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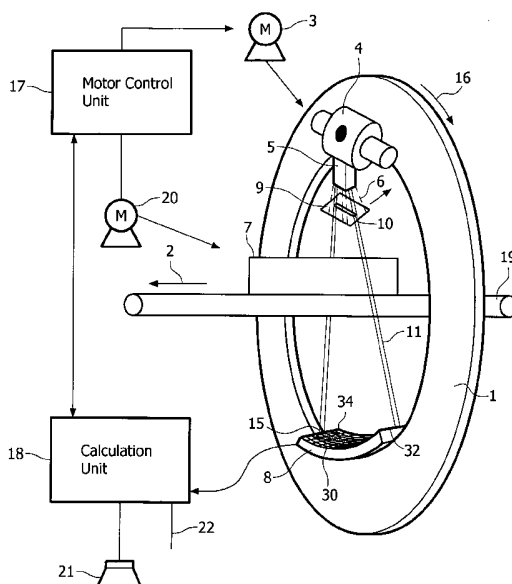
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(54) Title: FAN-BEAM COHERENT-SCATTER COMPUTER TOMOGRAPHY



(57) Abstract: In CSCT, by using a fan-shaped primary beam, combined with a 2D detector, single-slice transmission tomography and scatter tomography can be measured simultaneously. In such a System blurred scatter functions are measured unless a monochromatic source of radiation is used. According to the present invention, an energy resolving 1D or 2D detector System is proposed, which, in combination with a tomographic reconstruction, provides a good spectral resolution, even with a polychromatic primary beam. Furthermore, according to an aspect of the present invention, only one energy resolving detector-line is required to achieve the full spectrum. Advantageous applications of the system and method according to the present invention are in medical imaging and material analysis, such as baggage inspection.



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Fan-beam coherent-scatter computer tomography

5 The present invention relates to the fields of coherent-scatter computer tomography (CSCT) where a fan-beam is applied to an object of interest. In particular, the present invention relates to a computer tomography apparatus for examination of an object of interest and to a method of examining an object of interest with a computer tomography apparatus.

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US 4,751,722 describes a device based on the principle of registration of an angled distribution of coherent scattered radiation within angles of 1° to 12° as related to the direction of the beam. As set forth in the US 4,751,722, the main fraction
15 of elastic scattered radiation is concentrated within angles of less than 12° , and the scattered radiation has a characteristic angle dependency with well marked maximas, the positions of which are determined by the irradiated substance itself. As the distribution of the intensity of the coherently scattered radiation in small angles depends on molecular structure of the substance, different substances having equal absorption
20 capacity (which cannot be differentiated with conventional transillumination or CT) can be distinguished according to the distribution of the intensity of the angled scattering of coherent radiation typical for each substance.

Due to the improved capabilities of such systems to distinguish different object materials, such systems find more and more application in medical or industrial
25 fields.

The dominant component of low-angle scatter is coherent scatter. Because coherent scatter exhibits interference effects which depend on the atomic arrangement of the scattering sample, coherent scatter computed tomography (CSCT) is in principle a sensitive technique for imaging spatial variations in the molecular
30 structure of tissues across a 2D object section.

Harding et al "Energy-dispersive x-ray diffraction tomography" Phys.

Med. Biol., 1990, Vol. 35, No. 1, 33-41 describes an energy dispersive x-ray diffraction tomograph (EXDT) which is a tomographic imaging technique based on an energy analysis at fixed angle, of coherent x-ray scatter excited in an object by polychromatic radiation. According to this method, a radiation beam is created by the use of suitable aperture systems, which has the form of a pencil and thus is also referred to as a pencil beam. Opposite to the pencil beam source, one detector element suitable for an energy analysis is arranged for detecting the pencil beam altered by the object of interest.

Due to the use of the pencil beam in combination with only one detector element, only a limited number of photons emitted by the source of radiation and thus only a reduced amount of information can be measured. In case EXDT is applied to larger objects such as for example to pieces of baggage, EXDT has to be used in a scanning mode thus causing extremely long measurement times.

A coherent scatter set-up applying a Fan-beam primary beam and a 2D detector in combination with CT was described in US 6,470,067 B1 thus overcoming the long measurement time involved in EXDT scanning mode. The shortcoming of the angle-dispersive set-up in combination with a polychromatic source are blurred scatter functions, which is described in e.g. Schneider et al. "Coherent Scatter Computed Tomography Applying a Fan-Beam Geometry" Proc. SPIE , 2001, Vol. 4320 754-763.

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It is an object of the present invention to provide for an improved material discrimination on the basis of computer tomography.

According to and exemplary embodiment of the present invention as set forth in claim 1, the above object may be solved with a computer tomograph apparatus for examination of an object of interest, which comprises a detector unit with an x-ray source and a scatter radiation detector. The detector unit is rotatable around a rotation axis extending through an examination area for receiving the object of interest. The x-ray source generates a fan-shaped x-ray beam adapted to penetrate the object of interest in the examination area in a slice plane. The scatter radiation detector is arranged at the detector unit opposite to the x-ray source with an offset from the slice plane in a direction parallel to the rotational axis. The scatter radiation detector includes a first detector line, with a plurality of first detector elements arranged in a line. According to

an aspect of the present invention, these first detector elements are energy-resolving detector elements. Preferably, the energy resolving detector elements are direct-converting semiconductor detectors. Direct-converting semiconductor detectors directly convert the radiation into electrical charges – without scintillation. Preferably, these

5 direct-converting semiconductor detectors have an energy resolution better than 20% FWHM, i.e. $\Delta E/E < 0.2$, with ΔE being the Full-width at half maximum (FWHM) of the energy resolution of the detector. The scatter radiation detector measures a spectrum (I) for each projection which is the intensity I depending on the energy E of photons. Advantageously, this spectrum may then be used for the tomograph reconstruction, as

10 for example with ART (Algebraic Reconstruction Technique) or FBP (Filtered Back-projection).

Advantageously, the computer tomograph apparatus according to this exemplary embodiment allows to significantly reduce a scanning or measurement time in comparison to the apparatus suggested by Harding et al in US 4,751,722, since an

15 energy resolving detector line including a plurality of energy resolving detector elements is applied in combination with a fan-beam, which allows an integral measurement of the line at the same time. In other words, a whole projection of the object of interest along the slice plane is measured at the same time. While significantly reducing the time required for measurements, according to this exemplary embodiment

20 of the present invention, an improved characterization of tissue of the object of interest is made possible since an increased amount of photons emitted by the source of radiation are detected and thus more information with respect to the tissue is detected. In contrast to US 6,470,067, the use of energy-resolving detectors allows a better resolution of the coherent scatter structure function when using a polychromatic source.

25 According to another exemplary embodiment of the present invention as set forth in claim 2, besides the scatter radiation detector, which is arranged at the detector unit outside the slice plane, a primary radiation detector is provided for receiving primary radiation attenuated by the object of interest. In other words, two radiation detectors are provided, one for detecting the scatter radiation and one for

30 detecting the primary radiation. Advantageously, this may provide for a further improvement with respect to the material discrimination and identification due to improved attenuation correction of the scattered radiation.

According to another exemplary embodiment of the present invention as set forth in claim 3, the energy resolving elements are direct-conversion semiconductor cells, eg. CdZnTe or cadmiumtelluride cells and the primary radiation detector includes a detector line with a plurality of scintillator cells. According to this exemplary
5 embodiment of the present invention, the primary radiation detector detects the attenuation of the primary radiation in the slice plane. Advantageously, the attenuation of the primary beam is used to improve the quality of the reconstruction of the scatter data $I(E)$ as described by Schneider et al.

According to another exemplary embodiment of the present invention as
10 set forth in claim 4, at least one of a plurality of first detector lines for the energy resolving measurement of the scatter radiation and a plurality of second detector lines for the measurement of the primary radiation attenuated by the object of interest are provided. Advantageously, this may further reduce the scanning time required for scanning the object of interest. Furthermore, according to this exemplary embodiment
15 of the present invention, at least one of the primary radiation detector and the scatter radiation detector is provided with collimator elements such as lamella or blades, which avoids that the respective detector elements measure unwanted dispersed radiation.

According to another exemplary embodiment of the present invention as set forth in claim 5, there is provided a calculation unit for reconstructing an image
20 from readouts of the primary radiation detector and the scatter radiation detector, by, as already mentioned above, for example ART or a filtered back projection. Furthermore, the computer tomograph apparatus may also be adapted for the detection of explosives, for example for the application as x-ray baggage inspection system at airports, which automatically discriminates explosive materials on the basis of the reconstructed
25 coherent scatter function images based on readouts of the primary radiation detector and the scatter radiation detector by, for example, comparing the reconstructed scatter functions to predetermined tables of characteristic measurements for such explosives.

According to another exemplary embodiment of the present invention as set forth in claim 6, the above object may also be solved with a method of examining an
30 object of interest with a computer tomograph apparatus, wherein an x-ray source is energized, such that it generates a fan-shaped x-ray beam, which penetrates the object of interest in an examination area in a slice plane. Then, a measurement of the scattered

radiation is performed by means of a scatter radiation detector with a first detector line with a plurality of first energy resolving detector elements arranged in a line. The energy-resolved intensity $I(E)$ from the scatter radiation detector is read out. For acquiring a plurality of projections of the object of interest, the x-ray source and the
5 scatter radiation detector are rotated around a rotational axis extending through an examination area containing the object of interest.

Advantageously, according to this exemplary embodiment of the present invention in combination with a suited reconstruction method (see claim 8), a method may be provided which allows for a fast and dependable material discrimination of the
10 object of interest.

According to another exemplary embodiment of the present invention as set forth in claim 7, a primary radiation attenuated by the object of interest is read out.

According to another exemplary embodiment of the present invention as set forth in claim 8, an image is reconstructed from the readouts of the primary
15 radiation detector and the scatter radiation detector, for example by ART or a filtered back projection technique. Furthermore, according to this exemplary embodiment of the present invention, an automatic determination may be carried out on the basis of the readouts of the primary radiation detector and the scatter radiation detector, whether the object of interest comprises explosives or not. In case it is determined that the object of
20 interest contains explosives, an alarm may be issued.

According to another exemplary embodiment of the present invention as set forth in claim 9, the readouts of a plurality of lines of the scatter radiation detector or a plurality of lines of the primary radiation detector is performed and a collimation of the respective radiation is carried out, which may allow to further improve the material
25 discrimination.

It may be seen as the gist of an exemplary embodiment of the present invention that an image reconstruction is performed or a material discrimination is performed by using measurements of an energy spectrum of photons scattered from a fan-beam by an object of interest which are measured by means of a detector line
30 including energy resolving detector elements. An improved material discrimination may be provided by further using the attenuation of the primary beam of the fan-beam measured by means of, for example, a line of scintillator elements in the slice plane.

These and other aspects of the present invention will become apparent from and elucidated with reference to the embodiments described hereinafter.

Exemplary embodiments of the present invention will be described in the following with reference to the following drawings:

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Fig. 1 shows a schematic representation of an exemplary embodiment of a computer tomograph according to the present invention.

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Fig. 2 shows a schematic representation of the geometry of the computer tomograph of Fig. 1 for the measurement of coherent scatter radiation.

Fig. 3 shows another schematic representation of the geometry of the computer tomograph of Fig. 1.

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Fig. 4 shows another schematic representation of the measurement geometry of the computer tomograph of Fig. 1 for further explaining the present invention.

Fig. 5 shows a schematic representation of a side view of the geometry of the computer tomograph of Fig. 1.

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Fig. 6 shows a flow-chart of an exemplary embodiment of a method for operating the computer tomograph of Fig. 1 according to the present invention.

Figs. 7a and 7b show a flow-chart of another exemplary embodiment of a method for operating the computer tomograph of Fig. 1 according to the present invention.

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Fig. 8 shows a diagram depicting the relation of a position in the object and a wave vector amount carried over for different energies measured with the computer tomograph of Fig. 1.

Fig. 1 shows an exemplary embodiment of computer tomograph according to the present invention. With reference to this exemplary embodiment, the present invention will be described for the application in baggage inspection to detect
30 hazardous materials such as explosives in items of baggage. However, it has to be noted that the present invention is not limited to applications in the field of baggage inspection, but can also be used in other industrial or medical applications, such as for

example in bone imaging or a discrimination of tissue types in medical applications.

The computer tomograph depicted in Fig. 1 is a fan-beam coherent scatter computer tomograph (CSCT), which allows in combination with an energy-resolving detector and with tomographic reconstruction a good spectral resolution, even
5 with a polychromatic primary fan-beam. The computer tomograph depicted in Fig. 1 comprises a gantry 1, which is rotatable around a rotational axis 2. The gantry 1 is driven by means of a motor 3. Reference character 4 designates a source of radiation, such as an x-ray source, which, according to and aspect of the present invention, emits a polychromatic radiation.

10 Reference character 5 designates a first aperture system, which forms the radiation beam emitted from the radiation source 4 to a cone shaped radiation beam 6. Furthermore, there is provided another aperture system 9 consisting of a diaphragm or a slit collimator. The aperture system 9 has the form of a slit 10, such that the radiation emitted from the source of radiation 4 is formed into a fan-beam 11. According to a
15 variant of this exemplary embodiment of the present invention, the first aperture system 5 may also be omitted and only the second aperture 9 may be provided.

The fan-beam 11 is directed such that it penetrates the item of baggage 7, arranged in the center of the gantry 1, i.e. in an examination region of the computer tomograph and impinges onto the detector 8. As may be taken from Fig. 1, the detector
20 8 is arranged on the gantry 1 opposite to the radiation source 4, such that the slice plane of the fan-beam 11 intersects a row or line 15 of the detector 8. The detector 8 depicted in Fig. 1 has seven detector lines, each comprising a plurality of detector elements. As mentioned above, the detector 8 is arranged such that the primary radiation detector 15, i.e. the middle line of the detector 8 is in the slice plane of the fan-beam 11.

25 As can be taken from Fig. 1, the detector 8 comprises two types of radiation detector lines: a first type of detector lines 30 and 34, which are indicated without hatching in Fig. 1, which are detector lines consisting of energy resolving detector cells. According to an aspect of the present invention, these first detector elements (lines 30 and 34) are energy-resolving detector elements. Preferably, the
30 energy resolving detector elements are direct-converting semiconductor detectors. Direct-converting semiconductor detectors directly convert the radiation into electrical charges – without scintillation. Preferably, these direct-converting semiconductor

detectors have an energy resolution better than 20% FWHM, i.e. $\Delta E/E < 0.2$, with ΔE being the Full-width at half maximum (FWHM) of the energy resolution of the detector.

Such detector cells of lines 30 and 34 may be cadmiumtelluride or CZT based detector cells, which are both outside of the slice plane of the fan-beam 11. In
5 other words, both energy resolving lines 30 and 34 are arranged at the gantry 1 opposite to the x-ray source 4 with an offset from the slice plane in a direction parallel to the rotational axis 2. The detector line 30 is arranged with a positive offset with respect to the direction of the rotational axis 2 depicted in Fig. 1, whereas the line 34 is arranged with a negative offset from the slice plane with respect to the direction of the rotational
10 axis 2 depicted in Fig. 1.

The detector lines 30 and 34 are arranged at the gantry 1 such that they are parallel to the slice plane and out of the slice plane with such an offset in a positive or negative direction of the rotational axis 2 of the gantry 1, such that they receive or measure a scatter radiation scattered from the item of baggage 7 in the examination area
15 of the computer tomograph. Thus, in the following, lines 30 and 34 will also be referred to as scatter radiation detector. It has to be noted that instead of the provision of two energy resolving lines 30 and 34, it may also be efficient to provide only one line which includes energy resolving detector elements, such as, for example, only the line 30. Furthermore, instead of providing only two energy resolving lines 30 and 34, it is also
20 possible to provide three, four or an even greater number of energy resolving lines. Thus, if, in the following the term "scatter radiation detector" is used, it includes any detector with at least one line of energy resolving detector cells, which is arranged out of the fan plane of the fan-beam 11, such that it receives photons scattered from the item of baggage 7.

25 The second type of detector lines provided on the detector 8, which are indicated by a hatching, are scintillator cells. In particular, line 15 is arranged such that it is in the slice plane of the fan-beam 11 and measures the attenuation of the radiation emitted by the source of radiation 4, caused by the item of baggage 7 in the examination area. As depicted in Fig. 1, right and left of the line 15, there may be provided further
30 detector lines including scintillator detector cells.

As already indicated with respect to the energy resolving lines 30 and 34, where the provision of only one energy resolving line 30 or 34 is sufficient, the

provision of only the line 15 measuring the attenuation caused by the item of baggage 7 of the primary beam of the fan-beam 11 in the slice plane is sufficient. However, as in the case of the energy resolving lines 30 and 34, a provision of a plurality of detector lines 32, each comprising a plurality of scintillator cells, may further increase the measurement speed of the computer tomograph. In the following, the term “primary radiation detector” will be used to refer to a detector, including at least one line of scintillator or similar detector cells for measuring an attenuation of the primary radiation of the fan-beam 11.

As may be taken from Fig. 1, the detector cells of the detector 8 are arranged in lines and columns, wherein the columns are parallel to the rotational axis 2, whereas the lines are arranged in planes perpendicular to the rotational axis 2 and parallel to the slice plane of the fan-beam 11.

The apertures of the aperture systems 5 and 9 are adapted to the dimensions of the detector 8 such that the scanned area of the item of baggage 7 is within the fan-beam 11 and that the detector 8 covers the complete scanning area. Advantageously, this allows to avoid unnecessary excess radiation applied to the item of baggage 7. During a scan of the item of baggage 7, the radiation source 4, the aperture systems 5 and 9 and the detector 8 are rotated along the gantry 1 in the direction indicated with arrow 16. For rotation of the gantry 1 with the source of radiation 4, the aperture systems 5 and 9 and the detector 15, the motor 3 is connected to a motor control unit 17, which is connected to a calculation unit 18.

In Fig. 1, the item of baggage 7 is disposed on a conveyor belt 19. During the scan of the item of baggage 7, while the gantry 1 rotates around the item of baggage 7, the conveyor belt 19 displaces the item of baggage 7 along a direction parallel to the rotational axis 2 of the gantry 1. By this, the item of baggage 7 is scanned along a helical scan path. The conveyor belt 19 can also be stopped during the scans to thereby measure single slices.

The detector 8 is connected to a calculation unit 18. The calculation unit 18 receives the detection results, i.e. the readouts from the detector elements of the detector 8 and determines a scanning result on the basis of the scanning results from the detector 8, i.e. from the energy resolving lines 30 and 34 and the lines 15 and 32 for measuring the attenuation of the primary radiation of the fan-beam 11. In addition to

that, the calculation unit 18 communicates with the motor control unit 17 in order to coordinate the movement of the gantry 1 with the motors 3 and 20 or with the conveyor belt 19.

The calculation unit 18 is adapted for reconstructing an image from
5 readouts of the primary radiation detector, i.e. detector lines 15 and 32 and the scatter radiation detector, i.e. lines 30 and 34. The image generated by the calculation unit 18 may be output to a display (not shown in Fig. 1) via an interface 22.

Furthermore, the calculation unit 18 is adapted for the detection of
explosives in the item of baggage 7 on the basis of the readouts of the lines 30 and 34
10 and 15 and 32. This can be made automatically by reconstructing scatter functions from the readouts of these detector lines and comparing them to tables including characteristic measurement values of explosives determined during preceding measurements. In case the calculation unit 18 determines that the measurement values read out from the detector 8 match with characteristic measurement values of an
15 explosive, the calculation unit 18 automatically outputs an alarm via a loudspeaker 21.

During the subsequent description of Figs. 2 to 7, the same reference numbers as used in Fig. 1 will be used for the same or corresponding elements.

Fig. 2 shows a simplified schematic representation of a geometry of the CSCT scanning system depicted in Fig. 1. As may be taken from Fig. 2, the x-ray
20 source 4 emits the fan-beam 11 such that it includes the item of baggage 7 in this case having a diameter of u and covers the entire detector 8. The diameter of the object region may, for example, be 100 cm. In this case, an angle α of the fan-beam 11 may be 80°. In such an arrangement, a distance v from the x-ray source 4 to the center of the object region is approximately 80 cm and the distance of the detector 8, i.e. of the
25 individual detector cells from the x-ray source 4 is approximately $w = 150$ cm.

As can be taken from Fig. 2, according to an aspect of the present invention, the detector cells or lines can be provided with collimators 40 to avoid that the cells or lines measure unwanted radiation having a different scatter angle. The collimators 40 have the form of blades or lamellas, which can be focused towards the
30 source. The spacing of the lamellas can be chosen independently from the spacing of the detector elements.

Instead of a bent detector 8 as depicted in Figs. 1 and 2, it is also possible

to use a flat detector array.

Fig. 3 shows another schematic representation of a detector geometry as used in the computer tomograph of Fig. 1. As already described with reference to Fig. 1, the detector 8 may comprise one, two or more energy resolving detector lines 30 and 5 34 and a plurality of lines 15 and 32 for measuring the attenuation of the primary fan-beam caused by the item of baggage 7. As may be taken from Fig. 3, preferably the detector 8 is arranged such that one line of the lines 15 and 32, preferably the middle line 15 of the detector 8, is within the slice plane of the fan-beam 11 and thereby measures the attenuation in the primary radiation. As indicated by arrow 42, the 10 radiation source of x-ray source 4 and the detector 8 are rotated together around the item of baggage to acquire projections from different angles.

As depicted in Fig. 3, the detector 8 comprises a plurality of columns t.

Fig. 4 shows another schematic representation of the geometry of the computer tomograph depicted in Fig. 1 for further explaining the present invention. In 15 Fig. 4, a detector 46 is depicted, comprising only one line 15 and only one line 30. The line 15 is arranged in the slice plane of the fan-beam 11 formed by the aperture system 9, which in this case is a slit collimator and generated by means of the source of radiation or x-ray source 4. The line 15 comprises, for example, scintillator cells or other suitable cells for measuring the attenuation of the primary beam of the fan-beam 20 11 and allows for an integral measurement of the attenuation of the primary fan-beam caused by the object of interest in the object region or examination region.

Line 30 depicted in Fig. 4 includes energy resolving cells. As may be taken from Fig. 4, the line 30 is arranged parallel to the slice plane of the fan-beam 11 but out of the plane. In other words, the line 30 is arranged in a plane parallel to the 25 slice plane and parallel to the line 15.

Reference numeral 44 indicates a scatter radiation, i.e. a photon scattered by the object of interest, such as the item of baggage. As may be taken from Fig. 4, the scatter radiation leaves the slice plane and impinges onto a detector cell of the line 30.

Fig. 5 shows a side view of the detector geometry of the computer 30 tomograph of Fig. 1. Fig. 5 can also be contemplated as showing a side view of Fig. 4, where, however, instead only the provision of one line 30 and one line 15, in Fig. 5, there is provided a plurality of detector lines 32 between the line 30 and the line 15. The

detector element D_i of the line 30 is an energy resolving detector element. The detector element D_i is arranged with a fixed distance a from the slice plane of the primary fan-beam. According to an aspect of the present invention, for each detector element D_i of the column t and for each projection Φ (see Fig. 3) a spectrum $I(E, t, \Phi)$ is measured.

- 5 Performing this measurement for a plurality of projections Φ along a circular or helical scan path, a three-dimensional dataset is acquired. Each object pixel is described by three coordinates (x, y, q) . Thus, according to an aspect of the present invention, for reconstructing an image or for reconstructing further information from the three-dimensional dataset, a $3D \rightarrow 3D$ reconstruction method such as the one described in DE 10 10252662.1, which is hereby incorporated by reference.

On the basis of the spatial coordinates (x, y) , a distance d of each object voxel S_i to the detector 8 is calculated by means of the calculation unit 18. Then, the calculation unit 18 calculates a scatter angle θ for each object voxel S_i and spaces of the following equation:

15
$$\theta = \arctan(a / d) \quad (\text{Equation 1}).$$

Then, on the basis of this calculation, the calculation unit 18 calculates the wave-vector transfer parameter q on the basis of the following equation:

$$q = \frac{E}{hc} \sin(\theta / 2) \quad (\text{Equation 2}),$$

- 20 wherein h is the Planck's constant and c is the speed of light and E the photon energy.

Then, on the basis of the wave-vector transfer parameter q calculated in accordance with the above formula and on the basis of the readouts of the primary radiation detector, the calculation unit 18 may determine an image or may discriminate the material in the object slice.

- 25 Fig. 6 shows a flowchart of an exemplary embodiment of a method of operating a computer tomograph of Fig. 1.

- After the start in step S1, an object of interest, such as an item of baggage 7, is placed into the examination area in step S2. Then, this method continues to step S3, where the source of radiation is energized for generating a fan-beam 11 of polychromatic radiation. In the subsequent step S4, the radiation to be measured by the scatter radiation detector, i.e. by the lines 30 and 34 of the detector 8, is collimated by
- 30

means of the collimator means.

Preferably, as indicated in step S4, the radiation is collimated into a fan beam. Then, the method continues to steps S5 and S7. In S5, the energy resolved scatter projection is measured by means of the energy resolving lines; i.e. lines 30 and 34 of
5 the detector 8. In step S6, which is performed subsequent to step S5, the energy measurement of the scatter radiation detector, i.e. lines 30 and 34 is read out.

In step S7, the primary beam projection is measured by means of the primary radiation detector, i.e. lines 32 and 15. In step S8 following S7, the primary beam projections are read out. Then, in step S9, following steps S8 and S6, the x-ray
10 source 4 and the detector 8, including the scatter radiation detector and the primary radiation detector are rotated by an increment. Then, the method continues to step S10, where it is determined whether a sufficient number of projections was acquired. In case it is determined in step S10 that further projections have to be acquired, the method returns to steps S7 and S5, such that steps S7, S8 and S5, S6 are performed parallel to
15 each other.

In case it is determined in step S10 that a sufficient number of projections was acquired, the method continues to step S11, where images are reconstructed on the basis of the readout. The reconstruction of the images in step S11 may, for example, include the tomographic reconstruction on the basis of the ART
20 algorithm or the filtered back projection technique (FBP).

After step S11, the method continues to step S12, where a material in the object of the interest is determined on the basis of the readouts or the reconstructed images. In case it is determined in the subsequent step S13 that the material contains explosives, the method continues to step S14, where an alarm is issued.

25 In case it is determined in step S13 that no explosives are contained in the object of interest, the method continues to step S15.

In step S15, the object of interest is moved along the rotational axis. Then, the method continues to step S16, where it is determined whether the full object of interest was scanned. In case it is determined in step S16 that the full object of
30 interest has not yet been scanned, the method returns to steps S7 and S5.

In case it is determined in step S16 that the full object was scanned, the method continues to step S17, where it ends.

Advantageously, the method described with reference to Fig. 6, according to an exemplary embodiment of the present invention, is highly time efficient, since the measurement of the primary beam projections and the energy resolved scatter projections is performed at the same time.

5 Figs. 7a and 7b show a flowchart of another exemplary embodiment of a method for operating the computer tomograph of Fig. 1 according to the present invention.

After the start in step S20, an object of interest such as an item of baggage 7 is placed into the examination area in step S21. Then, the method continues
10 to step S22, where the source of radiation 4 is energized for generating a polychromatic radiation. In the subsequent step S23, the radiation to be measured is collimated into a cone beam.

Then, in the subsequent step S24, a primary beam projection is measured by means of the primary radiation detector, i.e. the one or a plurality of lines 15 or 32.
15 Then, the method continues to step S25, where the primary beam projections are read out from the primary radiation detector.

In the subsequent step S26, the x-ray source 4 and the primary radiation detector are rotated by an increment. Then, it is determined in the subsequent step S27 whether a sufficient number of projections was acquired. In case it is determined in step
20 S27 that further projections have to be acquired, the method returns to step S24.

In case it is determined in step S27 that a sufficient number of projections was acquired, the method continues to step S28, where CT images are reconstructed on the basis of the readouts. Then, in the subsequent step S29, it is determined whether materials with suspicious attenuation values are in the object of
25 interest. In case it is determined in step S29 that there are no suspicious materials, i.e. materials with suspicious attenuation values in the object of interest, the method continues to step S30, where the object of interest is moved along the rotational axis. Then, from step S30, the method returns to step S23.

In case it is determined in step S29 that there is a material in the object of
30 interest which has suspicious attenuation values, the method continues to step S31, where the method jumps to step S40 in Fig. 7b. In step S41 of Fig. 7b, the object of interest is displaced such that a suspicious region containing the material with the

suspicious attenuation values of the object of interest is in the examination area. Then, in the subsequent step S42, the radiation emitted by the source of radiation 4 is collimated into a fan beam. In the subsequent step S43, a scatter radiation projection is measured by means of the scatter radiation detector, i.e. lines 30 and 34 of the detector

5 8. As mentioned above, the scatter radiation detector preferably consists of at least one line, comprising a plurality of energy resolving detector cells. Preferably these energy resolving detector cells are direct-converting semi-conductor detectors, which directly convert the radiation into electrical charges – without scintillation. Preferably, these direct-converting semi-conductor detectors have an energy resolution better than 20 %

10 FWHM.

Then, in the subsequent step S44, the energy resolved scatter data is read out and in the subsequent step S45, the x-ray source 4 and the scatter radiation detector are rotated by an increment.

In the subsequent step S46, it is determined whether a sufficient number

15 of projections was acquired. In case it is determined that further projections have to be acquired, the method returns to step S43. In case it is determined in step S46 that a sufficient number of projections was acquired, the method continues to step S47, where scatter function images are reconstructed on the basis of the readouts of step S44. Then, in the subsequent step S48, it is determined on the basis of the scatter function images,

20 whether or not the material with the suspicious attenuation values is an explosive or hazardous material. Then, in case it is determined in step S48 that there is a hazardous material or an explosive in the object of interest, the method continues to step S49, where the calculation unit 18 issues an alarm via the loud speaker 21. Then, from step S49, the method continues to step S50.

25 In case it is determined in step S48 that there is no material with a suspicious scatter function, i.e. no hazardous or explosive material in the object of interest, the method continues to step S50, where the method jumps back to step S32 in Fig. 7a. In step S32 in Fig. 7a, it is determined whether the full object was scanned. In case it is determined that the object is not yet fully scanned, the method continues to

30 step S20.

In case it is determined in step S32 that the full object was scanned, the method continues to step S33, where it ends.

According to an aspect of the present invention, the separation of the determination of the attenuation values and of the scatter radiation projections may be advantageous, insofar as a highly efficient method can be provided, where the measurement of the scatter radiation projection described with reference to Fig. 7b is
5 only performed for objects of interest containing material with suspicious attenuation values. Due to this, preferably a two step baggage detection system may be provided, which allows for a highly efficient and secure scanning of the objects of interest.

Advantageously, according to the present invention, a very good and improved spectral resolution can be achieved, even with a polychromatic primary
10 radiation emitted by a polychromatic source of radiation. Also, according to the present invention, as already mentioned above, only one energy resolving detector line may be necessary to measure the whole spectrum. In case a plurality of energy resolving detector lines are used, the q-range suitable for reconstruction can be extended. The q-range suited for reconstruction is explained in Fig. 8. Here exemplary an object
15 diameter of 40cm – centered around the Center of Rotation (CoR, Fig. 1, reference character 2) is assumed. Furthermore one detector line is placed 50cm from the CoR and 20mm off-set along the axis of rotation. From these geometrical considerations and using equation 2 it can be calculated that for all voxels in the object slice and for all rotational steps (projections) a q-range from $\sim 0.5\text{nm}^{-1}$ to 1.8nm^{-1} is measured by the
20 detector assuming further that the energy-resolved detectors measure the energy ranges 20...160 keV. If more than one detector line is used the same calculation has to be carried out for each line. The covered q-range is the sum of all individual q-range for each line. The q-ranges of the detector lines will overlap. The redundancy can advantageously increase the amount of detected photons for a given q-value, which in
25 turn reduces the measurement time and the dose applied to the object of interest and/or the noise of the data. Dose reduction is of primary concern particular in medical applications.

The energy resolving lines 30 and 34 may, for example, be assembled from individual cadmiumtelluride (CdTe), CZT or other direct-converting
30 semiconductor cells, which are arranged in a row.

Fig. 8 shows a diagram of measurements showing the relationship between a position of an object voxel S_i in the object, i.e. in the item of baggage 7 and

the wave vector transfer for various energies. The position of the object voxel S_i is indicated by a distance from the center of rotation CoR of the gantry 1. The distance a (see Fig. 5), namely the distance of the energy resolving detector element D_i to the slice plane is 20 mm and a distance between the CoR and the middles of the detector 8 is 500 mm. In other words, the detector line 30 or 34, which is energy resolving, is arranged at a distance of 20 mm from the slice plane.

Along the axis of abscissae of the diagram of Fig. 8, the distance from the CoR is mapped in millimeters and along the axis of ordinates, the wave vector transfer q , as calculated with the above formula (equation 2), is mapped in nm^{-1} . The various graphs in the diagram of Fig. 8 map the measurements for different energies in a range from 20 keV to 160 keV.

As can be taken from Fig. 8, in case a radiation is detected in the range from 20 to 160 keV, a complete dataset can be acquired for an object with a diameter of 400 mm for a wave vector transfer from $q = 0.5 \dots 1.8 \text{ nm}^{-1}$ as shown in the area between lines 50 and 52 in Fig. 7. In this range, most structures used for a material discrimination are located.

Advantageously, from the hardware point of view, except for the detector 8, a normal cone beam CT scanner or even a fan-beam scanner as known in the art may be used. For the application of the present invention, it is only necessary to provide a suitable aperture system and to add at least one energy resolving line 30 or 34 to the already existing detector.

CLAIMS:

1. A computer tomography apparatus for examination of an object of interest, the computer tomography apparatus comprising: a detector unit with an x-ray source and a scatter radiation detector; wherein the detector unit is rotatable around a rotational axis extending through an examination area for receiving the object of
5 interest; wherein the x-ray source generates a fan-shaped x-ray beam adapted to penetrate the object of interest in the examination area in a slice plane; wherein the scatter radiation detector is arranged at the detector unit opposite to the x-ray source with an offset with respect to the slice plane in a direction parallel to the rotational axis; wherein the scatter radiation detector includes a first detector line with a plurality of
10 first detector elements arranged in a line; wherein the plurality of first detector elements are energy-resolving detector elements.
2. The computer tomography apparatus according to claim 1, wherein the scatter radiation detector is arranged at the detector unit opposite to the x-ray source
15 parallel to the slice plane and out of the slice plane with such an offset along the rotational axis such that the scatter radiation detector is arranged for receiving a scatter radiation scattered from the object of interest, and wherein the computer tomography apparatus further comprises: a primary radiation detector; wherein the primary radiation detector is arranged at the detector unit opposite to the x-ray source in the slice plane
20 for receiving a primary radiation attenuated by the object of interest.
3. The computer tomography apparatus according to claim 2, wherein the energy resolving elements are direct-converting semi-conductor cells; and wherein the primary radiation detector includes a second detector line with a plurality of second
25 detector elements; wherein the second detector elements are scintillator cells.
4. The computer tomography apparatus according to claim 2, further comprising: at least one of a plurality of first detector lines and a plurality of second

detector lines; wherein at least one of the primary radiation detector and the scatter radiation detector is provided with collimator elements; and wherein the x-ray source is a polychromatic radiation source.

5 5. The computer tomography apparatus according to claim 2, further comprising: a calculation unit for reconstructing an image from readouts of the primary radiation detector and the scatter radiation detector; and wherein the computer tomography apparatus is adapted for the detection of explosives in the object of interest on the basis of the readouts of the primary radiation detector and the scatter radiation
10 detector.

6. A method of examining an object of interest with a computer tomography apparatus, the method comprising: energizing an x-ray source such that it generates a fan-shaped x-ray beam which penetrates the object of interest in an
15 examination area in a slice plane; performing an integral energy measurement of a scatter radiation by means of a scatter radiation detector with a first detector line with a plurality of first energy-resolving detector elements arranged in a line; reading-out the energy measurement from the scatter radiation detector; rotating the x-ray source and the scatter radiation detector around a rotational axis extending through an examination
20 area containing the object of interest.

7. The method of claim 6, further comprising the step of: reading-out a primary radiation attenuated by the object of interest by means of a primary radiation detector which is arranged opposite to the x-ray source in the slice plane.
25

8. The method of claim 7, further comprising the steps of: reconstructing an image from the readouts of the primary radiation detector and the scatter radiation detector; and determining whether the object of interest comprises explosives on the basis of the readouts of the primary radiation detector and the scatter
30 radiation detector by applying reconstruction; and issuing an alarm in case it is determined that the object of interest comprises explosives.

9. The method of claim 7, further comprising the steps of:
reading out measurements of at least one of a plurality of first detector lines of the
scatter radiation detector and a plurality of second detector lines of the primary
radiation detector; collimating the radiation for at least one of scatter radiation detectors
5 and the primary radiation detector; wherein the fan-shaped x-ray beam includes
polychromatic radiation.

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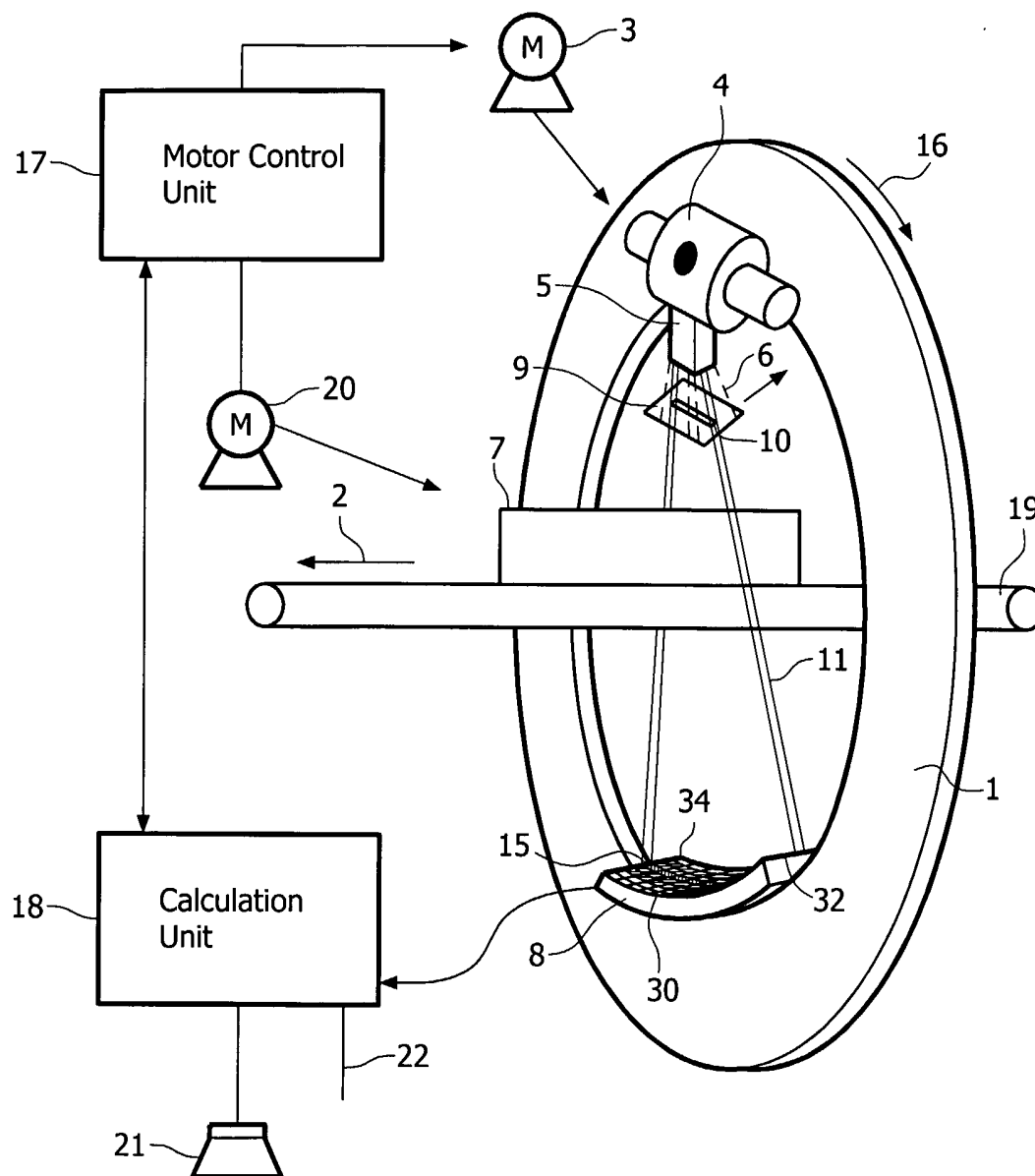


FIG. 1

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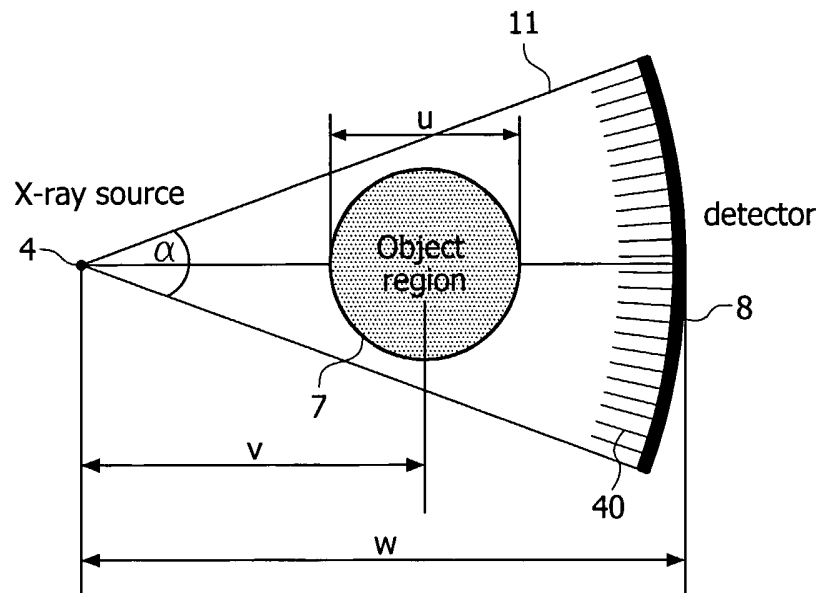


FIG. 2

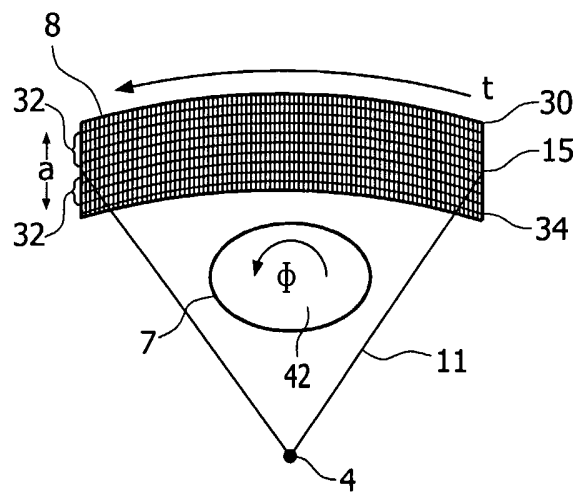


FIG. 3

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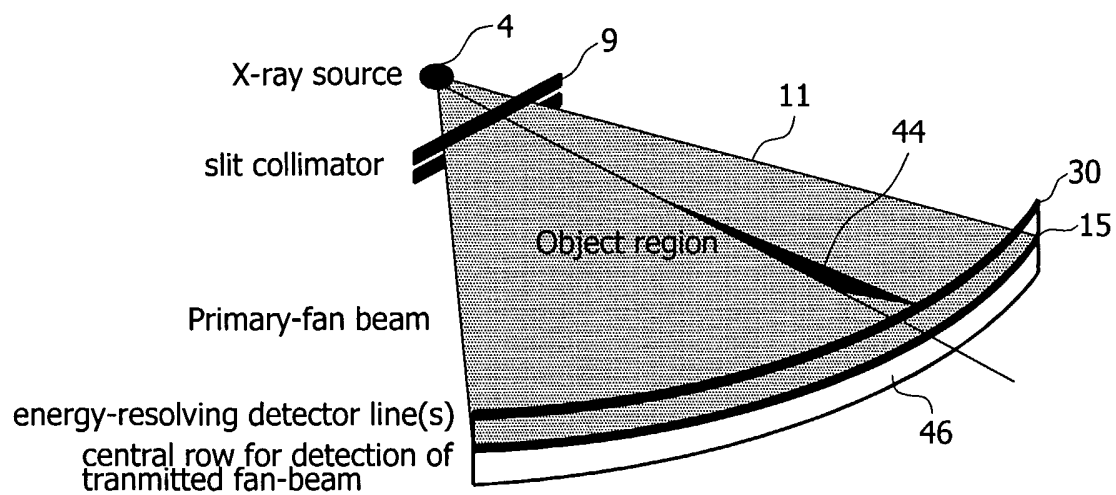


FIG. 4

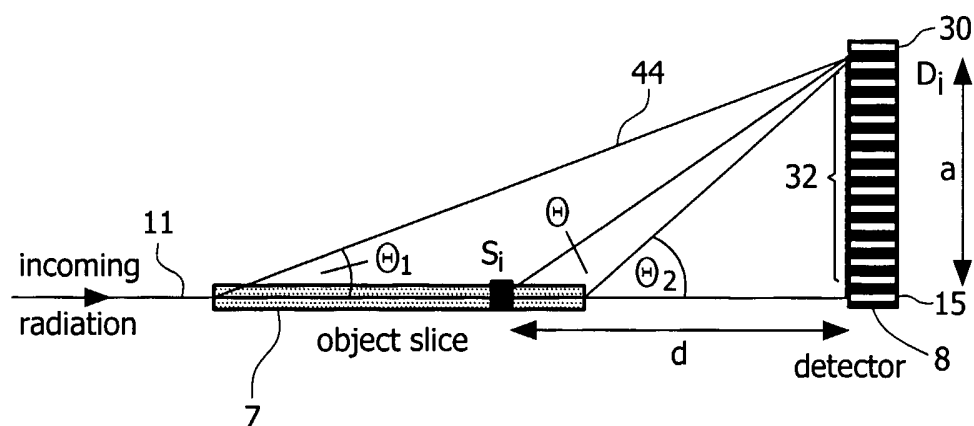


FIG. 5

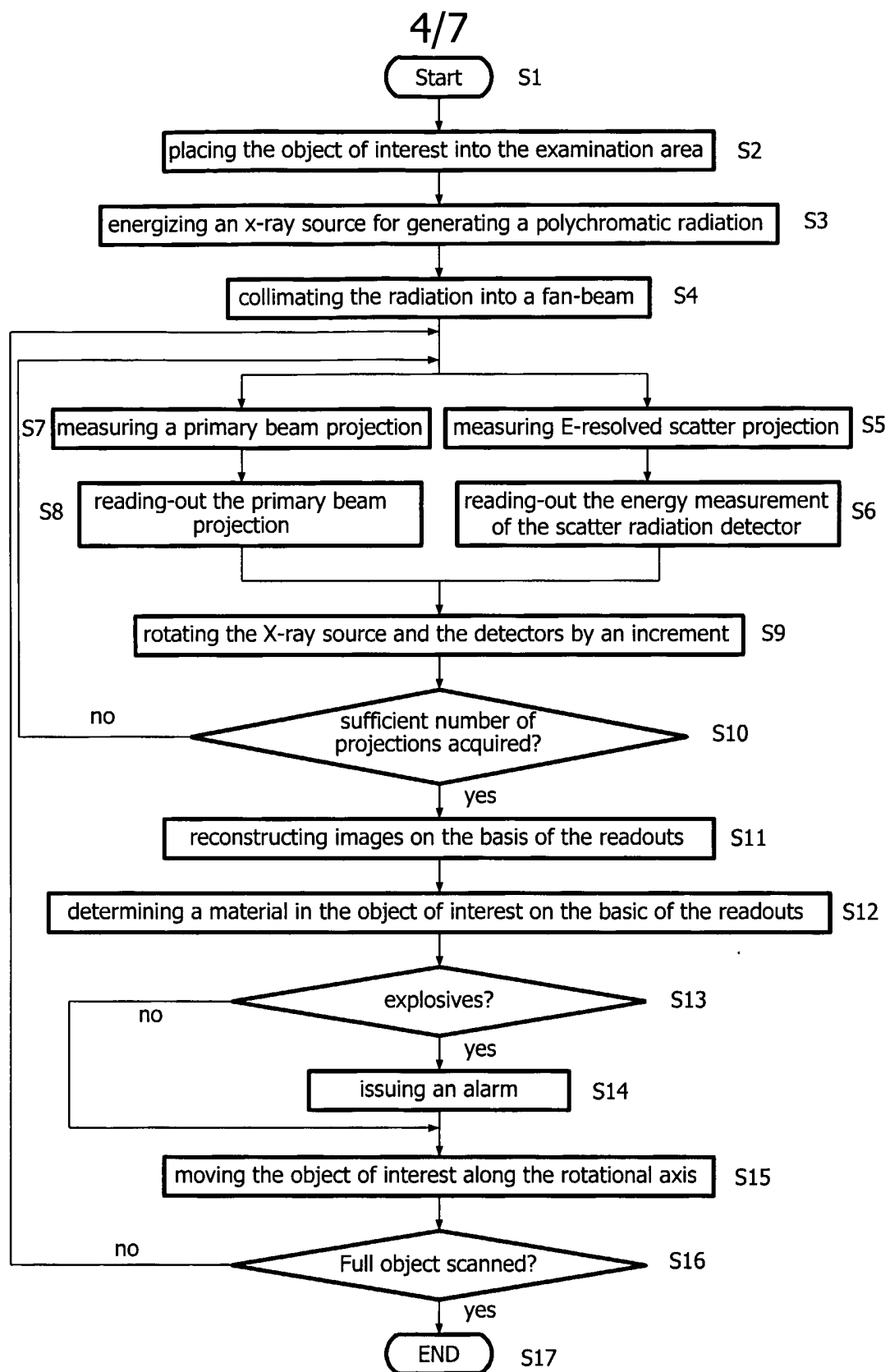


FIG. 6

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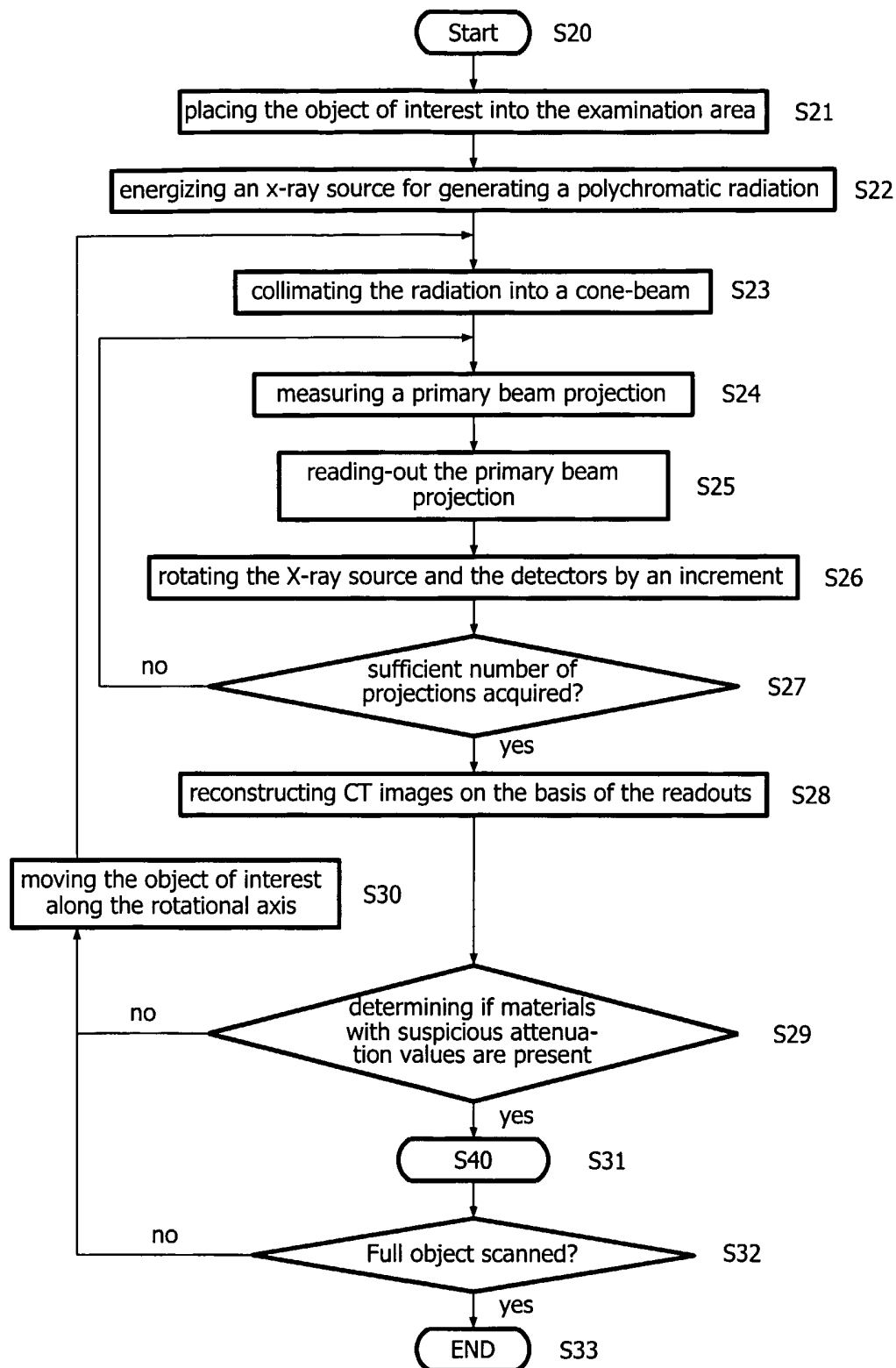


FIG. 7a

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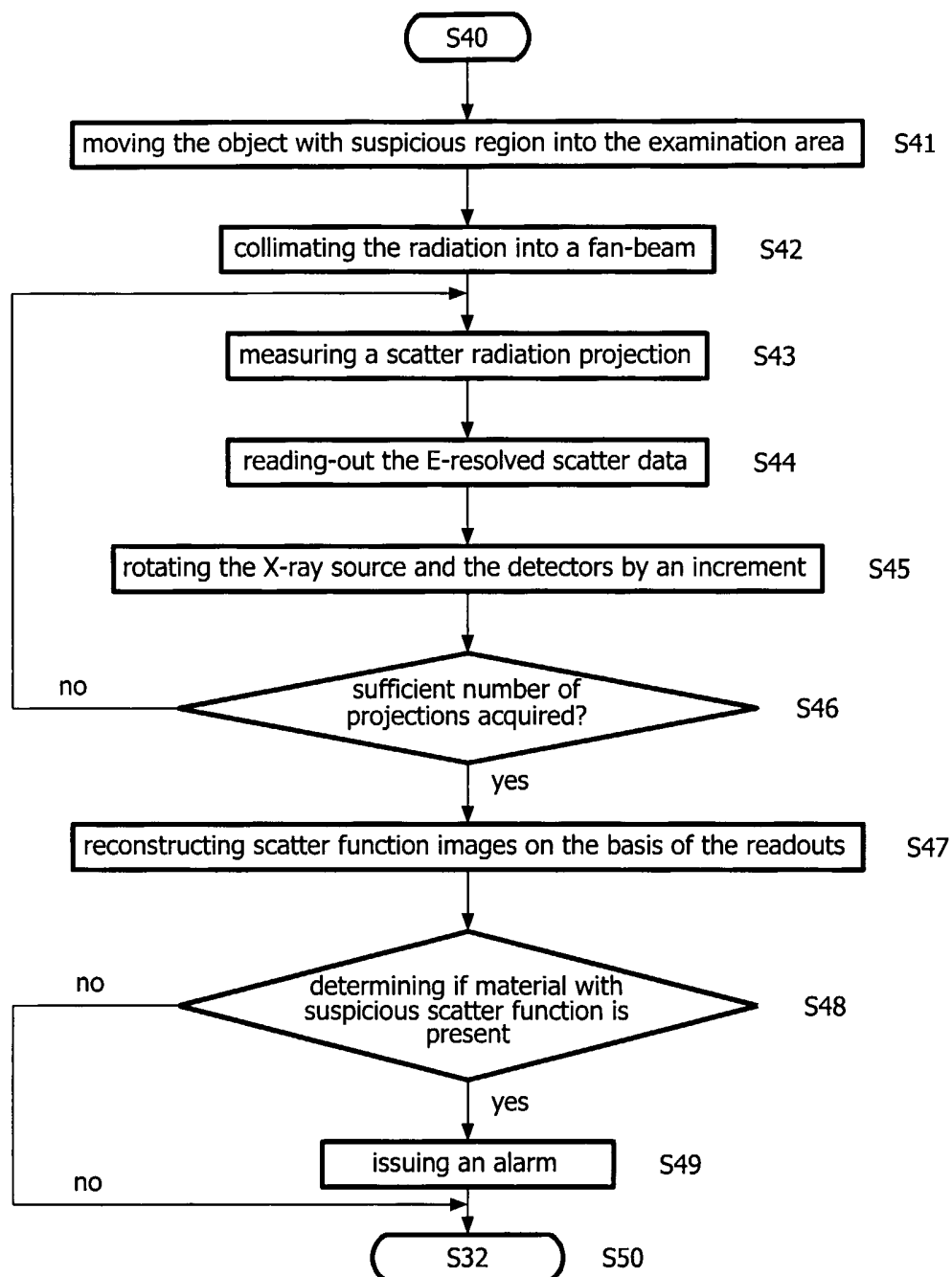


FIG. 7b

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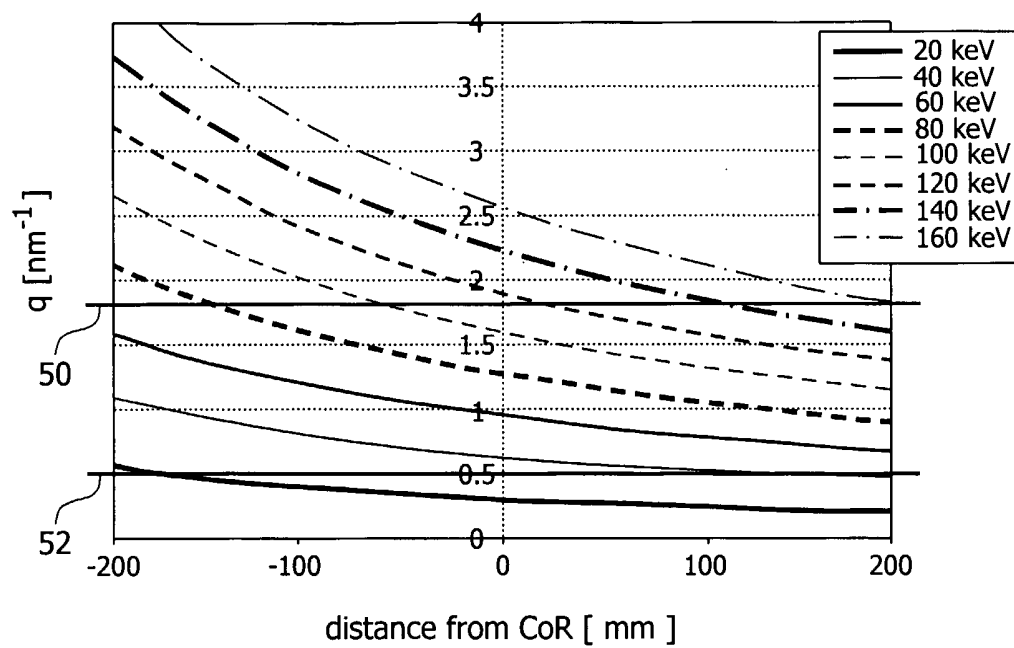


FIG. 8

INTERNATIONAL SEARCH REPORT

IB2004/050733

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A61B6/03 G01N23/04

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61B G01N

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 02/082065 A (KONINKL PHILIPS ELECTRONICS NV) 17 October 2002 (2002-10-17)	1-3,5-8
Y	abstract; figure 1 page 3, line 30 -page 4, line 34 page 6, line 25 -page 7, line 5	4,9
Y	US 5 696 806 A (GRODZINS LEE ET AL) 9 December 1997 (1997-12-09) abstract; figure 3 column 5, line 46 -column 7, line 61	4,9
A	US 4 754 469 A (NEITZEL ULRICH ET AL) 28 June 1988 (1988-06-28) column 3, line 12 - line 52	3
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☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

3 September 2004

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 008 911 A (HARDING GEOFFREY) 16 April 1991 (1991-04-16) abstract column 4, line 41 - line 44 ----	3
A	WO 98/33062 A (QUANTA VISION INC) 30 July 1998 (1998-07-30) abstract page 3, line 6 - line 24 page 4, line 16 -page 5, line 14 page 6, line 20 -page 10, line 11 -----	1,2,5,8

INTERNATIONAL SEARCH REPORT

Information on patent family members

IB2004/050733

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 02082065	A	17-10-2002	EP 1392167 A2 03-03-2004 WO 02082065 A2 17-10-2002 JP 2004519309 T 02-07-2004 US 2002150202 A1 17-10-2002
US 5696806	A	09-12-1997	US RE37899 E1 05-11-2002
US 4754469	A	28-06-1988	DE 3526015 A1 22-01-1987 DE 3682453 D1 19-12-1991 EP 0209952 A2 28-01-1987 JP 2607241 B2 07-05-1997 JP 62022052 A 30-01-1987
US 5008911	A	16-04-1991	DE 3832146 A1 05-04-1990 DE 3909147 A1 27-09-1990 DE 58909546 D1 08-02-1996 EP 0360347 A2 28-03-1990 JP 1903053 C 08-02-1995 JP 2191436 A 27-07-1990 JP 6028657 B 20-04-1994
WO 9833062	A	30-07-1998	RU 2119659 C1 27-09-1998 RU 2119660 C1 27-09-1998 AU 5929198 A 18-08-1998 AU 6039798 A 18-08-1998 CN 1216109 A 05-05-1999 CN 1216109 T 05-05-1999 EP 0898704 A1 03-03-1999 JP 2000512764 T 26-09-2000 WO 9833062 A1 30-07-1998 WO 9833063 A1 30-07-1998