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(71) Applicant: EMPIRE TECHNOLOGY DEVELOPMENT LLC [US/US]; 2711 Centerville Road, Suite 400, Wilmington, DE 19808 (US).

(72) Inventor: ADAM, Quentin, Authur, Carl; 7/238 Longueville Road, Lane Cove, New South Wales 2066 (AU).

(74) Agents: ENG, Kimton et al.; Dorsey & Whitney LLP, 701 Fifth Avenue Suite 6100, Seattle, WA 98104 (US).

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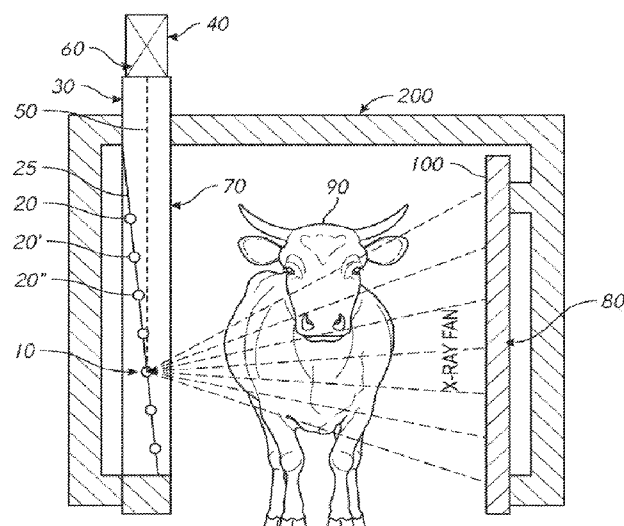


FIG. 1

(57) Abstract: An apparatus for creating x-ray beams suitable for imaging at least part of a body, comprising an x-ray tube comprising: an electrode gun providing an electron beam; at least one anode surface; an electron beam control means for controlling the location and angle that the electrons strike the anode surface, the electrons creating a beam of x-rays from the anode surface, the direction and position of the created x-ray beam being dependent on the location and angle the electrons strike the anode surface; and wherein the electron beam control means varies at least one of the location and angle that the electron beam strikes the anode surface to produce an array of x-ray beams at different angles to the anode surface.

X-RAY IMAGING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION(S)

- [001] This application claims priority to U.S. Provisional Application No. 62/165,740 filed May 22, 2015, the application of which is incorporated by reference in its entirety for any purpose.

BACKGROUND

- [002] Medical x-ray imaging systems, including computed tomography (CT) scanners facilitate internal imaging of bodies. Valuation of animals for food production is influenced by the overall composition of the animal and the arrangement of fat and lean meat within the muscles of the animal. X-ray imaging enables the inside of an animal to be imaged and can provide useful information. However, it is impractical to scale up existing medical x-ray imaging apparatus, for example computed tomography (CT) scanners, to the size required for imaging large animals including cattle. Additionally, the scanning times required by medical CT scanning apparatus would make imaging of live animals difficult due to significant blurring being produced on the image due to movement of the animal.

SUMMARY OF THE INVENTION

- [003] In some embodiments, an apparatus for creating x-ray beams suitable for imaging at least part of a body comprises an x-ray tube comprising: an electrode gun configured to provide an electron beam; at least one anode surface; an electron beam controller configured to control the location and angle that the electrons strike the anode surface, the electron beam creating a beam of x-rays from the anode surface, the direction and position of the created x-ray beam being dependent on the location and angle the electrons strike the anode surface. The electron beam controller may be configured to vary at least one of the location and angle that the electron beam strikes the anode surface to produce an array of x-ray beams at different angles to the anode surface.

- [004] In embodiments, the electron beam controller may be configured to vary at least one of the location and angle that the electrons strike the anode surface to produce a sweeping motion of the x-ray beam. In some embodiments, the sweeping motion of the electron beam may be in a plane.
- [005] In some embodiments, a plurality of x-ray beams may be produced in a plane.
- [006] In an embodiment, the energy of the electron beam is around 130 kV.
- [007] Embodiments comprise two or more anode surfaces, the anode surfaces being spatially separated.
- [008] In an embodiment, an anode surface is rotatable.
- [009] Embodiments comprise one or more bearings that support the anode surface within the ex-ray tube.
- [010] In an embodiment, the one or more bearings comprise electromagnetic bearings, ball bearings, roller bearings, liquid metal hydrodynamic bearings, or combinations thereof.
- [011] In an embodiment, the anode surfaces are located on a single anode.
- [012] In an embodiment, the anode surfaces are positioned on separate anodes.
- [013] In an embodiment, the anodes are arranged in a ladder formation, each anode forming a rung of the ladder.
- [014] In an embodiment, the electron beam control means is a magnet.
- [015] In an embodiment, the anode surfaces are partially at least one of cylindrical, curved, barrel or hourglass shaped.
- [016] In an embodiment, different voltages are applied across different anode surfaces.
- [017] In an embodiment, the x-ray tube comprises a narrow slot collimator to control the width of the x-ray beams emitted from the anode.
- [018] In an embodiment, the x-ray tube comprises a cooled mass positioned to reduce a temperature of at least one anode surface.
- [019] In some embodiments, an x-ray imager comprises an apparatus for creating x-ray beams suitable for imaging at least part of a body, for example such as described herein, and an x-ray detector, the x-ray detector being aligned to receive x-rays from the x-ray tube.

- [020] In some embodiments, an x-ray tube is moveable and movement of an x-ray detector is synchronized with the x-ray tube to retain alignment to receive x-rays from the x-ray tube.
- [021] In some embodiments, an x-ray tube and an x-ray detector are moveable in a vertical or horizontal plane.
- [022] In some embodiments, an x-ray tube and an x-ray detector are rotatable around at least part of an imaging subject.
- [023] In some embodiments, the invention comprises an animal x-ray imaging apparatus.
- [024] In some embodiments, a method for creating x-ray beams for imaging at least part of a body comprises providing an electron beam; and controlling the location and angle that the electron beam strikes an anode surface, the electrons creating a beam of x-rays from the anode surface, the direction and position of the created x-ray beam being dependent on the location and angle the electrons strike the anode surface; and changing at least one of the location and angle that the electron beam strikes the anode surface to produce x-ray beams at different angles to the anode surface.
- [025] In some embodiments, at least one of the location and angle that the electron beam strikes the anode surface may be varied, for example sequentially changed, to produce a sweeping motion of one or more x-ray beams.
- [026] In some embodiments, one or more x-ray beams are produced, each having a direction that may be swept in a plane.
- [027] In some embodiments, an energy of an electron beam may be adjusted, for example by adjusting an accelerating voltage applied to the electron beam.
- [028] In some embodiments, the angle of direction that the electron beams strike the anode may be controlled using a magnetic field and/or an electric field.
- [029] Embodiments comprise applying different voltages to different anode surfaces to produce x-ray beams of different energies.
- [030] Embodiments comprise rotating the anode within the x-ray tube.
- [031] In a fifth aspect, the invention provides a method for imaging an animal.

BRIEF DESCRIPTION OF THE DRAWINGS

- [032] Figure 1 is an illustration of an embodiment of an x-ray imaging apparatus;

- [033] Figure 2 is a top view of the embodiment of Figure 1;
- [034] Figure 3 is a representation of an anode ladder included in an x-ray imaging apparatus;
- [035] Figure 4 is an illustration of the x-ray patterns produced by an anode ladder in an x-ray imaging apparatus;
- [036] Figure 5 is an illustration of x-rays produced by an anode ladder in an x-ray imaging apparatus;
- [037] Figure 6 is an illustration of a top view of an x-ray tube;
- [038] Figures 7A-D illustrate multiple arrangements of x-ray tubes and x-ray detectors;
- [039] Figures 8A-D illustrate multiple arrangements of x-ray tubes and x-ray detectors;
- [040] Figure 9 illustrates multiple configurations of x-ray tubes and x-ray detectors;
- [041] Figure 10 illustrates further x-ray tubes.
- [042] Figures 11A-D illustrate multiple examples of bearings for x-ray tubes.
- [043] Figures 12A-B illustrate x-ray tubes having different collimators.
- [044] Figures 13A-D illustrate anodes having different shapes.
- [045] Figures 14A-C illustrate anode ladders having different shapes.
- [046] Figure 15 illustrates an anode ladder.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

- [047] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

[048] An embodiment of an x-ray apparatus suitable for imaging an animal, for example cattle, is shown in Figure 1. An x-ray tube 10 is positioned on one side of the apparatus. The x-ray tube 10 includes a series of anodes 20 20' 20'' etc. positioned in a ladder configuration 25 where the anodes form the rungs of the ladder. The axes of the anodes are offset with respect to each other in the vertical plane as shown in Figure 1. Anodes 20 20' 20'' are supported by a support structure forming the sides of anode ladder 25.

[049] Anode ladder 25 is positioned in glass vacuum tube 30. An electron gun 40 is located above the anodes and arranged to direct electrons on to anodes 20. Electrons from electron gun 40, shown in electron beam 50, are directed onto anodes 20. Anodes 20 are cylindrical or faceted tungsten which generate x-rays after collision of the electrons with the anodes at different angles depending on the angle of incidence at which the electron strikes the anode. Control of the angle and position at which the electron beam strikes the anode is provided by coil magnets or electrostatic deflector plates 60 positioned between the cathode and the anode.

[050] Some embodiments include a primary anode in the form of a ring that the electrons pass through, between the cathode and the target anode. In such embodiments most of the electron acceleration will occur between the cathode and primary anode. The deflection devices of magnetic field or electrostatic plates can be positioned on one or both sides of the primary anode to control the direction of the electron beam.

[051] For a particular anode, the electron beams are progressively directed across the perimeter to produce x-rays at different angles. This produces a fanning effect of x-rays covering a wide area. As the electrons are progressively moved across each anode in turn starting at 20, then on to 20', and on to then 20'' etc., the x-rays produce a fanning effect. The production of x-rays is discussed in more detail below with reference to Figure 2.

[052] A narrow slit collimator 70 runs lengthwise along the vacuum tube 30 to control the width of the x-ray beams protruding from the system. Collimator 70 limits the width of the emitted beam to produce a single 2D plane of x-rays. The system generates a large number of intersecting ray paths required for tomographic reconstruction.

[053] An x-ray detector 80 is positioned on the opposite side of the imaged object 90. X-ray detector 80 includes a narrow slot collimator 100 aligned with the incoming x-rays from the x-ray tube to limit receipt of x-rays to those in the plane of the x-ray tube. Further embodiments do not include a narrow slot collimator on the x-ray detector and allow receipt of x-rays out of the plane and at different positions. On detection of the different x-rays, x-ray detector 80 constructs an x-ray image of the object. The in-plane imaging would occur in the order of a millisecond.

[054] There are two main known imaging techniques, namely filtered back projection (FBP) and iterative reconstruction (IR). The first is an analytical method based on Fourier transform, FFT and convolution that comes together as filtered back projection (FBP) and implemented on a computer. The other method is iterative reconstruction (IR). IR is a computer intensive search method. IR can be useful because it is suited to limited angle tomography and truncated projections.

[055] The x-ray tube 10 and x-ray detector 80 are carefully aligned in order that those x-rays emitted by the anodes 20 and passing through collimator 70 are detected by detector 80.

[056] Referring now to Figure 2, in order to image in 3D x-ray tube 10 and x-ray detector 80 are mounted on a 1-axis translating gantry 200, the axis being perpendicular to the 2D scanning plane. Moving at a mechanical translating speed of 1 – 2 m/s, the gantry would sweep an animal, for example a cow, in a few seconds. The linear gantry 200 travelling at 1 m/s images planes at 1 mm intervals.

[057] The structural configuration of different embodiments of the system is shown in Figure 7. The structure of Figure 7C includes gantry 700 coupling x-ray tube 710 to x-ray detector 720 similar to the system of Figures 1 and 2. The gantry arrangement provides overall structural support and maintains alignment of the x-ray tube with the x-ray detector. X-ray tube 710 and x-ray detector 720 are connected onto a guide rail 730 via wheel systems 740 740'. In Figure 7C the anodes have length of around 500 mm and x-ray detector has a similar dimension.

[058] In the structure of Figure 7B, x-ray tube 712 is moveable along guide rail 732 via wheel system 742. X-ray detector 722 is a panel detector screen stretching the length of the guide rail and is fixed in position. Such systems simplify the x-ray detector.

- [059] The embodiment of Figure 7A includes a similar structure to that of Figure 7C without the gantry. X-ray tube 714 and x-ray detector 724 are moveable along the guide rails and movement is synchronized electronically.
- [060] Figure 7D shows a further embodiment including an x-ray detector 726 cantilevered to the x-ray tube 716.
- [061] In further embodiments the anodes extend along the length of the apparatus, for example up to 3 m, and the electron gun moves along length of the anode. While such embodiments require much longer anodes they provide an alternative to the short, moving, anode systems.
- [062] The x-ray arrangement may be configured to move in the horizontal plane, as shown in Figures 1, 2 and 7 or in the vertical plane as shown in Figure 8A. Embodiments configured to move in the vertical plane are useful in scanning hanging carcasses. Such vertical plane embodiments would also be useful in scanning standing human subjects.
- [063] Some embodiments may provide for rotational movement of the x-ray arrangements or the imaging subjects, as shown in the examples of Figures 8B to 8D. In the structure of Figure 8B, for example, x-ray tube 810 and x-ray detector 820 may rotate around imaging subjects via rotating Y-frame 830.
- [064] Figure 8D shows an example in which x-ray tube 814 and x-ray detector 824 are coupled to a track base 840 which may rotate, causing rotation of the x-ray tube 814 and x-ray detector 824 about a subject.
- [065] The rotating structural components used to couple the x-ray arrangements, such as Y-frame 830 or track base 840, may be positioned below hanging subjects, as shown, or above standing subjects in some embodiments.
- [066] Figure 8C illustrates an example having a static x-ray tube 812 and static x-ray detector 822 positioned around a rotating subject. A spreader 850 is provided for structural support and to facilitate rotation of the subject. The spreader 850 may hold portions of a subject in position for rotation, such as by propping open the legs of a carcass as shown.
- [067] Conventional CT scanning involves 3D images based on the attenuation of x-ray flux through the carcass. This gives geometric features and is used medically. The

direction of the technology is such that actual objective tissue characterization can be achieved with multispectral x-ray detectors and/or dual/multi energy x-ray generation.

[068] Different tissues will attenuate x-ray only very slightly so multi-spectral detector will help resolve this. The other technology is dual energy x-rays. In embodiments, x-ray generator operates at more than two voltage levels, for example 70 kV and 130 kV and the attenuation from these will vary slightly and show up in the projections.

[069] The basic machine operating at one voltage will show the tissue geometry and delineate muscle groups but the machine would have to accommodate multispectral and multi-energy technology.

[070] Anode ladder is now discussed in more detail with reference to Figures 3, 4 and 5. The following description concerns the production of x-rays only and assumed that the electron beams move in one dimension only in order to create a 2 dimensional plane of x-rays. In Figure 3, anodes 300, 300' and 300'' are positioned in a linear array at an acute angle to the vertical. Each anode is partially in the shadow of the previous anode with respect to the view from the electron gun. In Figure 3, electron beams A-E are produced by a single electron gun and are angled using the magnetic coils system. When striking the anodes, they are in a near parallel configuration.

[071] The angle of the x-rays created by the electrons depends on the angle of incidence of the electron beam onto the anode. Each distinct angle of incidence of the electron beam produces a different range of X-ray deflection angles. In this arrangement some electron beams will produce X-rays off the anodes emanating at angles too small or too large (grazing angle) to be detected by the x-ray detector (not shown), for example beams A' and E'' respectively. Figure 3 illustrates how a fanning effect of x-rays is produced by progressively changing the angle of incidence of the electron beam on the anode from beam A to beam E.

[072] In embodiments the electron beam is incrementally moved around the surface of the anode and down the anode ladder. This changes the angle of incidence as well as the contact point to produce x-rays at different angular ranges moving down the anode ladder producing a fanning effect. In further embodiments electron gun moves along the anodes. It is beneficial to change the collision point of the electron beam with the anode (the 'spot') since the temperature at the spot can get very high and burn out.

Changing this collision point can greatly increase the number of x-rays produced and prevent burnout of the anode.

[073] Beam spreading will cause the X-rays to fan out due to X-ray fluorescence or Bremsstrahlung at an angle of approximately 30 degrees. The collimator is used to control the alignment of x-rays coming out of the tube if needed. Figure 12A is a top view of the anode ladder 1200 with a narrow collimator 1210 to produce a column shaped x-ray beam. In some embodiments, as shown in Figure 12B, the width of the collimator 1240 is increased to produce a cone shaped x-ray beam 1250. Such embodiments require a wider detector plate 1260 to catch and analyze x-rays.

[074] Additional control of beam spreading for each x-ray fan in the imaging slice plane can be achieved by reducing the cylindrical anodes into quarter sectors and orientating them to control the angular limits of the X-ray fans as shown in Figure 5.

[075] Figure 4 shows a simplified version of an embodiment in which only three anodes 400, 400', 400'' are shown, representing the top, middle and bottom anodes in the anode ladder. Vertical 410 is shown for illustration purposes to show the angle of the anode ladder. Further embodiments may include 20 or more anodes in the anode ladder. The angular range of x-rays required to be produced from each anode depends on the dimensions of the system and the size and position of the imaging subject. Factors affecting the angle limit required from each anode would also depend on, for example, the distance of the imaging subject from the anode ladder (f). The x-ray fan shapes from each anode are shown as F400, F400' and F400'' respectively. The number of anodes, distance to the subject, minimum number of intersecting X-ray paths and practical fan angles would all influence the performance of the concept.

[076] The angular range for each anode may be configured for the system or, additionally, may be configured for the particular imaging subject. The angular range can be controlled by the angle of incidence of the electron beam on the anode, the position the electron beam strikes the anode and the angular positioning of the anode. In embodiments these angular requirements and physical coordination is determined automatically by processors in the system.

[077] Figure 5 below illustrates the orientation of the anodes and the lateral X-axis displacement in a system including only three anodes N500, N500', N500''. As shown in the configuration of Figure 5, each angle of electron beam incidence onto an anode

produces a range of x-ray deflection angles. As the electron beam path progresses to the right each anode in turn creates a fan of rays within the angular limits shown in Figure 5. Each anode is rotated slightly anti-clockwise with respect to the one above.

[078] In an anode ladder having vertical height of 2 m and anodes having radius of 15 mm, then the step displacement ΔX varies between anodes but is typically around 6 mm. For 20 anodes this means the ladder would have to project $20 \times 6 \text{ mm} = 120 \text{ mm}$ in the X-axis.

[079] As each fan of X-rays sweeps clockwise around each anode target the intensity of the incident X-rays on the column of detectors would vary so that when the electron beam passes over all 20 anodes the detectors would see 20 fast flashes with variable intensity distributions. The variations are calibrated and handled by the electronic hardware and software so that adjusted intensity is flattened out. Alternatively, the intensity may be flattened out by electronic control of the electron gun current or the dwell time/speed variation over portions of each anode surface. In embodiments, the electron beam is arranged to digitally step through locations over the cylindrical surface of the anodes if the electron beam diameter (perhaps $< 50 \text{ }\mu\text{m}$) is small enough relative to the anode radius.

[080] In embodiments, each anode is switched into the circuit one by one in a cascading sequence so the electric field appears to stretch rapidly along the anode ladder. Embodiments use voltages between 50 kV to 150 kV.

[081] The anode ladder is supported structurally by a beam or channel implemented of steel, stainless steel, aluminum, copper, or combinations thereof. In embodiments, the supporting beam includes holes to receive the anodes. In some embodiments, a computer controlled mill is used to drill the holes so that the precision of locating the anodes relative to each other is handled relatively economically by this operation with the right angle sides of the sector used as a reference. In embodiments, the anodes are clipped into place but have to be connected electrically.

[082] Typically, electron beam tomography does not require anode cooling because the electron beam does not stay on any one anode for any length of time, for example 0.05s in the example discussed above. The anode does have a thermal mass and this would have an impact on the size of the anode, particularly the width (axis wise) and how the anode is fabricated (carbon core/tungsten outer etc.). In embodiments, the

anode materials and dimensions are selected to meet the requirements of the system including the required cooling properties. In some examples, anode cooling may be provided for use with high voltages..

[083] Figure 6 illustrates the cross section of the evacuated glass tube 600 containing the ladder 610 including multiple anode rungs 620 620' 620'' and is the view as seen from the electron gun. The anodes are supported by structural beam 630. Collimating slot 640 limits the path of x-rays from the x-ray emitter. The electron beam's focal point moves up and down this ladder to strike the different anodes. In an embodiment, the depth of the beam is about 140 mm and the inside diameter of the tube about 160 mm for the 2 m vertical ladder described previously. The cross sectional shape of glass tube 600 may be circular, as shown, or a variety of other shapes, for example elliptical.

[084] Glass is relatively transparent to low energy X-rays and used to form the vacuum tube 600 in embodiments. For higher energy rays it is possible to integrate the ladder beam/channel and the tube into one metal part with a thin window, implemented of aluminum, titanium, beryllium, or combinations thereof, that would be transparent at low energies but filter out 'softer' X-rays. Any out of fan plane X-rays are blocked by the collimating slot. The design of the collimator slot depends on how the vacuum seals are implemented on the pressure envelope and the choice of X-ray energy. In embodiments, annular and cylindrical surface joints used due to their sealing properties but further embodiments use different methods to seal the vacuum including O-rings and gaskets. Embodiments include a vacuum pump as a permanent part of the system.

[085] Further embodiments of the invention include multiple x-ray tubes and x-ray detectors, as shown in Figure 9. Multiple x-ray tubes and detectors can be arranged in different configurations as shown in Figures 9B to 9E. In Figure 9B, the beams from x-ray tubes 900 are offset to capture images of different cross sectional portions of the imaging subject.

[086] The arrangements of crossed beams shown in Figure 9C and perpendicular beams shown in Figure 9D provide further opportunities for different imaging patterns. Such embodiments use the IR and FBP reconstruction techniques discussed above but the projections coming from multiple angles increases accuracy within the imaged slice plane.

[087] Particularly for imaging vertically-oriented subjects, such as hanging carcasses, multiple x-ray tubes 910 can be arranged end-to-end in the vertical plane, as shown in Figure 9E. Such embodiments may feature rotating x-ray arrangements or rotating imaging subjects, as shown in Figures 8B to 8D.

[088] In the embodiments described above the anodes are discrete elements within the anode ladder, illustrated from a side view in Figure 10A, which shows anode ladder 1010 and cathode 1014 inside x-ray tube 1012. However, in further embodiments alternative anode configurations are used to create x-rays. In the embodiment of Figure 10 B, for example, flat bar anode 1020 is included in place of discrete anodes within x-ray tube 1022. The angular range of X-rays emanating from the surface of anode 1020 will vary depending on the different angles formed by deflecting the incident electron beam via one or more deflection devices 1028 placed between anode 1020 and cathode 1024. Anode 1020 may comprise various upper surface profiles. In one embodiment, for example, the surface of anode 1020 may be curved.

[089] Figure 10C illustrates a further embodiment comprising saw tooth anode 1030 within x-ray tube 1032. The saw tooth structure includes variable angles and pitch to facilitate different angles of x-ray creation at different angles of incidence of the electron beam. In embodiments, the anode is segmented into separate regions which can be activated separately for x-ray production. The segments simplify manufacturing and accommodate any thermal expansion of the anodes since the local temperature can increase to between a few hundred degrees C up to a couple of thousand at the ‘spot’ (in a tiny zone) where the electron beam strikes the anode.

[090]

[091]

[092] In some examples, variously-shaped anodes may be provided that may rotate within an x-ray tube. Rotating flat bar anode 1040 and rotating saw tooth anode 1050 are shown in Figures 10E and 10E, respectively. As shown, both embodiments include one or more bearings 1070, 1080 positioned near the ends of each anode to support rotation of each anode body.

[093] Rotating the anode may reduce damage inflicted on one or more anode surfaces by the incident electron beam, for example at high voltages. Increased focal spot temperatures of the anode surface driven by recurrent electron beam exposure may

cause the surface coating of the anode, often implemented of tungsten, tungsten alloys molybdenum, or combinations thereof, to wear. Rotating the anode may reduce the exposure time of the electron beam at discrete impact points along the anode surface, thereby dissipating the focal spot temperature and likely improving the lifespan of the anode in some examples.

[094] Some examples with rotating anodes may be able to accommodate higher energy loads. To counteract increased anode surface temperatures that may accompany higher energy levels, a cooled mass 1046, 1056 may be positioned adjacent to the anode within the x-ray tube to facilitate radiative cooling. Static anode arrangements may feature a cooled mass 1026, 1036 positioned outside the x-ray tube. In the examples depicted in Figures 10A to 10E, cooled masses 1026, 1036, 1046, 1056 may be implemented using water, various liquids, air, gas, or combinations thereof.

[095] The examples shown in Figures 10A to 10E also include deflection devices 1018, 1028, 1038, 1048, 1058. As illustrated, the deflection devices may be positioned in a portion of the x-ray tube near the cathode. Such deflection devices may also be positioned within the broader body of the x-ray tube. In some examples, one or more deflection devices may be positioned on one or both sides of a primary anode ring, also positioned in either the narrow portion or broader body of the x-ray tube.

[096] Examples of bearing arrangements used to secure each rotating anode within an x-ray tube are shown in Figure 11. The example illustrated in Figure 11A includes conductive ball/roller bearings 1110 comprised of a metallic material. Bearings 1110 are positioned within x-ray tube 1112, electrically linking x-ray tube 1112 to anode 1114. Establishing electrical contact with x-ray tube 1112 may ground anode 1114.

[097] Figure 11B shows an example including liquid metal hydrodynamic bearings 1120 that may establish electrical contact between x-ray tube 1122 and anode 1124, thereby grounding anode 1124. Bearings 1120 also establish thermal contact between x-ray tube 1122 and anode 1124, which may foster heat transfer, cooling anode 1124 in some examples.

[098] The example depicted in Figure 11C includes electromagnetic bearings 1130 positioned outside x-ray tube 1132, and a carbon or metallic shaft 1136 at the end of suspended anode 1134. As shown, a conductive carbon fiber brush 1138 may be used to connect x-ray tube 1132 to shaft 1136, thereby establishing electrical and thermal

contact between the two components. In some examples, magnetic bearings 1130 collect magnetic dust produced within x-ray tube 1132.

[0099] The example depicted in Figure 11D includes externally-positioned electromagnetic bearings 1140. Electrical contact may be made by inducing a local current in a joule-heated wire coil 1148 positioned inside a shaft 1146 at the end of suspended anode 1144. Due to thermionic emission, heating wire coil 1148 may generate a conductive electron cloud 1141 locally surrounding shaft 1146 which may establish electrical contact between anode 1144 and x-ray tube 1142. In some examples, a laser may be used to heat the coil.

[0100] Further embodiments include different shaped anodes. In some embodiments the rise of the saw-tooth is rounded. In some embodiments, the tip of each saw tooth could be bunted to stop over heating at the tip. Some embodiments include cuts in the anode to allow local expansion.

[0101] In embodiments, the surface of the anodes can be planar, as in the cylindrical anode embodiments shown in Figure 3 or could be convex or concave or some compound shape as shown in Figures 13A, B, C and D so the surface is cylindrical, conical or elliptical or a mix of these.

[0102] In further embodiments of the anode ladder, the shape of each anode can vary so it is not limited to cylindrical shapes but could be barrelled, pinched, conical, bi-conical or a compound geometry of these. Anodes of different shapes may be included as different rungs in a single anode ladder.

[0103] Figure 14 shows the view from the electron gun for anode ladders having straight (Figure 14A), convex (Figure 14B) and concave (Figure 14C) profiles. The different profiles generate different x-ray patterns. X-ray direction can be controlled by using multiple collimators as shown in Figure 15.

[0104] Embodiments have many different applications including 3D medical imaging as well the agricultural applications discussed above. Embodiments provide x-ray imaging at high speed and deliver lower radiation doses compared with other x-ray methods including CT scanning. The speed of the imaging makes the system less prone to image blurring due to movement of the subject. Embodiments enable patients to be scanned in vertical as well as horizontal positions. In particular, vertically traversing mini gantries provide a smaller system foot print compared with existing x-

ray systems. Also it would be possible to use the system as the medical equivalent of a 3D 'flatbed scanner' with the patient lying on or standing near a large surface array of detectors.

[0105] Example apparatus and methods include security screening of shipping containers, particularly large items that may be difficult to place in a helical/spiral CT scanner.

[0106] In some embodiments, the physical size of the equipment may be significantly smaller than conventional EBT or the large gantry ring of a spiral CT scanner and mechanically much simpler. Anode ladder makes using EBT more practical and economic.

[0107] In some examples, an x-ray tube (which may also be referred to as an x-ray source) comprises an electrode gun configured to provide an electron beam; an anode surface; and an electron beam controller configured to control the location and angle that the electron beam strikes the anode surface. The interaction of the electron beam and the anode surface generates a beam of x-rays from the anode surface where the electron beam is incident, and the path (such as the direction) of the x-ray beam may depend on the location and angle the electron beam strikes the anode surface. The electron beam controller may be configured to vary at least one of the location and angle that the electron beam strikes the anode surface to produce a plurality of paths of the x-ray beam. In some embodiments, an electron beam controller may be configured to vary at least one of the location and angle (e.g. relative to the anode surface) that the electron beam strikes the anode surface, for example to produce a plurality of x-ray beam paths. In some examples, the electron beam controller may produce a sweeping motion of the x-ray beam. In some examples, the sweeping motion of the electron beam may be in a plane.

[0108] In some examples, an anode may have a curved surface, so that the x-ray beam path may be adjusted by varying an incidence location where the electron beam is incident on the anode surface. In some examples, incidence location may be varied by at least one of: operation of the beam controller; movement of the anode (e.g. rotation of the anode, displacement of the anode, or some combination); and movement of the electron gun (e.g. displacement of the electron gun relative to the anode, angular

adjustment (e.g. directing the electron beam along a different angle relative to another apparatus component), or some combination thereof).

[0109] In some embodiments, a plurality of x-ray beams may be produced in a plane. In some embodiments, a plurality of electron beams may be directed (e.g. by one or more electron beam controllers) so that each electron beam is incident on a different anode surface, e.g. each electron beam is incident on a different anode of a plurality of anodes).

[0110] In some examples, an x-ray source may comprise a plurality of discrete anodes. In some examples, an x-ray source may comprise a plurality of anodes, the anodes being spatially separated. An electron beam may be directed onto one of the anodes, and the resulting x-ray beam path varied by e.g. adjusting the electron beam path using the electron beam controller. The electron beam may then be directed onto a second anode of the plurality of anodes, and the resulting x-ray beam path may then be varied. This approach may be repeated for the electron beam incident on some or all of the plurality of anodes.

[0111] In some embodiments, the energy of the electron beam may be in the range 50 kV – 200 kV. In some example, the energy of the electron beam may be about 130 kV. A similar range may be used for the electric potential between the electron gun and anode.

[0112] In some embodiments, a plurality of anode surfaces are located on a single anode. In some examples, an anode may be rotated or otherwise spatially adjusted to vary the path of an x-ray beam. For example, an anode may have a plurality of curved and/or plane surfaces, and e.g. rotation of the anode may adjust the x-ray beam path by varying e.g. an angle between the electron beam and the anode surface where the electron beam is incident on the anode surface. In some embodiments, a plurality of anode surfaces are positioned on spatially separate anodes.

[0113] In some embodiments, a plurality of anodes may be arranged in a ladder-like formation. For example, the anodes may be arranged in a linear array with generally equal spatial separations between the anodes. In some examples, anode separation may be varied between different neighboring anodes. In some examples, a plurality of anodes may be arranged spaced out along a direction of anode arrangement. In some examples, the direction of anode arrangement may be at an oblique angle to the

direction of elongation of an x-ray tube, for example to reduce shadowing of anodes from the electron beam by other anodes located closer to the electron gun.

[0114] In some embodiments, an electron beam controller may comprise a magnet configured to produce a magnetic field that may deflect the electron beam. For example, an electron beam controller may comprise an electromagnet. In some examples, an electron beam controller may comprise one or more electrodes configured to deflect an electron beam according to an electrical potential between the electrodes.

[0115] In some embodiments, an anode surface may be curved. In some examples, an anode surface may be at least in part at least one of cylindrical, barrel or hourglass shaped. In some examples, an anode surface may be generally planar. In some examples, the position and/or orientation of an anode surface may be adjusted to vary the path of an x-ray beam produced on the anode surface. In some examples, a motor, such as a stepper motor, may be used to rotate an anode (and any surface thereon). In some examples, an actuator may be used to move the anode surface.

[0116] In some embodiments, an x-ray source may comprise one or more a narrow slot collimators configured to control the width of (e.g. respective) one or more x-ray beams emitted from the anode(s).

[0117] In some embodiments, an x-ray imager comprises an x-ray tube, for example an x-ray tube such as described herein, and one or more x-ray detectors, the one or more x-ray detectors being configured (e.g. located) to receive x-rays generated by the x-ray tube.

[0118] In some embodiments, an x-ray tube may be moveable and movement of an x-ray detector may be synchronized with the x-ray tube to retain alignment to receive x-rays from the x-ray tube. In some embodiments, the movement of an x-ray detector may be synchronized with a change in an x-ray path through a subject, so that the x-ray absorption of the subject along the path (or subsequently reconstructed by tomography) may be determined.

[0119] In some embodiments, apparatus and methods configured to image a living subject, such as an animal, are provided. In some embodiments, an x-ray imaging apparatus may comprise apparatus as described herein. X-ray imaging methods may similarly use apparatus as described herein. However, the subject need not be limited to a living subject.

[0120] In some embodiments, a method for creating x-ray beams for imaging at least part of a subject comprises providing an electron beam, and controlling the location and angle that the electron beam strikes an anode surface to create an x-ray beam from the anode surface. The path (e.g. direction and position) of the x-ray beam may be varied dependent on the location and angle that the electron beam strikes the anode surface. Changing at least one of the location and angle that the electron beam strikes the anode surface may produce x-ray beams at different angles to the anode surface.

[0121] In some embodiments, the x-ray beams may be detected by one or more x-ray detectors after passing through a subject. In some examples, computed tomography may be used to reconstruct an x-ray absorption image of the subject from detected x-ray intensities. In some examples, characteristics of a subject may be rapidly determined, for example within a few minutes, so that a living subject such as an animal need not be immobilized for a prolonged period. In some examples, determined characteristics of the subject may include health parameters such as body fat percentage, lean meat percentage, and the like. In some examples, the subject may be a human, or an animal, such as a mammal, for example a livestock animal such as bovine mammal (such as cattle, buffalo, yaks, and the like), sheep, goats, an equine animal (such as a horse, donkey, or zebra), and the like. In some examples, the subject may be a marsupial, such as a kangaroo, wallaby, and the like.

[0122] In some embodiments at least one of the location and angle that the electron beam strikes the anode surface may be varied, for example sequentially and/or progressively changed, to produce a sweeping motion of one or more x-ray beams through a subject. In some examples, an x-ray beam path may be stepped through a plurality of angles, for example predetermined angles.

[0123] In some examples, x-ray imaging may be combined with identification of the subject, for example using tags attached to the subject. Characteristics of the subject may be stored in a computer memory and associated with the subject identity, and optionally other parameters such as a time, date, other collected parameters, and the like.

[0124] In some embodiments, one or more x-ray beams, such as a plurality of x-ray beams, are produced, each x-ray beam having a direction that may swept or otherwise varied in a plane allowing imaging of a subject. In some examples, an electron beam

may have a first portion that is incident on a first anode, a second portion that is incident on a second anode, and the like. The first and second portions of an electron beam may be parallel portions of an electron beam of appreciable lateral extent. In some examples, a plurality of electron beams may be simultaneously directed at a plurality of anode surfaces, for example each beam being directed at a different anode. In some examples, a single electron beam may be used, and directed towards a selected anode. An anode may be selected for electron beam incidence using e.g. the electron beam controller, electrical potentials applied to the anodes, movement of the anode and/or electron gun, and the like.

[0125] In some embodiments, the angle of direction that the electron beams strike the anode may be controlled using at least one of: a magnetic field, an electric field, movement of the electron beam (including lateral movement or angular movement of an electron gun), movement of the anode surface (for example, rotation and/or displacement of the anode), and the like.

[0126] In some embodiments, different voltages may be applied to different anode surfaces to produce x-ray beams of different energies. In some embodiments, an energy of an electron beam may be adjusted, for example by adjusting an accelerating voltage used to accelerate the electron beam towards the anode surface. For example, the electric potential between the electron gun and the anode may be higher for anodes that are physically further away from the electron gun. In some examples, an voltage may be selectively applied to one or more of the anodes, on which electron beam incidence is desired. Other anodes may be grounded, or imbued with an electric potential that may repel and/or steer an electron beam directed at another anode.

[0127] Modifications and variations as would be apparent to a skilled addressee are deemed to be within the scope of the present invention.

[0128] In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word “comprise” or variations such as “comprises” or “comprising” is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

CLAIMS

What is claimed is:

1. An apparatus for creating x-ray beams suitable for imaging at least part of a body, comprising:

an x-ray tube comprising:

an electrode gun providing an electron beam;

an anode surface;

an electron beam controller configured to control at least one of a location and an angle that the electron beam strikes the anode surface,

the electron beam generating a beam of x-rays from the anode surface when the electron beam strikes the anode surface,

the direction and position of the x-ray beam being dependent on the location and the angle that the electron beam strikes the anode surface; and

wherein the electron beam controller varies at least one of the location and angle that the electron beam strikes the anode surface to vary the direction of the beam of x-rays.

2. An apparatus according to claim 1 wherein the electron controller sequentially varies at least one of the location and the angle the electrons strike the anode surface to produce a sweeping motion of the x-ray beam.

3. An apparatus according to claim 2 wherein the sweeping motion of the x-ray beam is produced in a plane.

4. An apparatus according to claim 1 wherein the energy of the electron beam is around 130 kV.

5. An apparatus according to claim 1, 2, 3 or 4 comprising two or more anode surfaces, the anode surfaces being spatially separated.

6. An apparatus according to claim 5 wherein the anode surfaces are located on a single anode.

7. An apparatus according to claim 1, wherein the anode surface is rotatable.

8. An apparatus according to claim 1, wherein one or more bearings support the anode surface within the x-ray tube.

9. An apparatus according to claim 8, wherein the one or more bearings comprise electromagnetic bearings, ball bearings, roller bearings, liquid metal hydrodynamic bearings, or combinations thereof.

10. An apparatus according to claim 5 wherein the anode surfaces are positioned on separate anodes.

11. An apparatus according to claim 10 wherein the anodes are arranged in a ladder formation, each anode forming a rung of the ladder.

12. An apparatus according to claim 1 wherein the electron beam controller comprises a magnet.

13. An apparatus according to claim 5 wherein the anode surfaces are partially at least one of cylindrical, curved, barrel or hourglass shaped.

14. An apparatus according to claim 5 wherein different voltages are applied across different anode surfaces.

15. An apparatus according to claim 1 wherein the x-ray tube comprises a narrow slot collimator configured to control the width of the x-ray beam emitted from the anode.

16. An apparatus according to claim 1 wherein the x-ray tube comprises a cooled mass positioned to reduce a temperature of at least one anode surface.

17. An x-ray imaging apparatus comprising the apparatus of claim 1 and an x-ray detector, the x-ray detector being aligned to receive x-rays from the x-ray tube.

18. An x-ray imaging apparatus according to claim 17 wherein the x-ray tube is moveable and movement of the x-ray detector is synchronized with the x-ray tube to retain alignment to receive x-rays from the x-ray tube.

19. An x-ray imaging apparatus according to claim 18 wherein the x-ray tube and x-ray detector are moveable in a vertical or horizontal plane.

20. An x-ray imaging apparatus according to claim 18 wherein the x-ray tube and x-ray detector are rotatable around at least part of an imaging subject

21. An animal x-ray imaging apparatus comprising the apparatus of claim 1.

22. A method for creating x-ray beams for imaging at least part of a body, comprising the steps of:

providing an electron beam; and controlling the location and angle that the electron beam strikes an anode surface, the electrons creating a beam of x-rays from the anode surface, the direction and position of the created x-ray beam being dependent on the location and angle the electrons strike the anode surface; and

changing at least one of the location and angle that the electron beam strikes the anode surface to produce an array of x-ray beams at different angles to the anode surface.

23. A method according to claim 22 comprising sequentially changing at least one of the location and angle that the electrons strike the anode surface to produce a sweeping motion of x-ray beams.

24. A method according to claim 22 comprising producing x-ray beams in a plane.

25. A method according to claim 22 comprising varying the energy of the electron beam.

26. A method according to claim 22 comprising controlling the angle of direction that the electron beams strike the anode using a magnetic field.

27. A method according to claim 22 comprising applying different voltages to different anode surfaces to produce x-ray beams of different energies.

28. A method according to claim 22 comprising rotating the anode within the x-ray tube.

29. A method for imaging an animal according to any of claims 22 to 28.

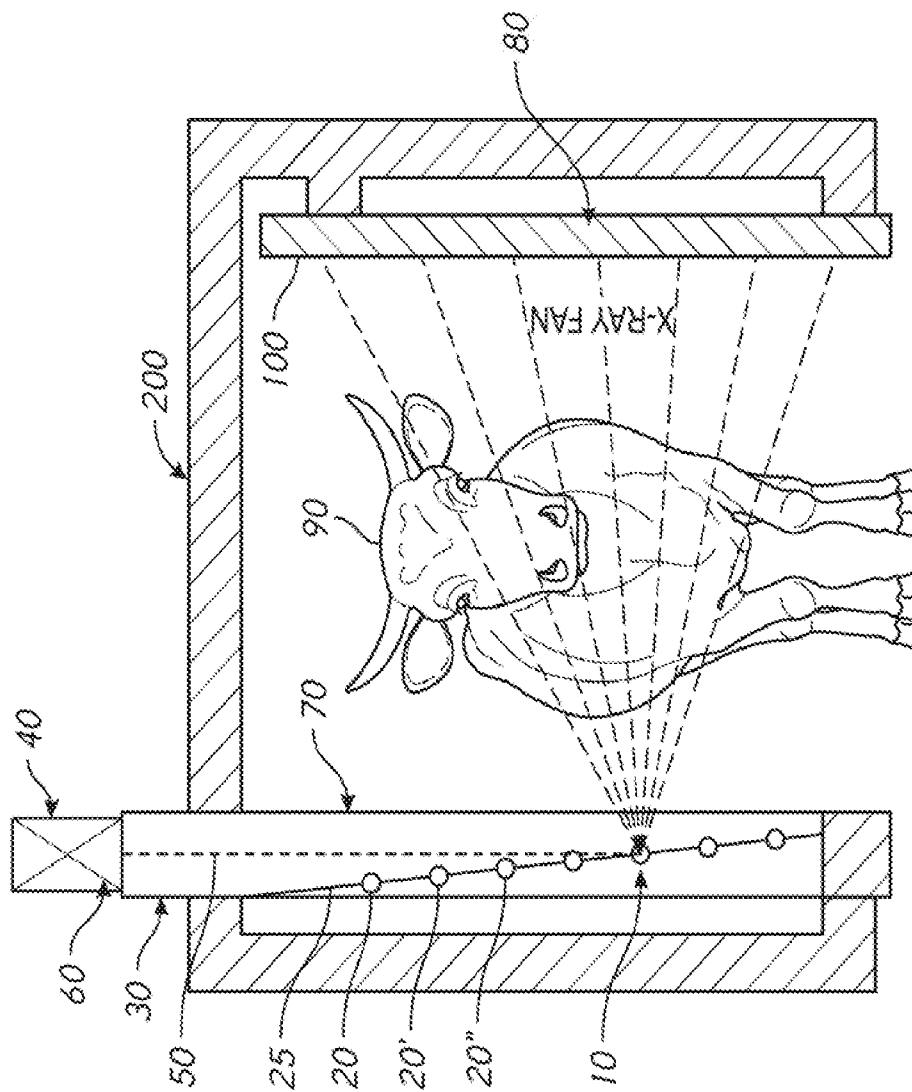


FIG. 1

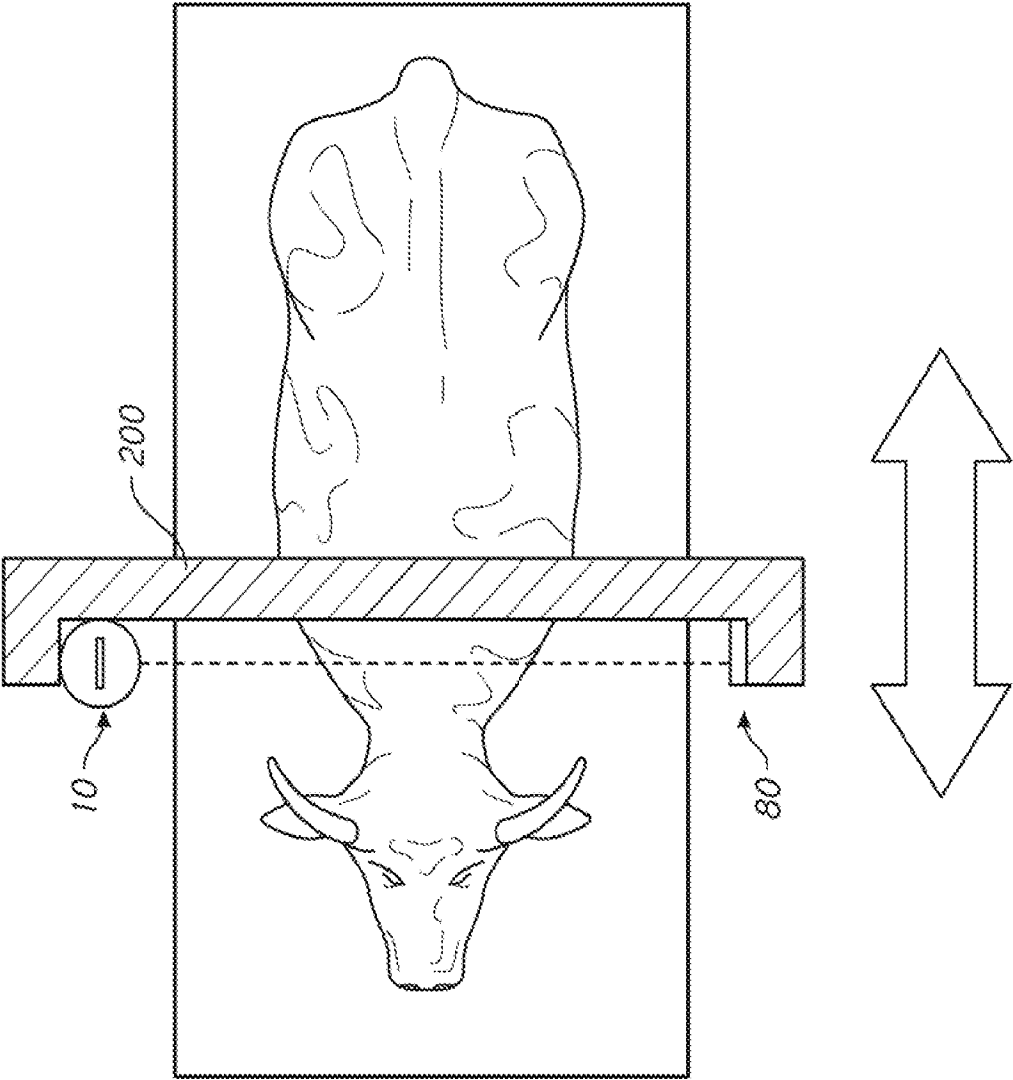
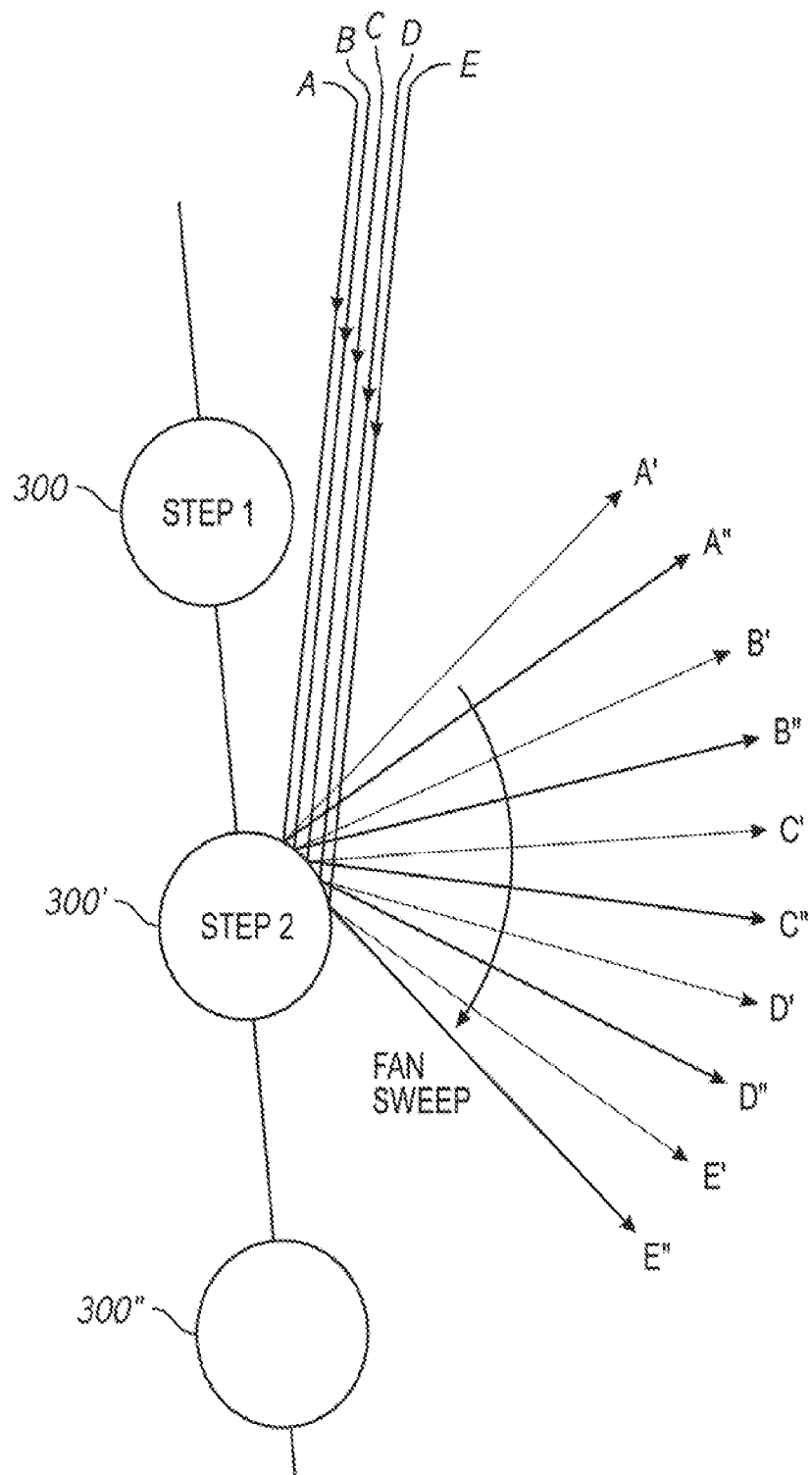
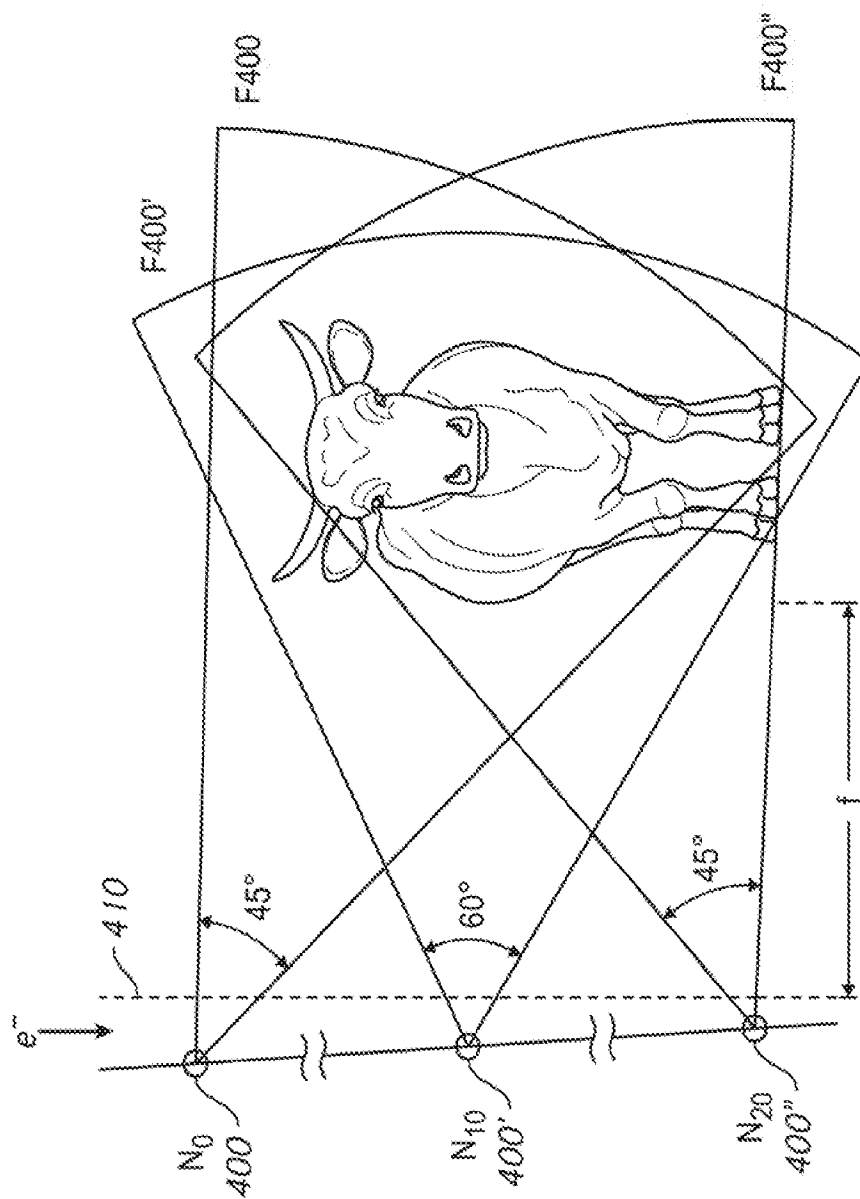


FIG. 2

*FIG. 3*



415

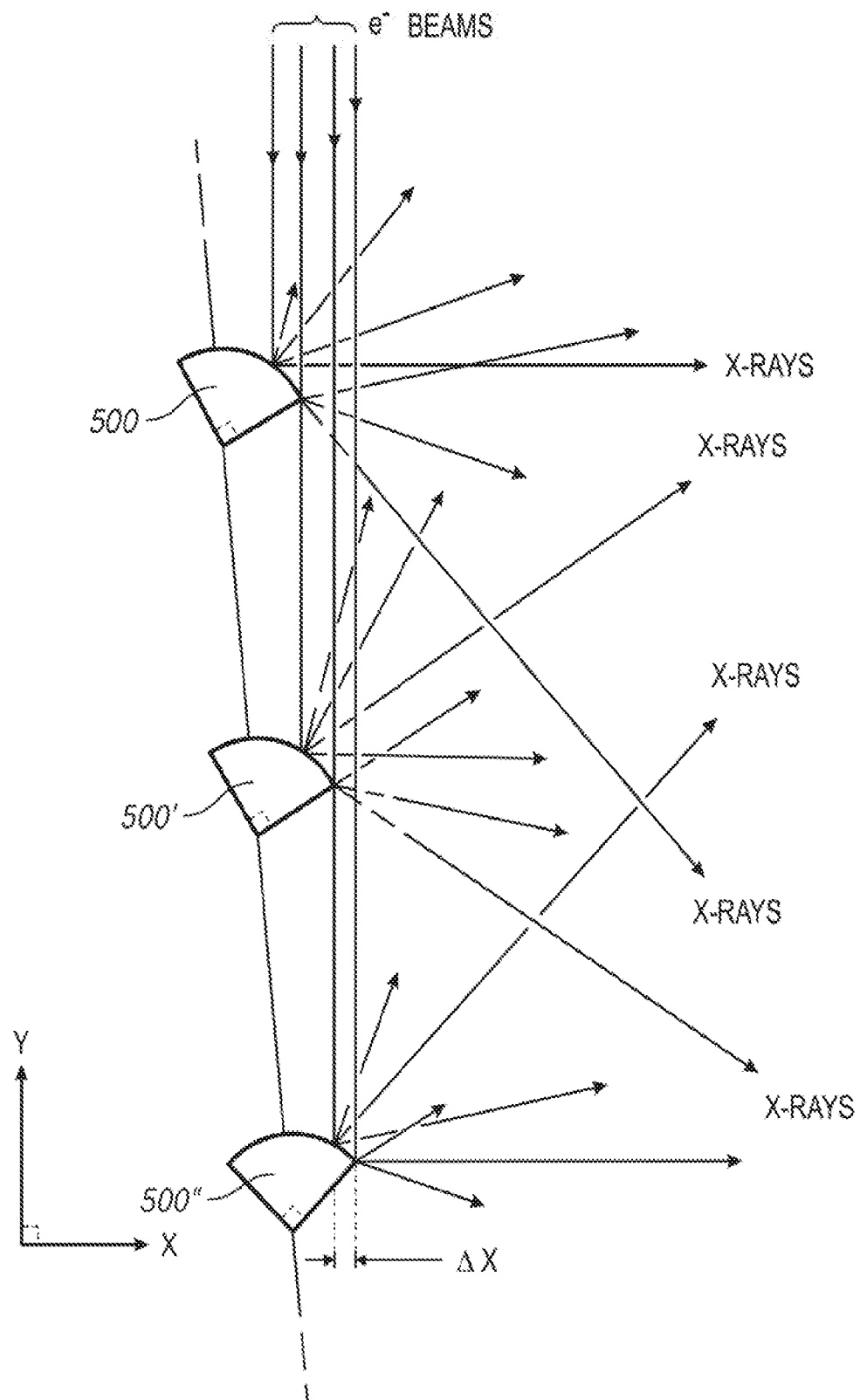


FIG. 5

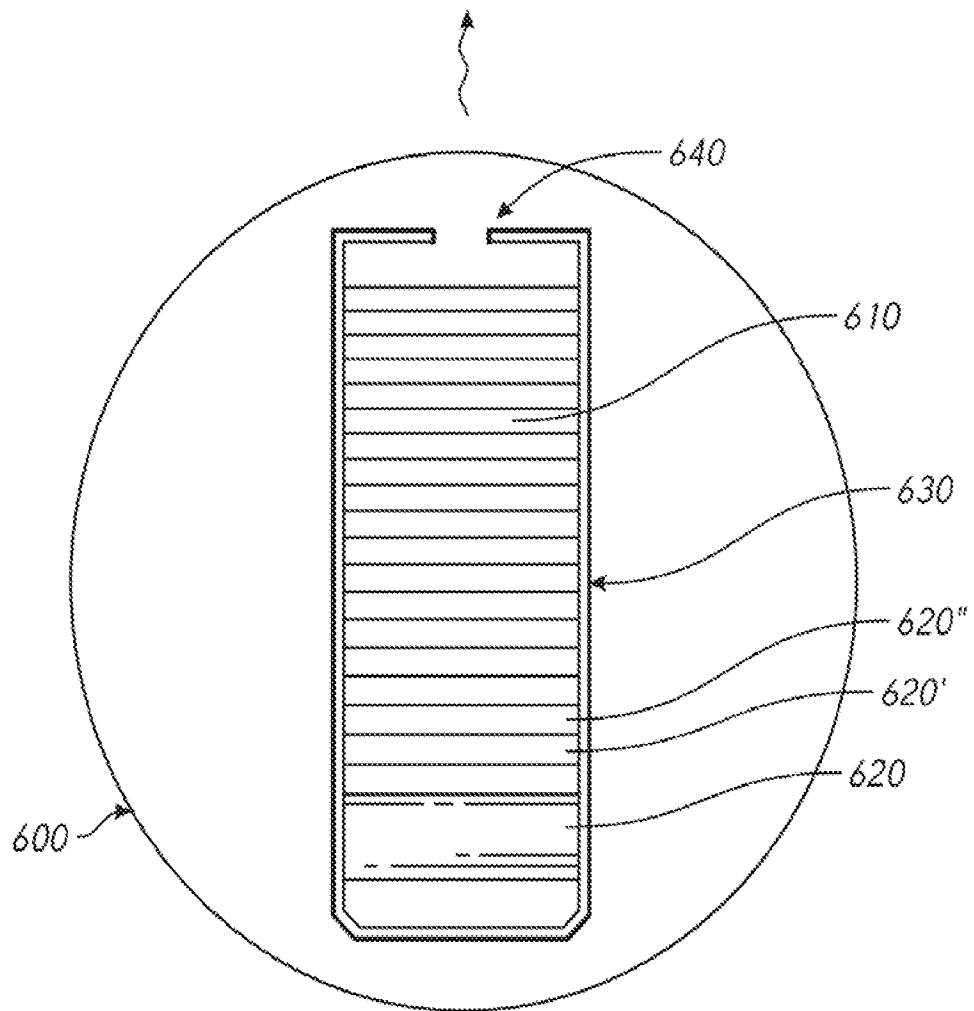


FIG. 6

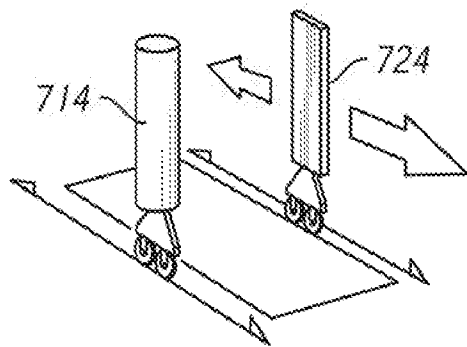


FIG. 7A

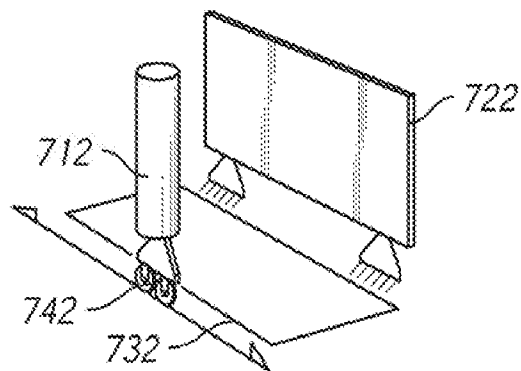


FIG. 7B

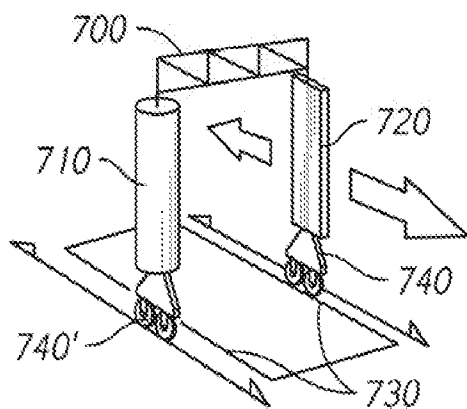


FIG. 7C

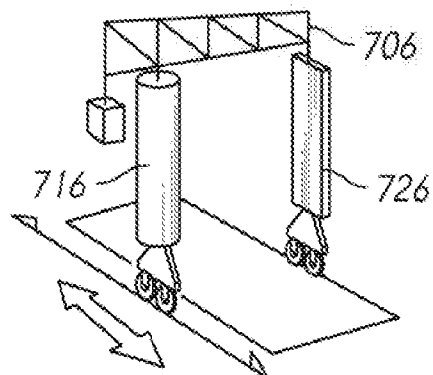


FIG. 7D

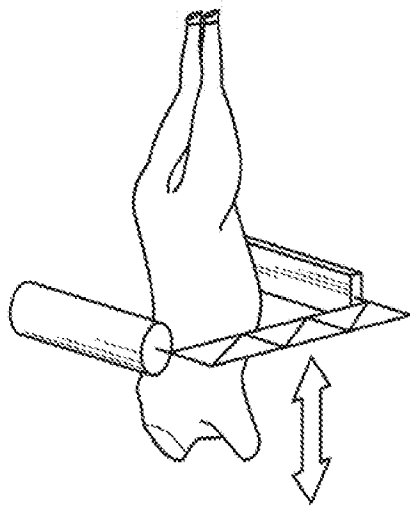


FIG. 8A

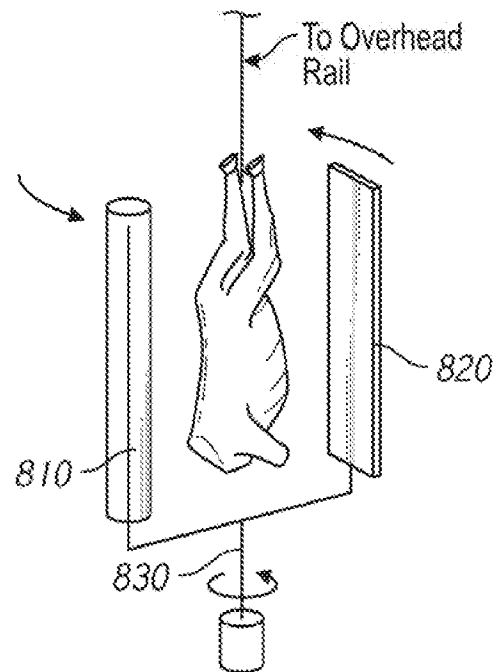


FIG. 8B

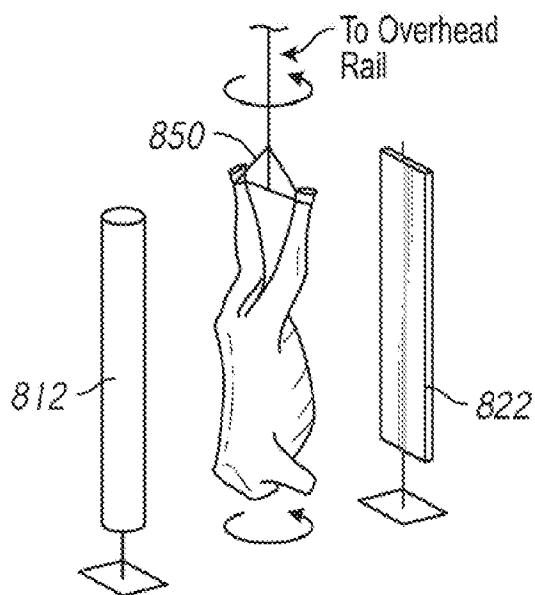


FIG. 8C

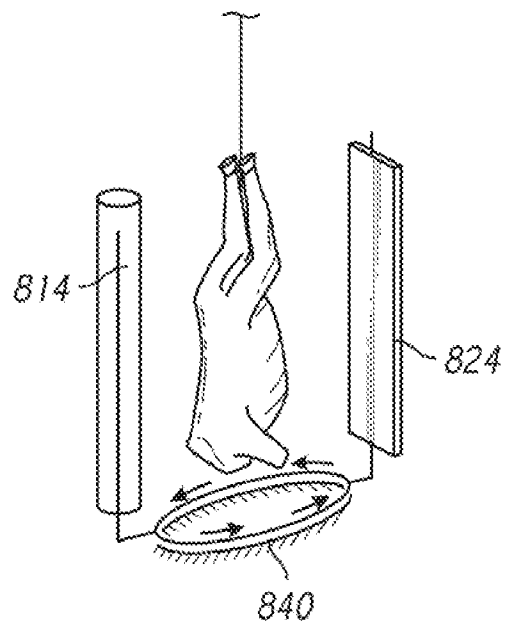


FIG. 8D

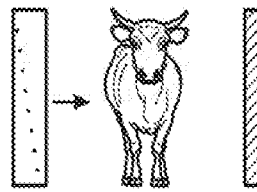


FIG. 9A

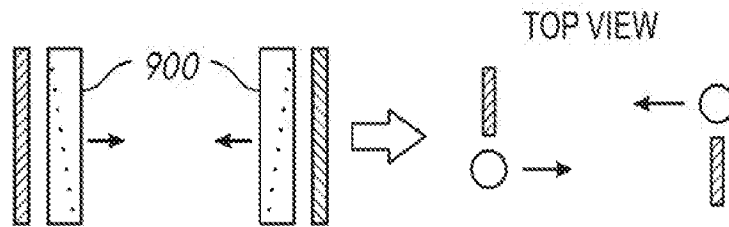


FIG. 9B

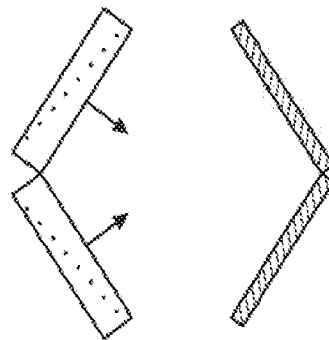


FIG. 9C

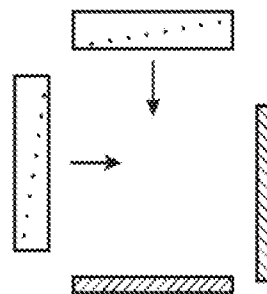


FIG. 9D

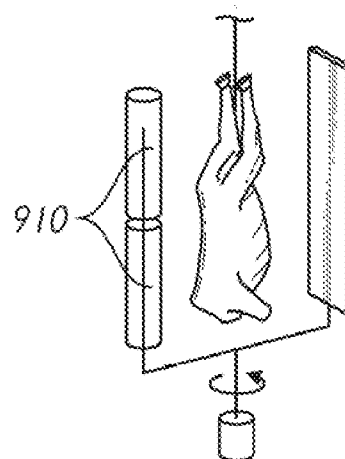


FIG. 9E

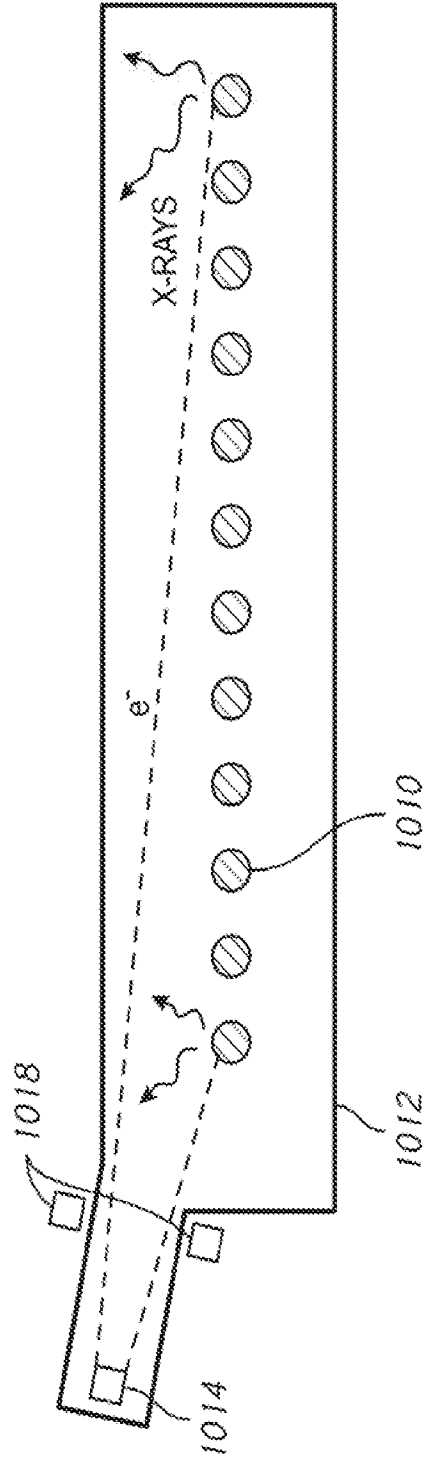


FIG. 10A

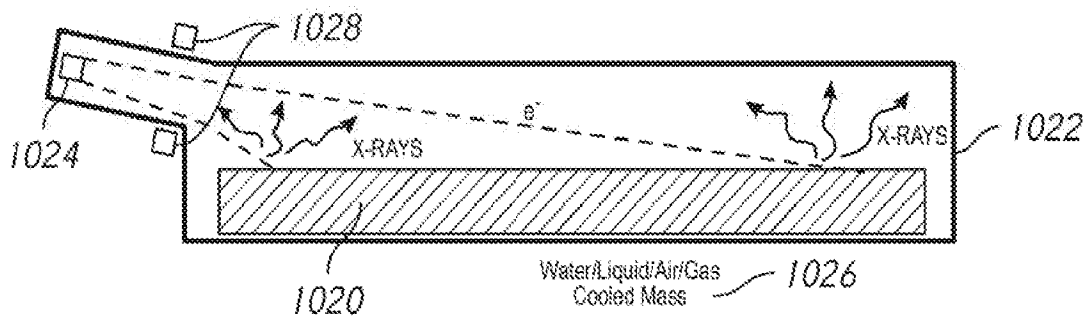


FIG. 10B

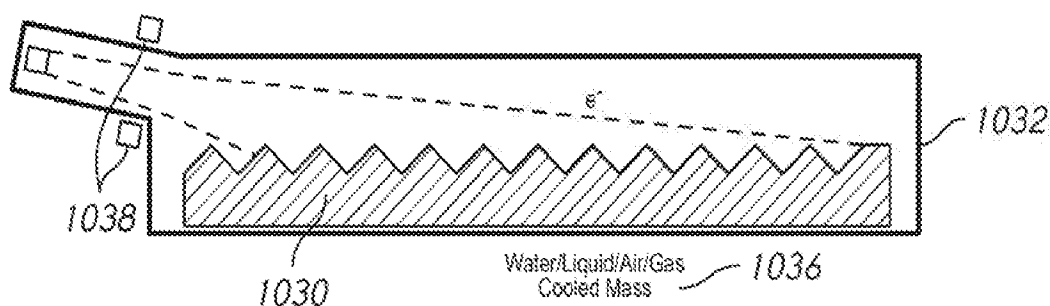


FIG. 10C

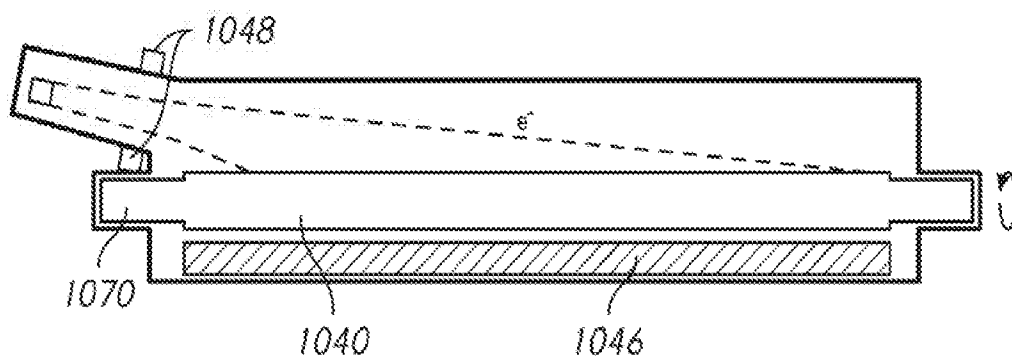


FIG. 10D

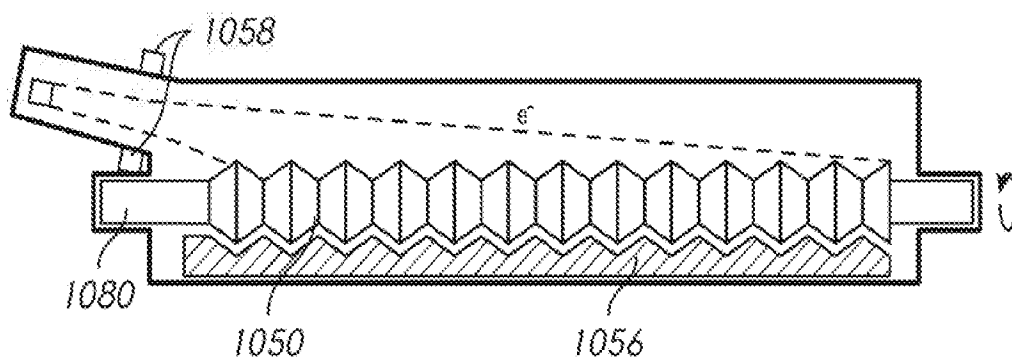


FIG. 10E

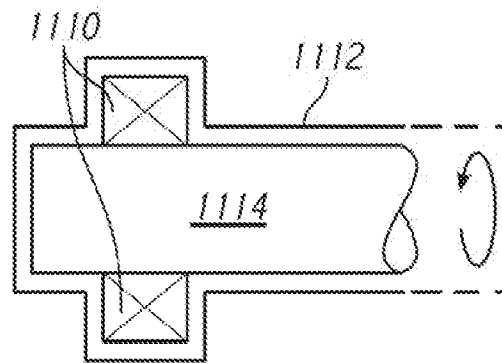


FIG. 11A

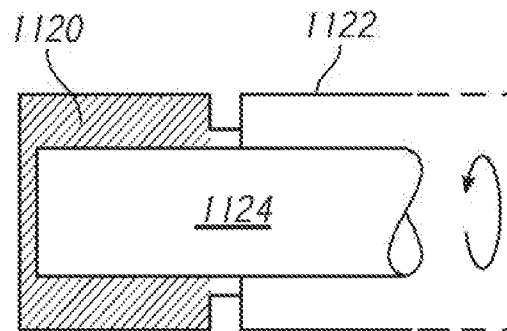


FIG. 11B

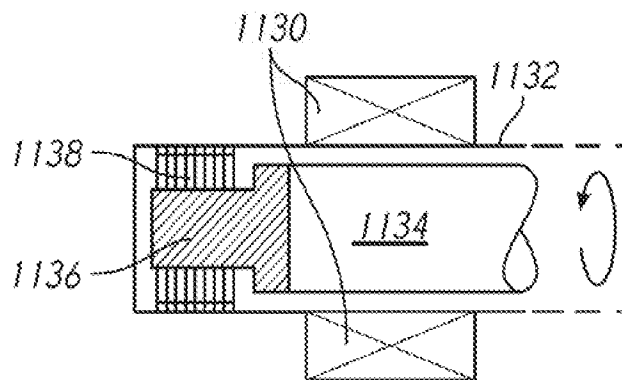


FIG. 11C

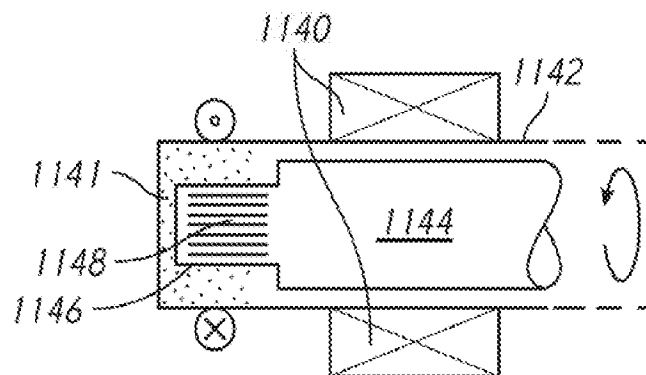
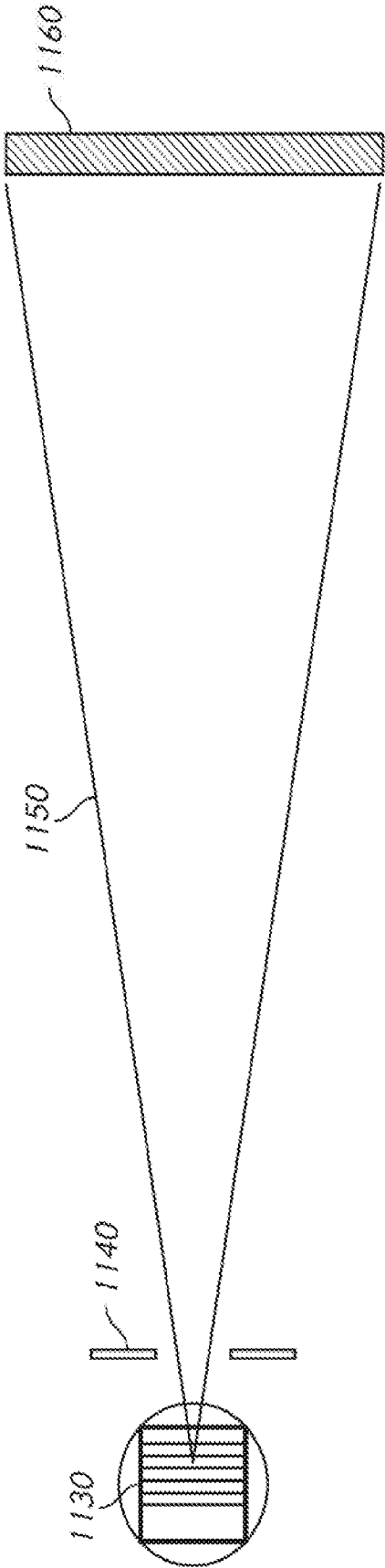
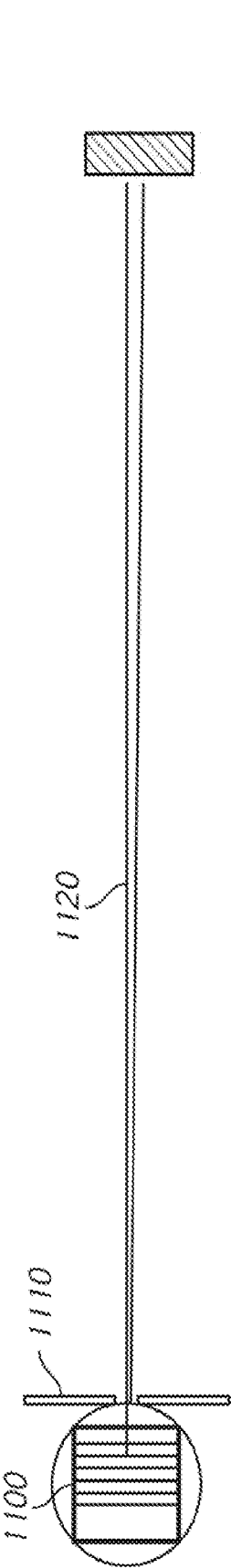


FIG. 11D



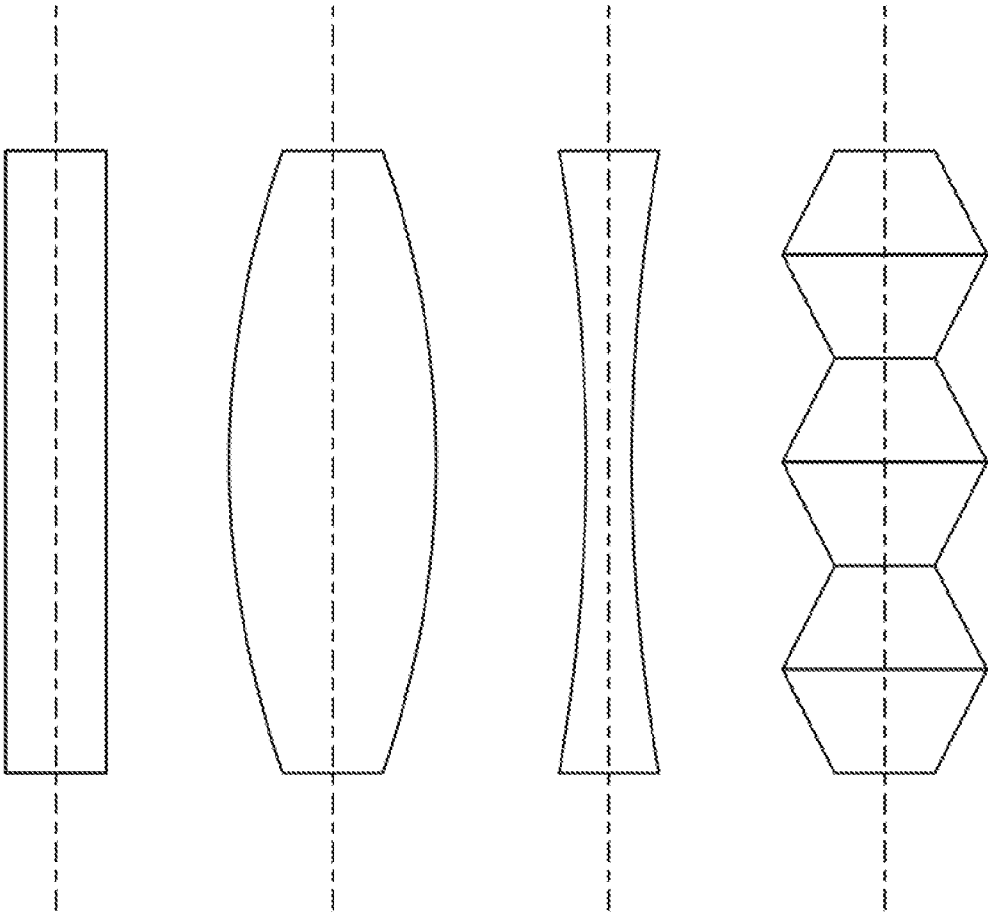


FIG. 13

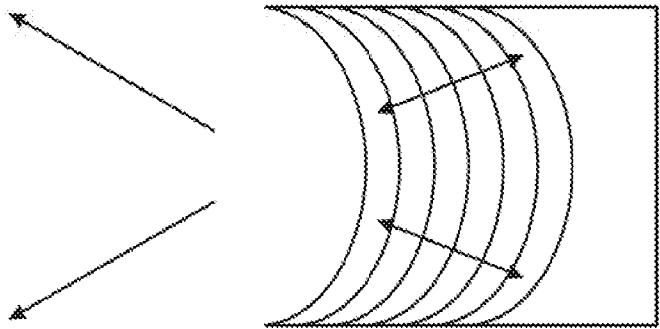


FIG. 14C

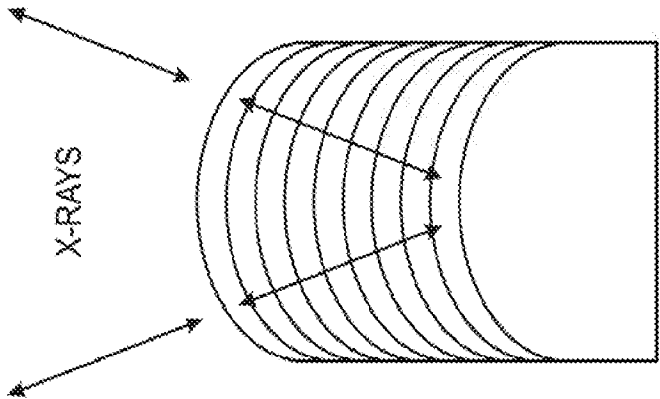


FIG. 14B

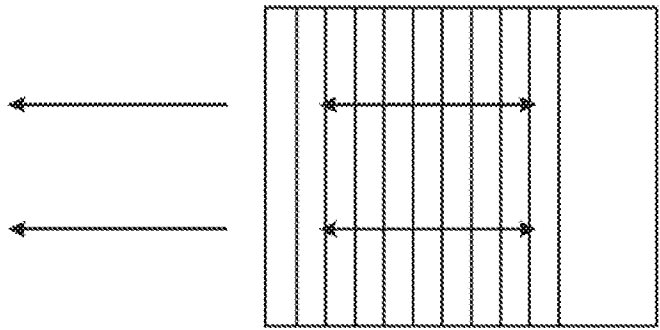


FIG. 14A

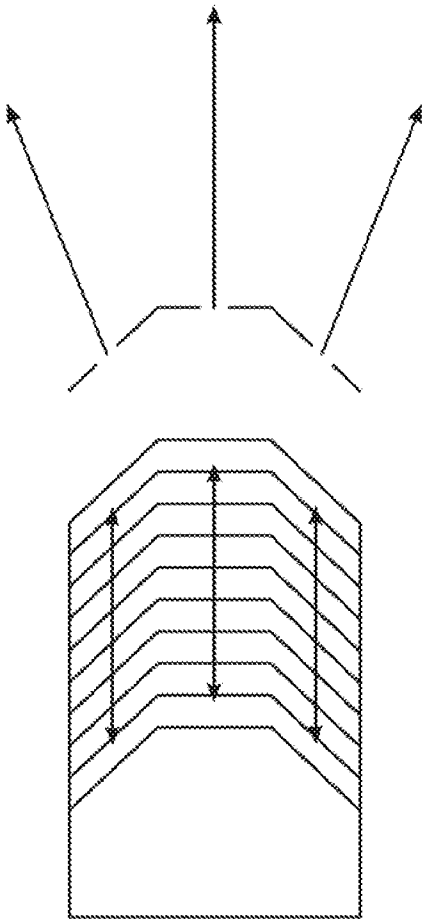


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2016/033513

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01J 35/02; H01J 35/00; H01J 35/04; H01J 35/10 (2016.01)

CPC - H01J 35/02; H01J 35/00; H01J 35/04; H01J 35/10 (2016.05)

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 - H01J 1/02; H01J 19/32; H01J 35/00; H01J 35/02; H01J 35/08; H01J 35/10

CPC - H01J 35/00; H01J 35/02; H01J 35/04; H01J 35/10

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

USPC - 313/540; 378/124; 378/141 (keyword delimited)

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

Orbit, Google Patents, Google

Search terms used: x-ray anode "plurality of anodes" angle cool animals

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 8,761,342 B2 (BEHLING) 24 June 2014 (24.06.2014) entire document	1-9, 13, 17-20, 22-24, 28 --- 10-12, 14-16, 21, 25-27, 29
Y	US 6,993,115 B2 (MCGUIRE et al) 31 January 2006 (31.01.2006) entire document	10-12, 14, 25-27
Y	US 7,003,077 B2 (JEN et al) 21 February 2006 (21.02.2006) entire document	15
Y	US 4,165,472 A (WITTRY) 21 August 1979 (21.08.1979) entire document	16
Y	US 8,350,219 B2 (KOREN et al) 08 January 2013 (08.01.2013) entire document	21, 29

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 July 2016

Date of mailing of the international search report

23 AUG 2016

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