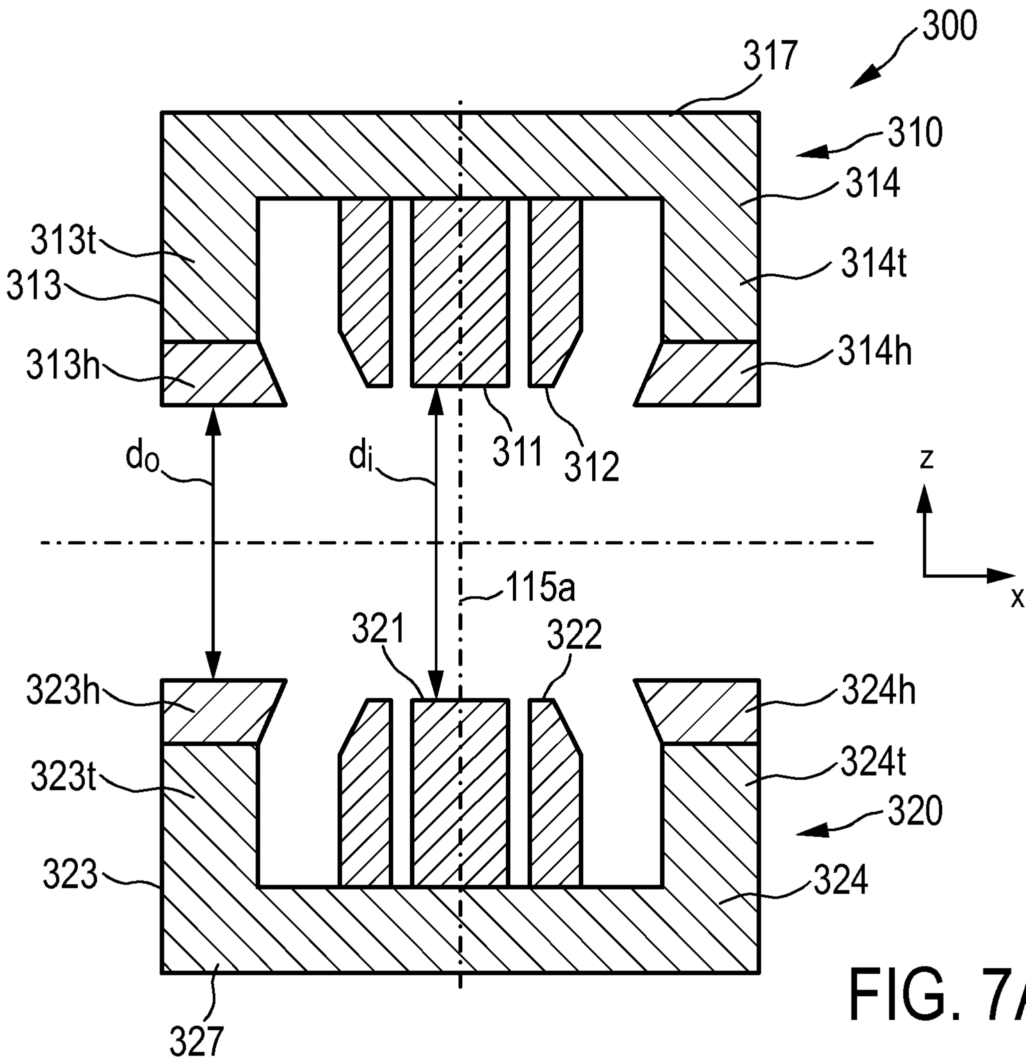

300
317
310
314
313t
314t
313
313h
314h
d_o
d_i
311
312
z
x
115a
321
322
323h
324h
323t
324t
320
323
324
327

FIG. 7A

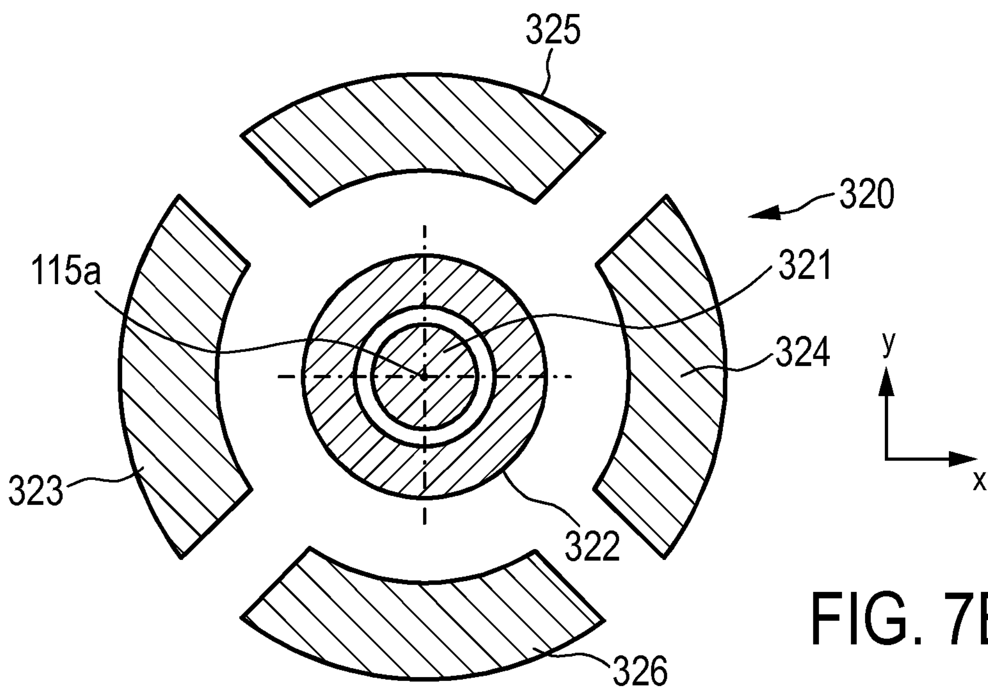

325
320
115a
321
324
y
x
323
322
326

FIG. 7B

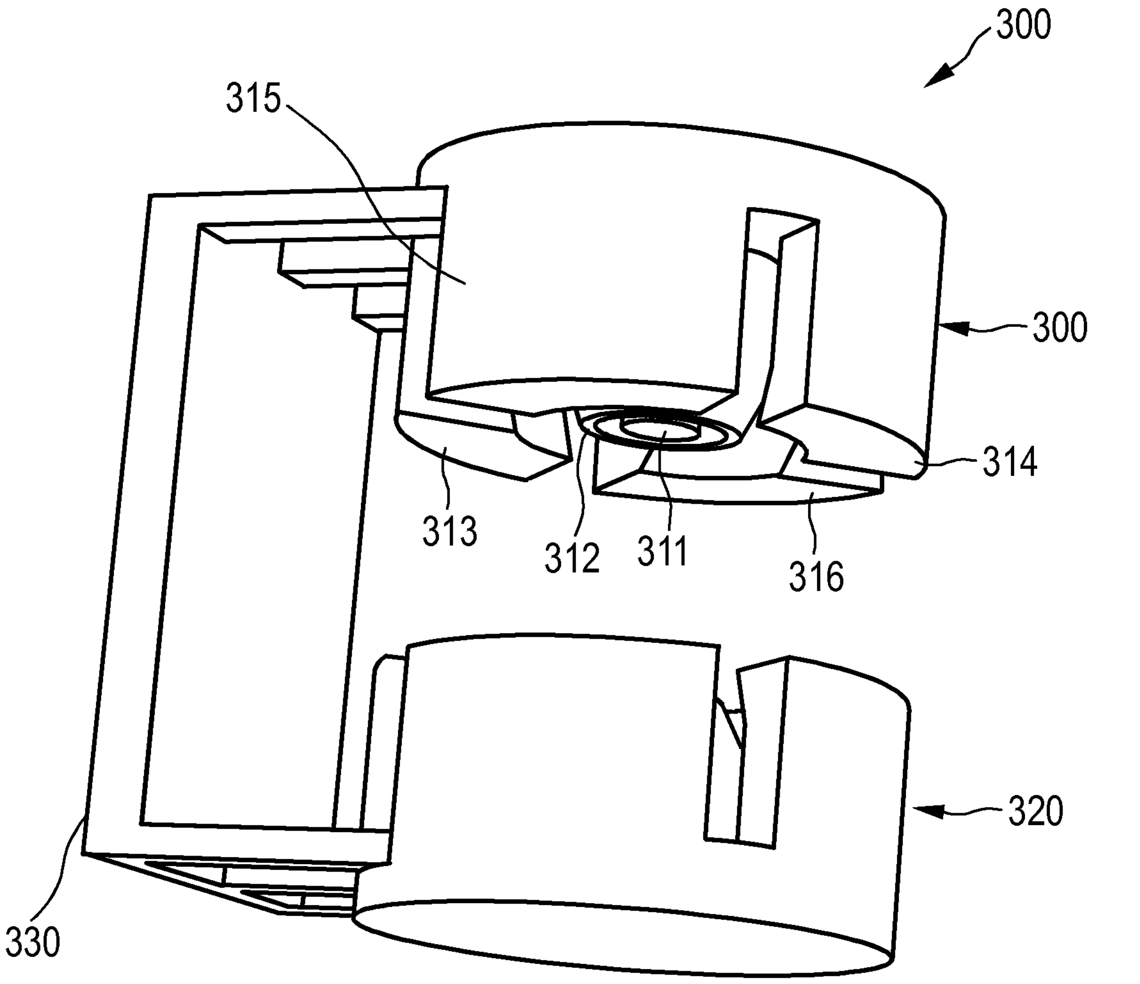


FIG. 8

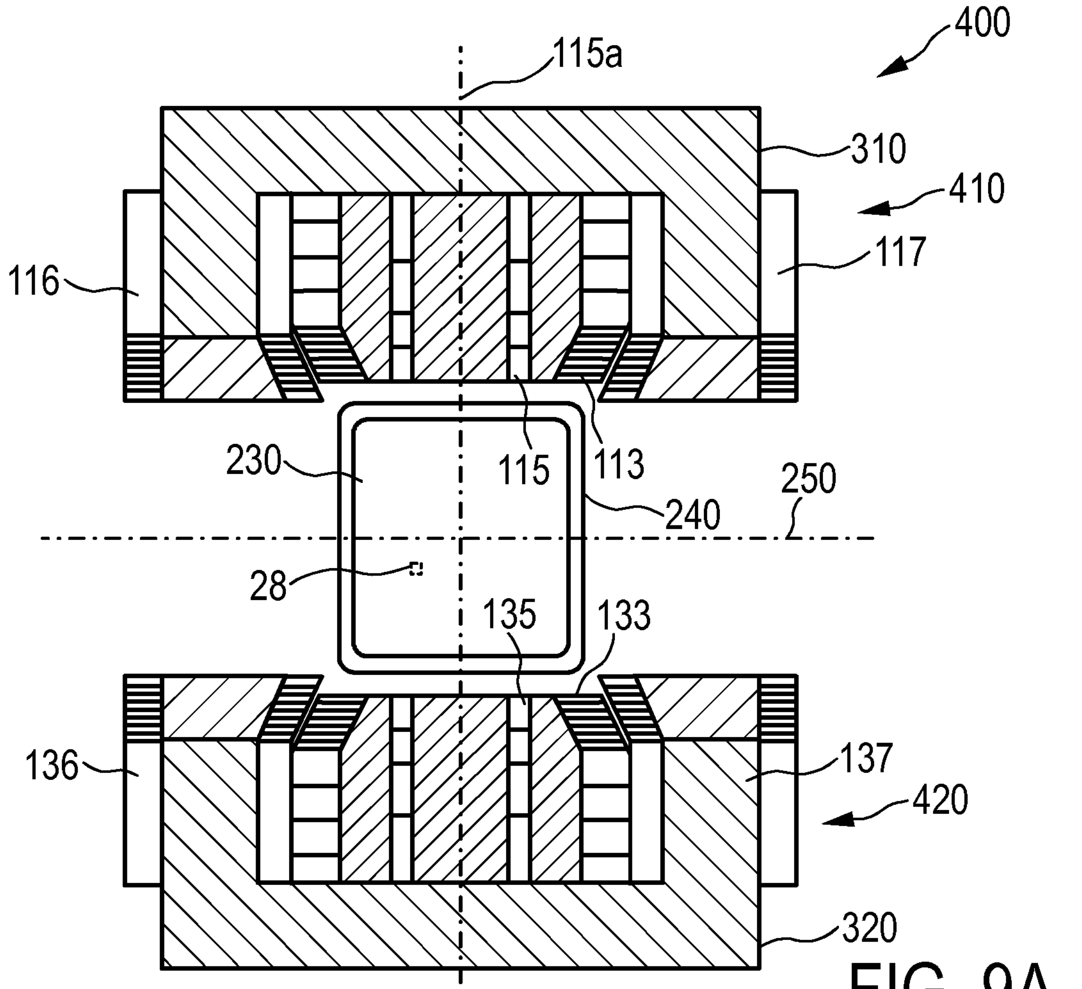

400
115a
310
410
116
117
115
113
230
240
250
28
135
133
136
137
420
320

FIG. 9A

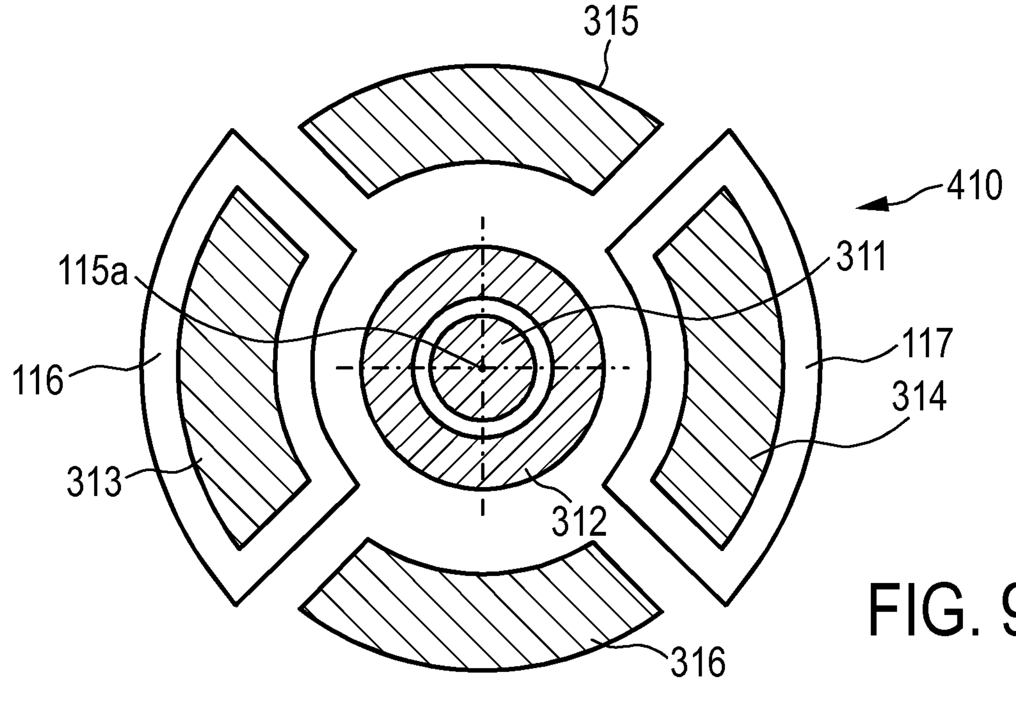

315
410
311
115a
117
116
314
313
312
316

FIG. 9B

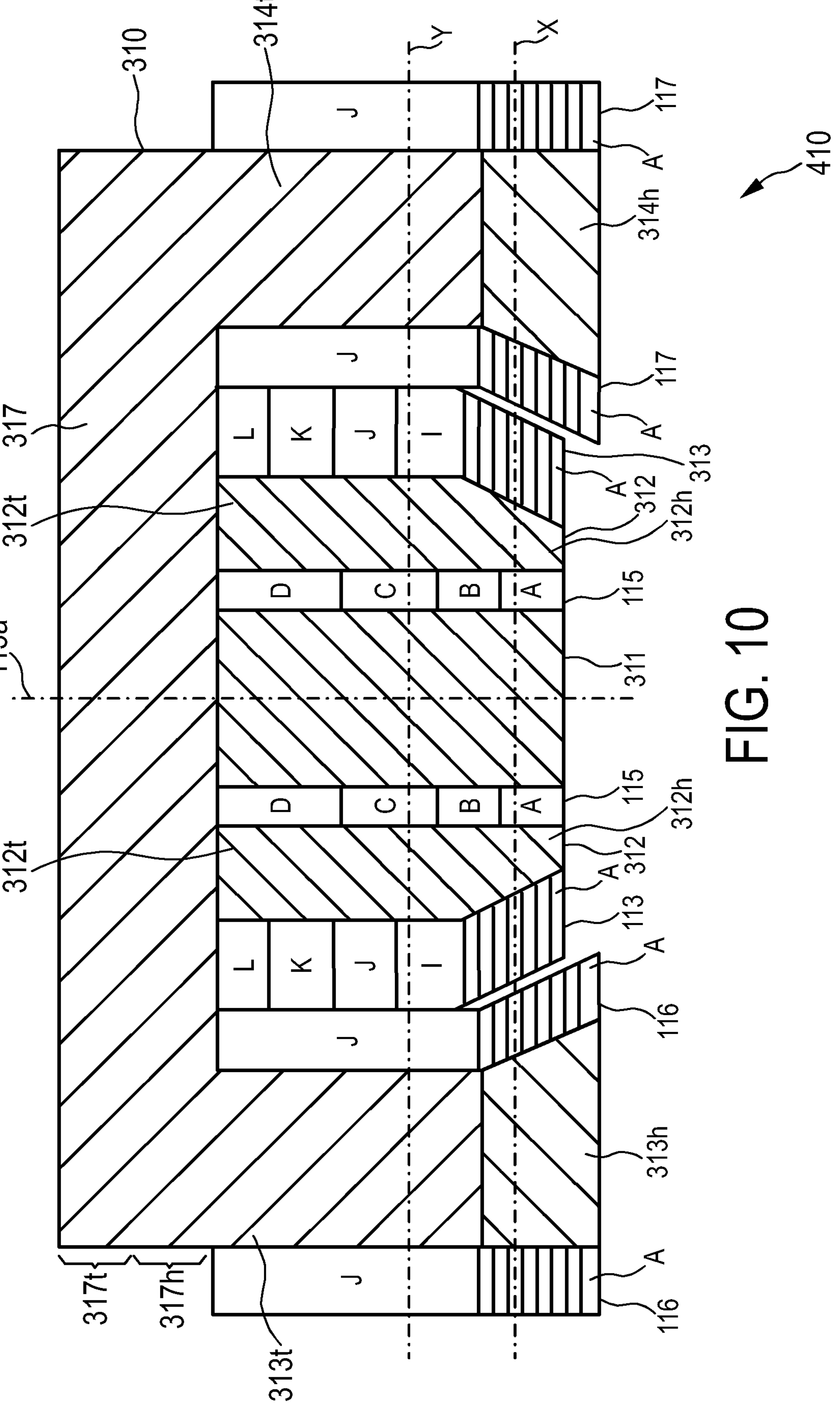
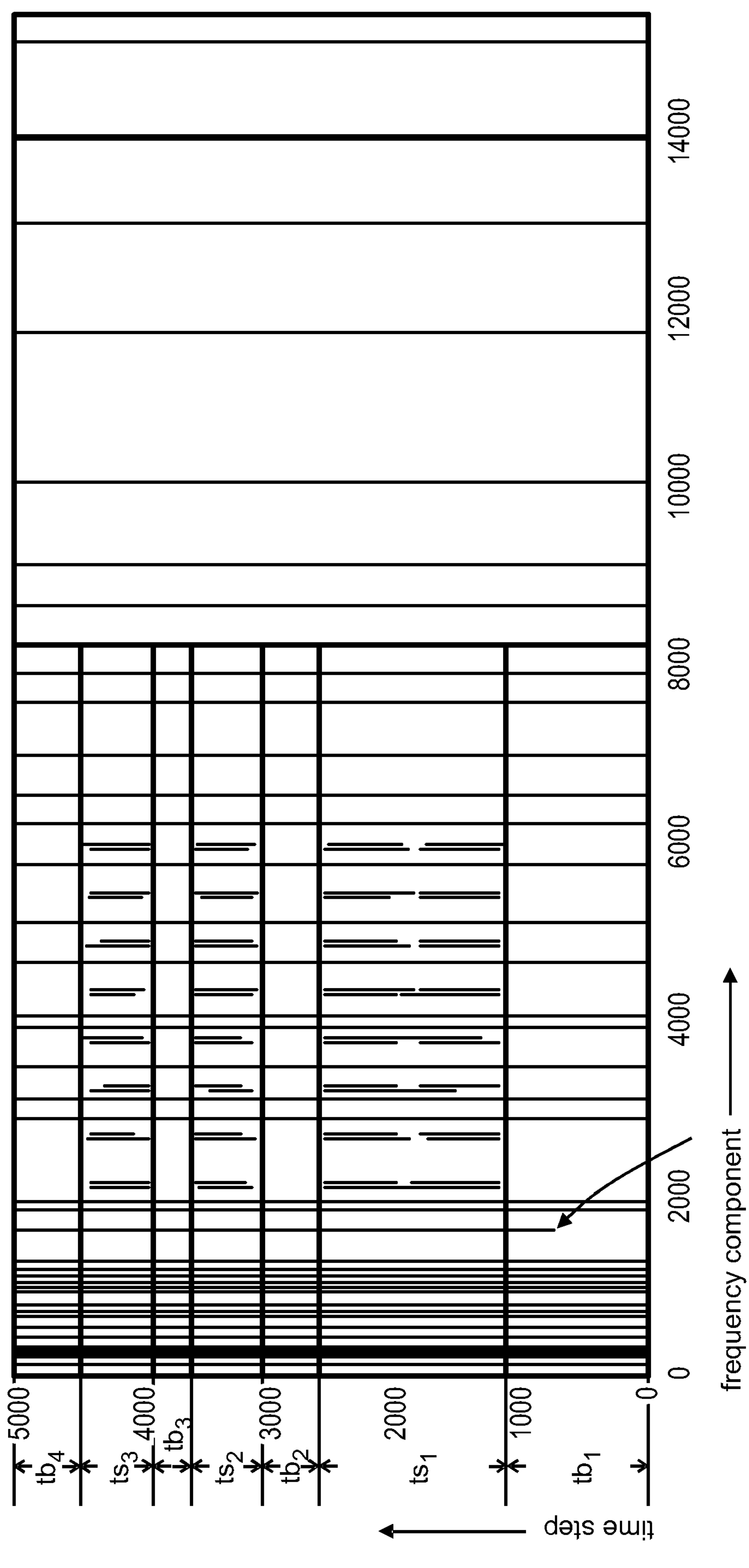
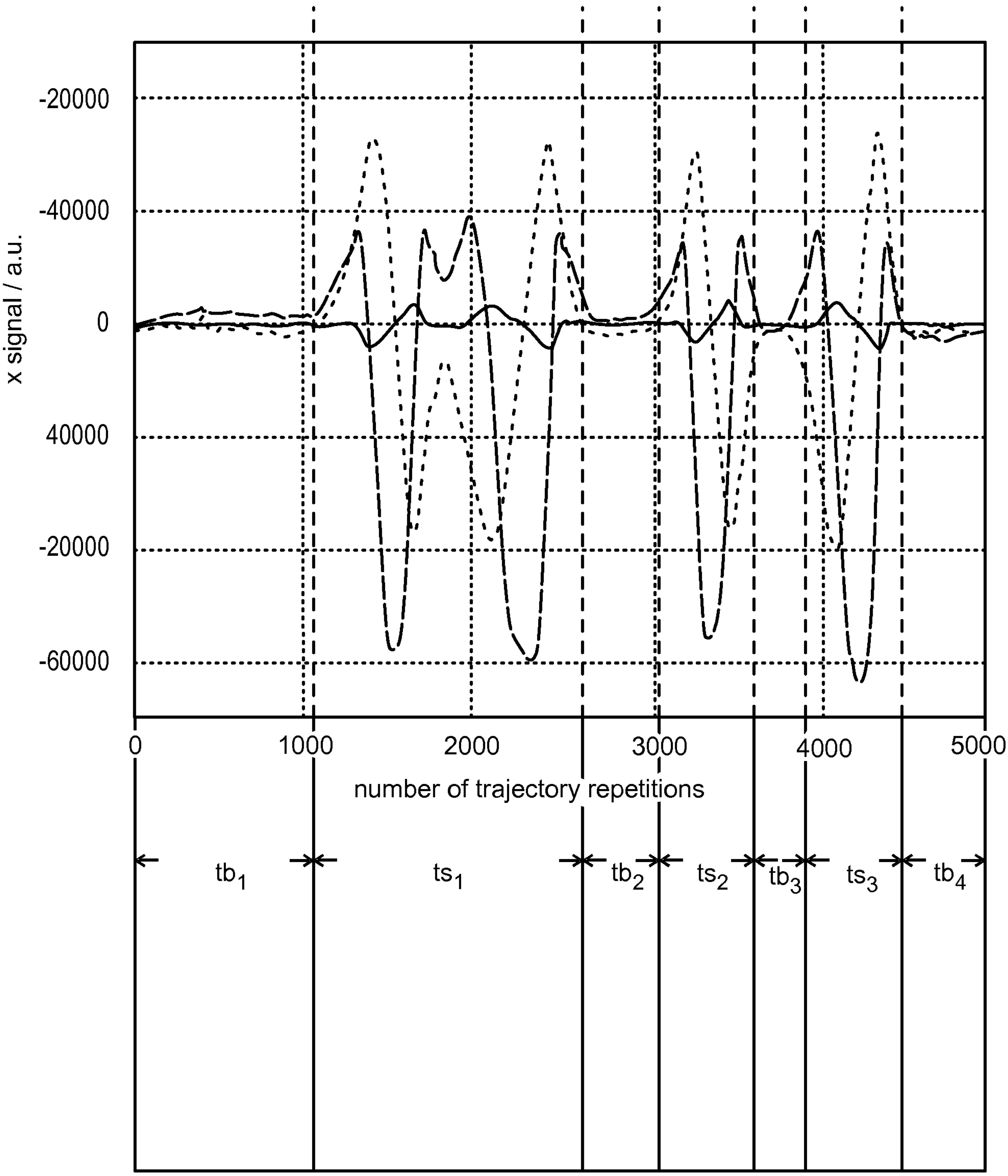

310
314t
Y
X
J
117
A
410
314h
317
312t
L
K
I
313
312
312h
D
C
B
115
115a
311
113
116
313h
317t
317h
313t

FIG. 10



frequency component
time step
0
2000
4000
6000
8000
10000
12000
14000
5000
4000
3000
2000
1000
tb4
ts3
tb3
ts2
tb2
ts1
tb1

FIG. 11



-20000
-40000
0
40000
-20000
-60000
x signal / a.u.
0
1000
2000
3000
4000
5000
number of trajectory repetitions
tb1
ts1
tb2
ts2
tb3
ts3
tb4

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/059068

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/05 G06T7/20
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)
A61B G06T

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2010/067298 A1 (PHILIPS INTELLECTUAL PROPERTY [DE]; KONINKL PHILIPS ELECTRONICS NV [NL) 17 June 2010 (2010-06-17) claim 1 page 2, lines 2-4 page 4, lines 14-17 -----	1-14
A	WO 96/31156 A1 (ANDERSSON MATS [SE]; KNUTSSON HANS [SE]; KRONANDER TORBJOERN [SE]) 10 October 1996 (1996-10-10) figure 4 page 1, lines 10, 11 page 2, lines 24, 25 page 6, lines 33-39 page 7, lines 31-34 -----	1-14

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

☒ See patent family annex.

* Special categories of cited documents :

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"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	Date of mailing of the international search report
11 December 2013	18/12/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Almeida, Mariana

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2013/059068

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