US011521820B2

(12) **United States Patent**
Fishman et al.

(10) **Patent No.: US 11,521,820 B2**
(45) **Date of Patent: *Dec. 6, 2022**

(54) **THREE-DIMENSIONAL BEAM FORMING X-RAY SOURCE**

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(73) Assignee: **EMPYREAN MEDICAL SYSTEMS, INC.**, Boca Raton, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **16/836,250**

(22) Filed: **Mar. 31, 2020**

(65) **Prior Publication Data**

US 2020/0234908 A1 Jul. 23, 2020

Related U.S. Application Data

(63) Continuation of application No. 15/941,547, filed on Mar. 30, 2018, now Pat. No. 10,607,802.

(Continued)

(51) **Int. Cl.**

H01J 35/14	(2006.01)
H01J 35/16	(2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01J 35/153*** (2019.05); ***H01J 35/16*** (2013.01); ***H01J 35/30*** (2013.01); ***H01J 35/32*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC .. H01J 35/14; H01J 35/16; H01J 35/32; H01J 35/30; H01J 35/153; H01J 35/12;

(Continued)

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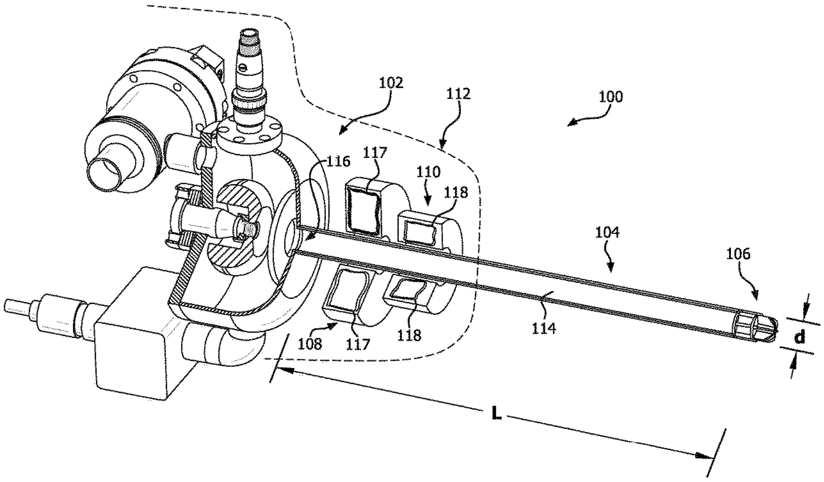
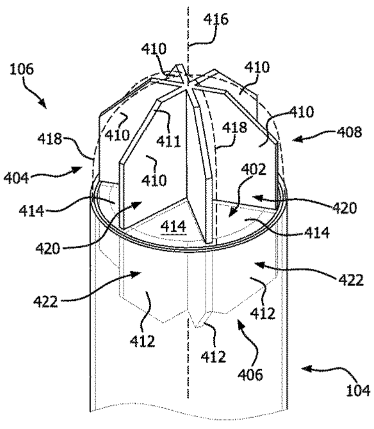
Primary Examiner — Jurie Yun
(74) *Attorney, Agent, or Firm* — Fox Rothschild LLP

(57) **ABSTRACT**

X-ray target element is comprised of a planar wafer. The planar wafer element includes a target layer and a substrate layer. The target layer is comprised of an element having a relatively high atomic number and the substrate layer is comprised of diamond. The substrate layer is configured to support the target layer and facilitate transfer of thermal energy away from the target layer.

20 Claims, 20 Drawing Sheets





Related U.S. Application Data

(60) Provisional application No. 62/479,455, filed on Mar. 31, 2017.

(51) **Int. Cl.**
H01J 35/32 (2006.01)
H01J 35/30 (2006.01)

(52) **U.S. Cl.**
CPC ... *H01J 2235/086* (2013.01); *H01J 2235/166* (2013.01)

(58) **Field of Classification Search**
CPC H01J 35/13; H01J 2235/166; H01J 2235/086; H01J 2235/12; H01J 2235/1204; H01J 2235/1229; H01J 2235/1233; H01J 2235/1241; H01J 2235/1266; H01J 2235/1291
See application file for complete search history.

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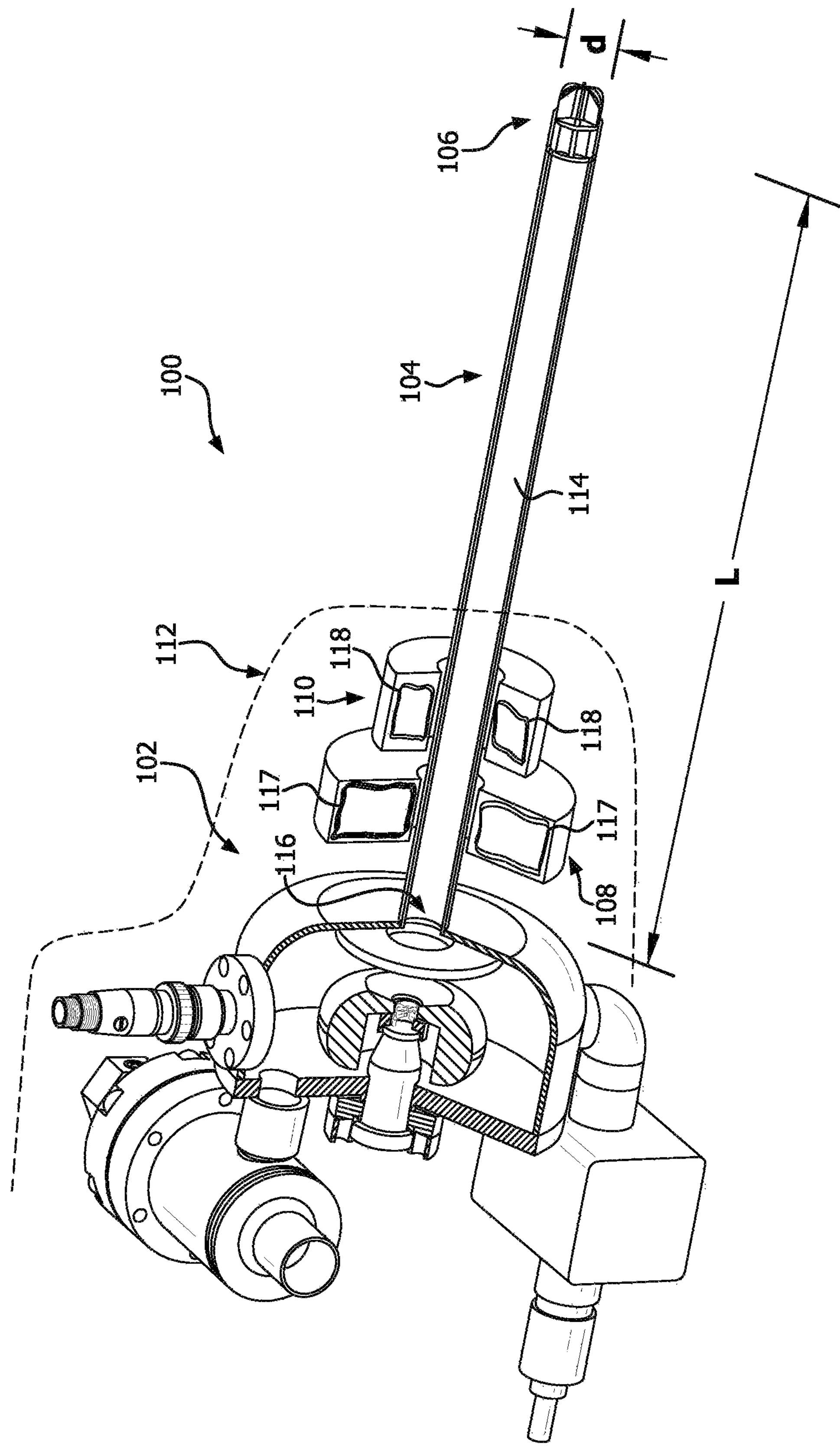

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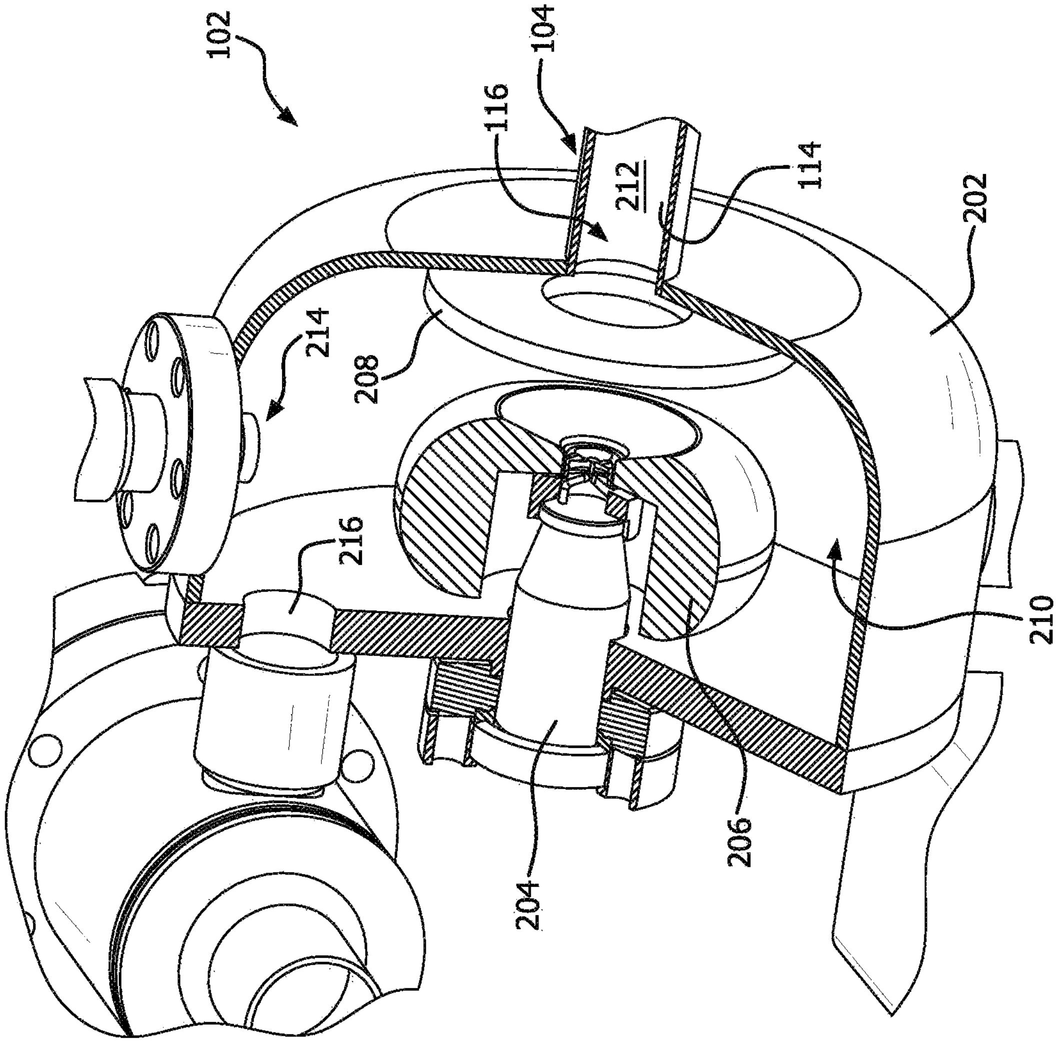

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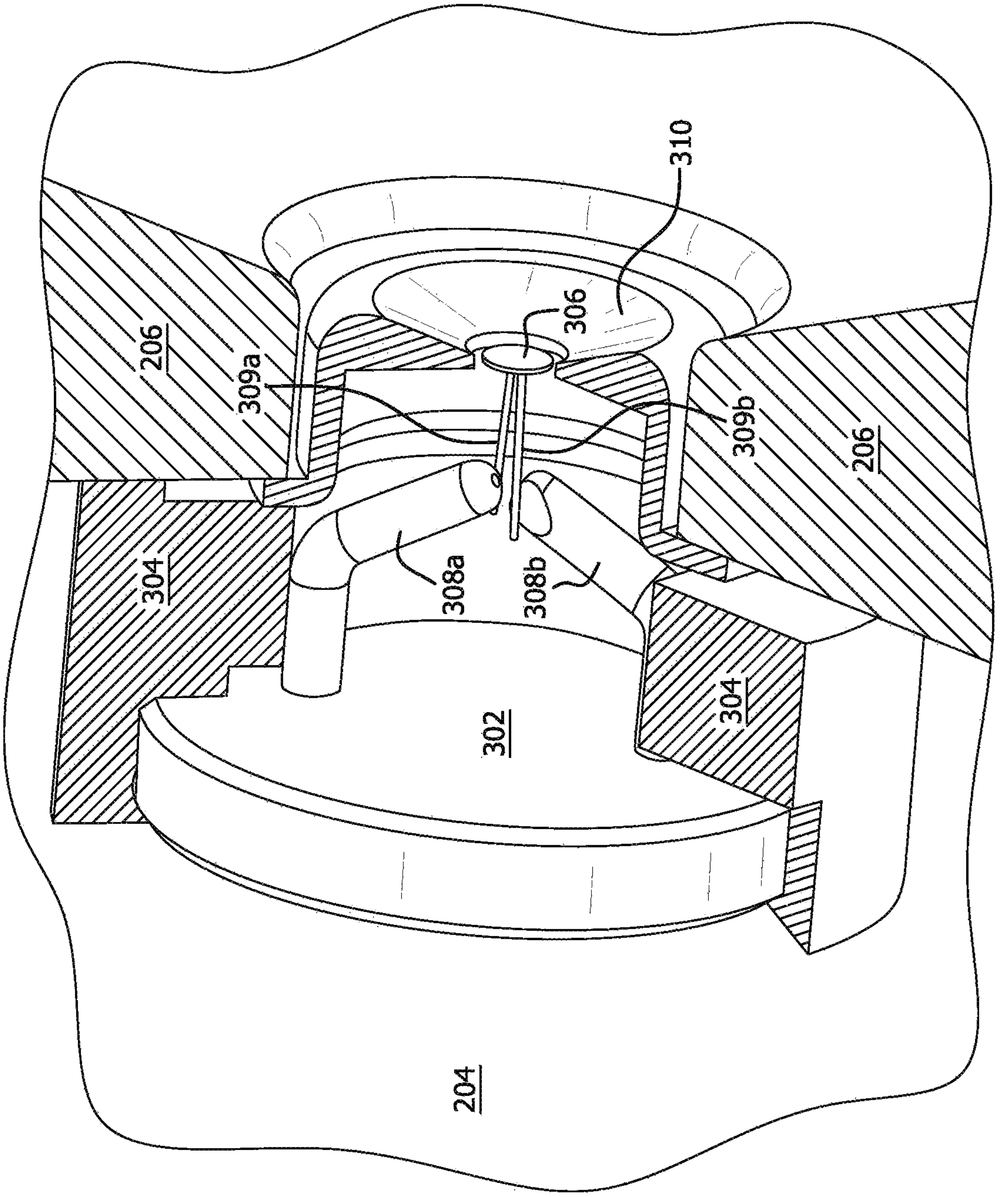

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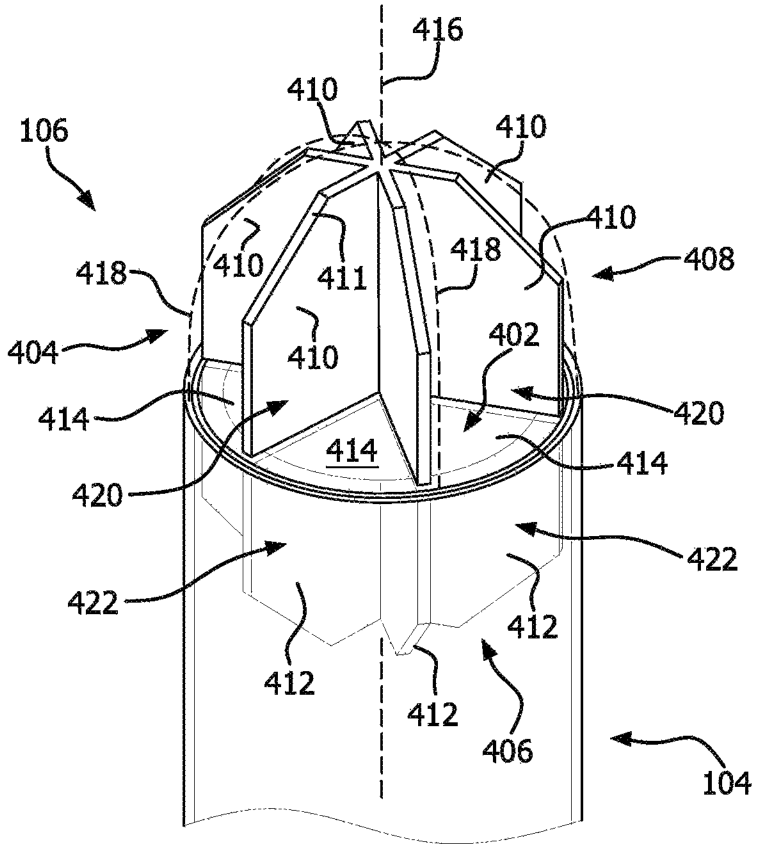
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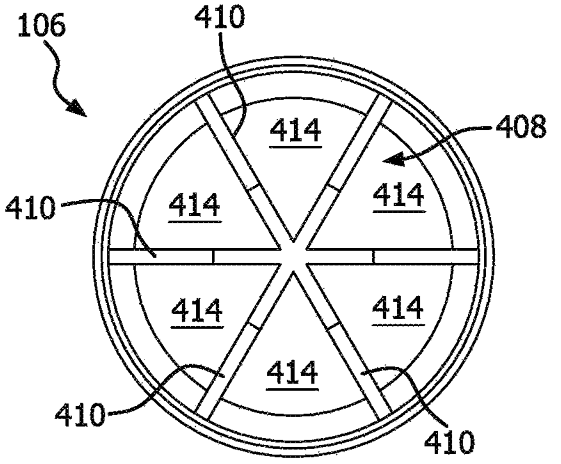
FIG. 4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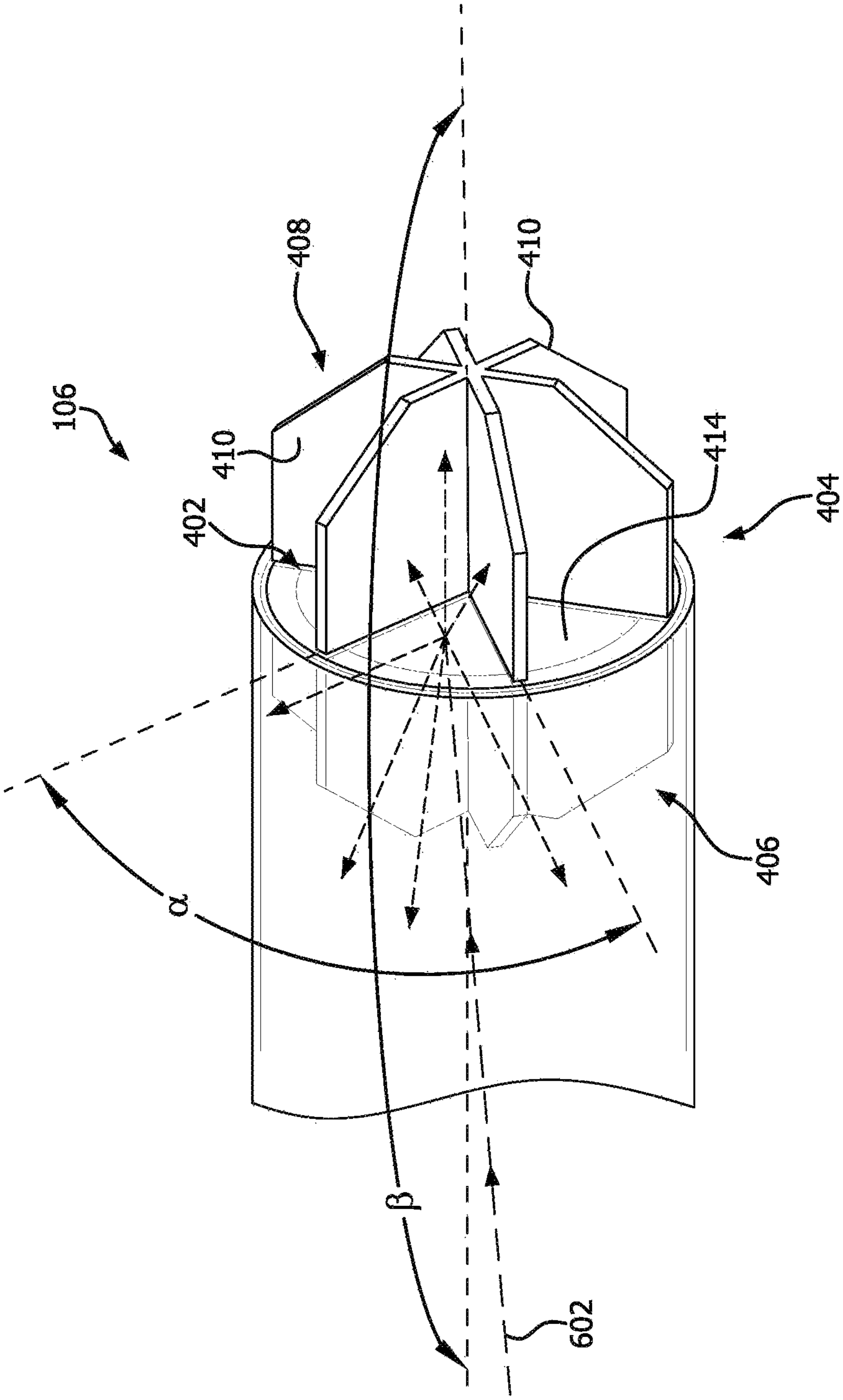

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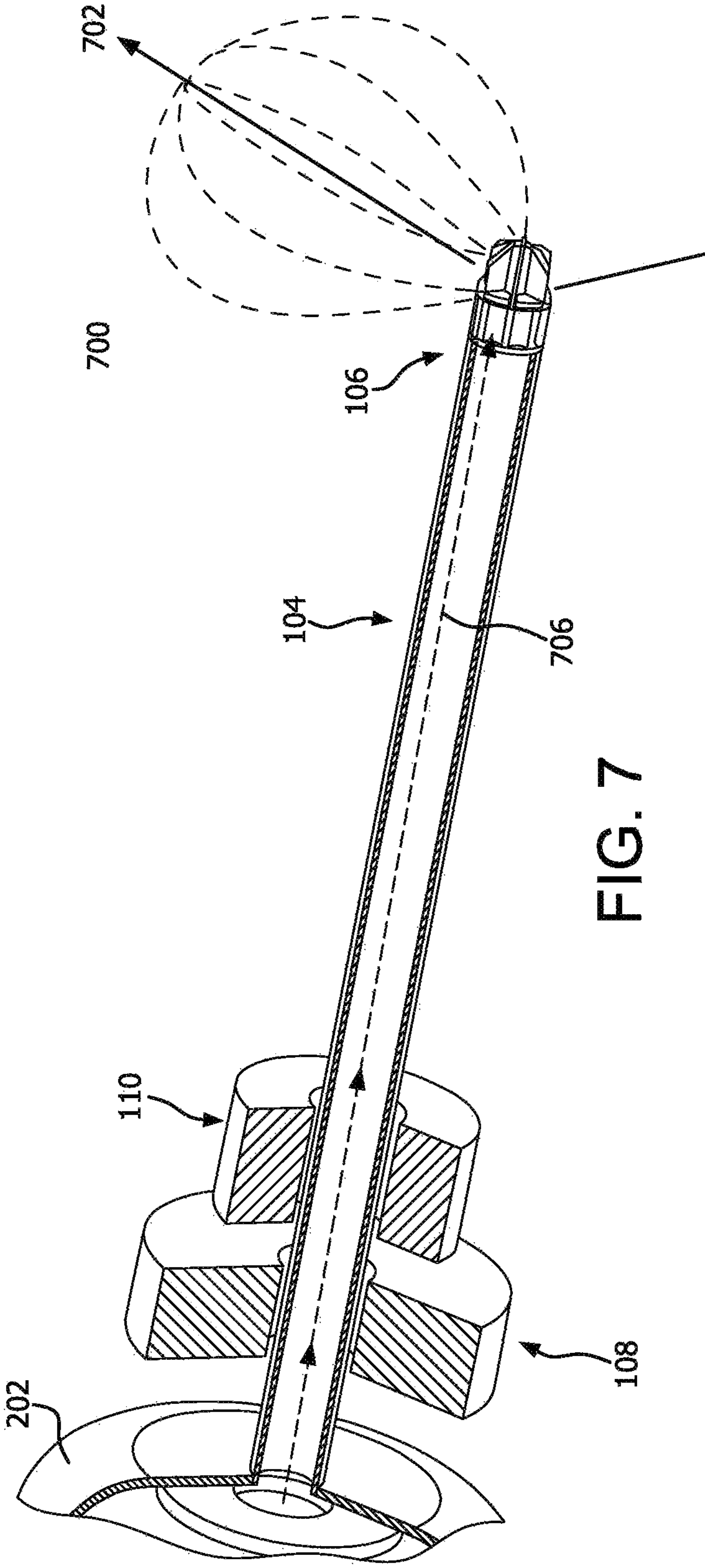

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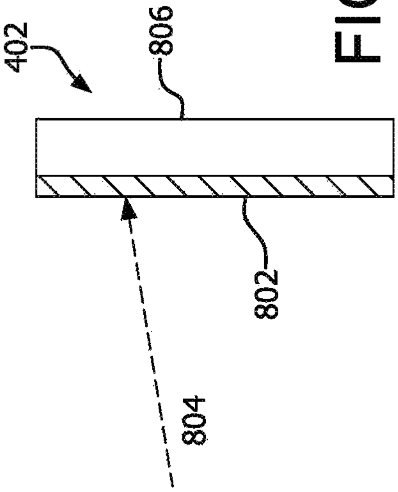

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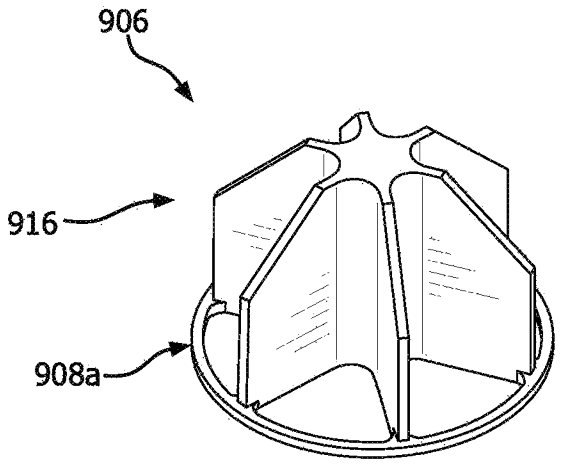
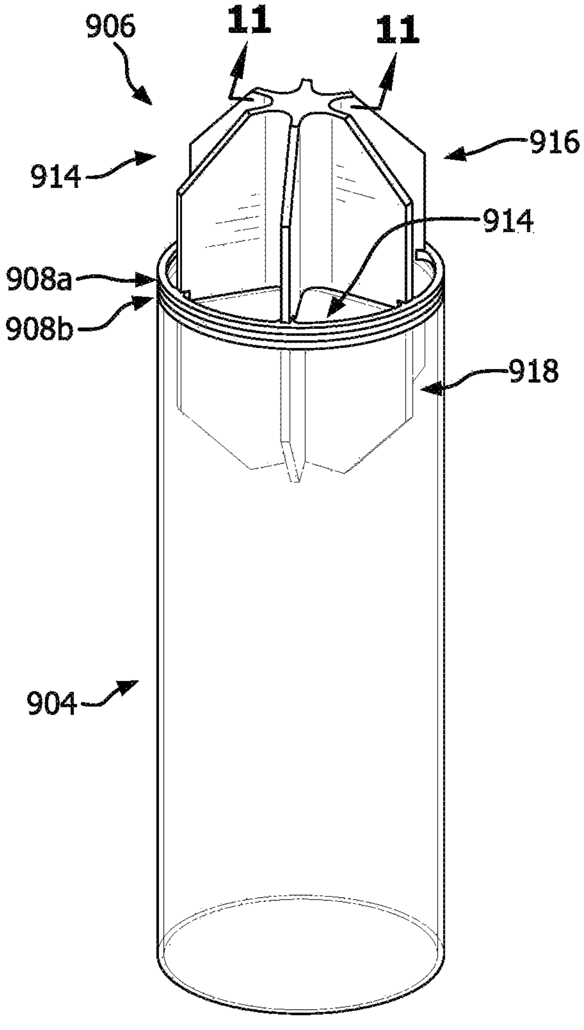


FIG. 9



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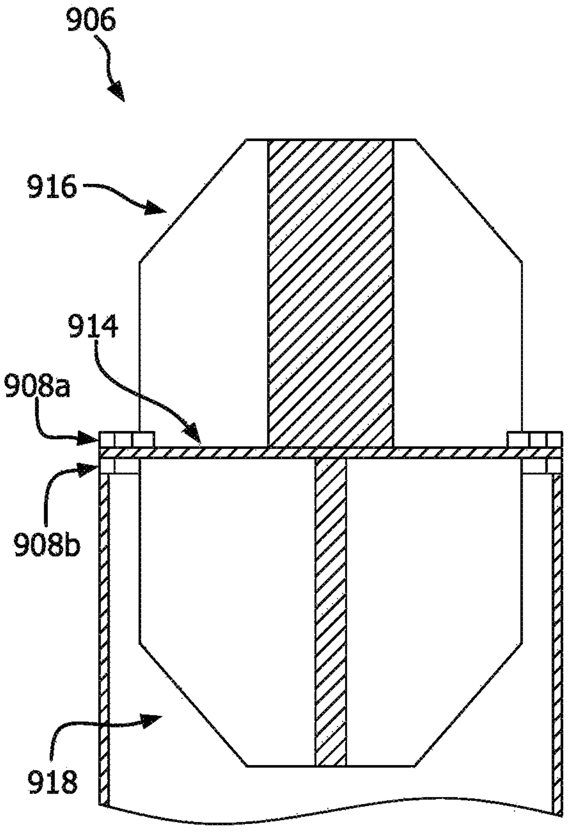

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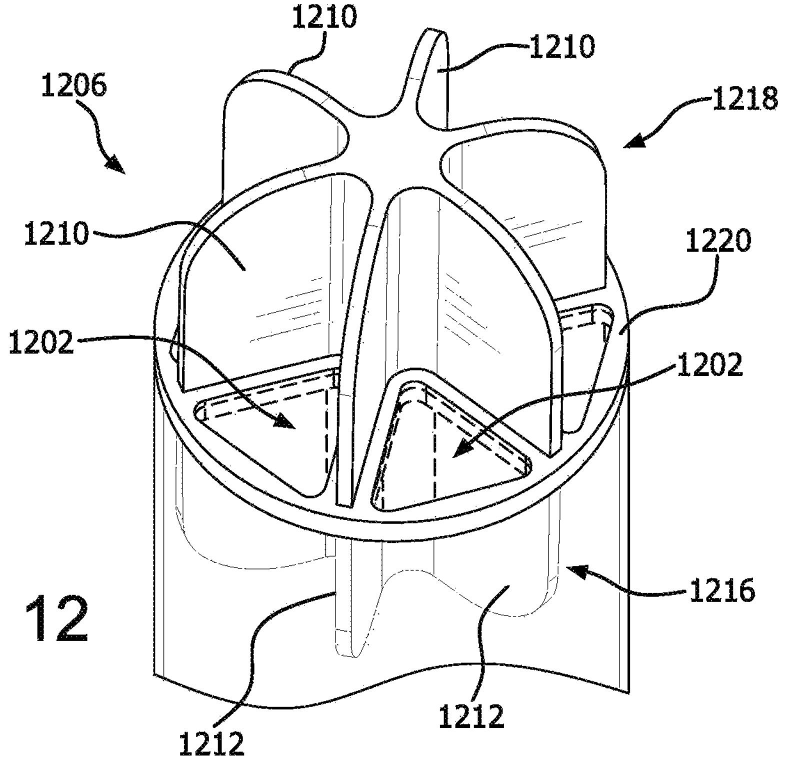
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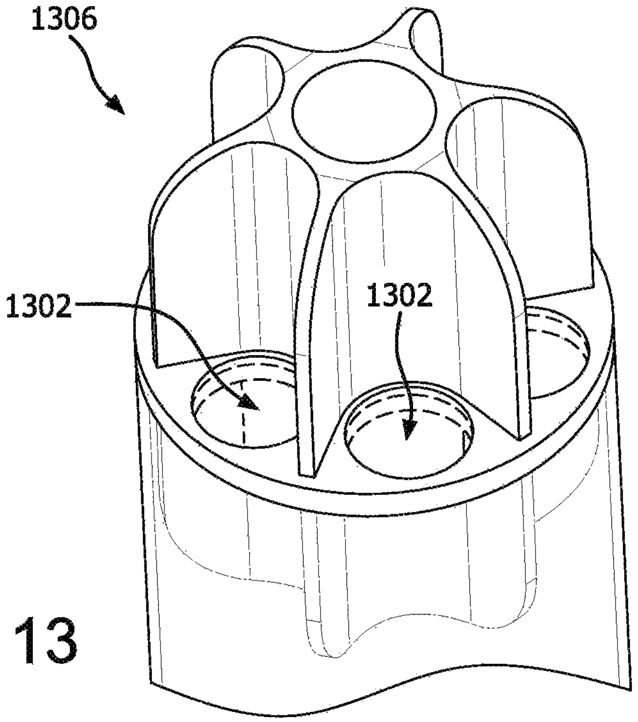
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FIG. 13

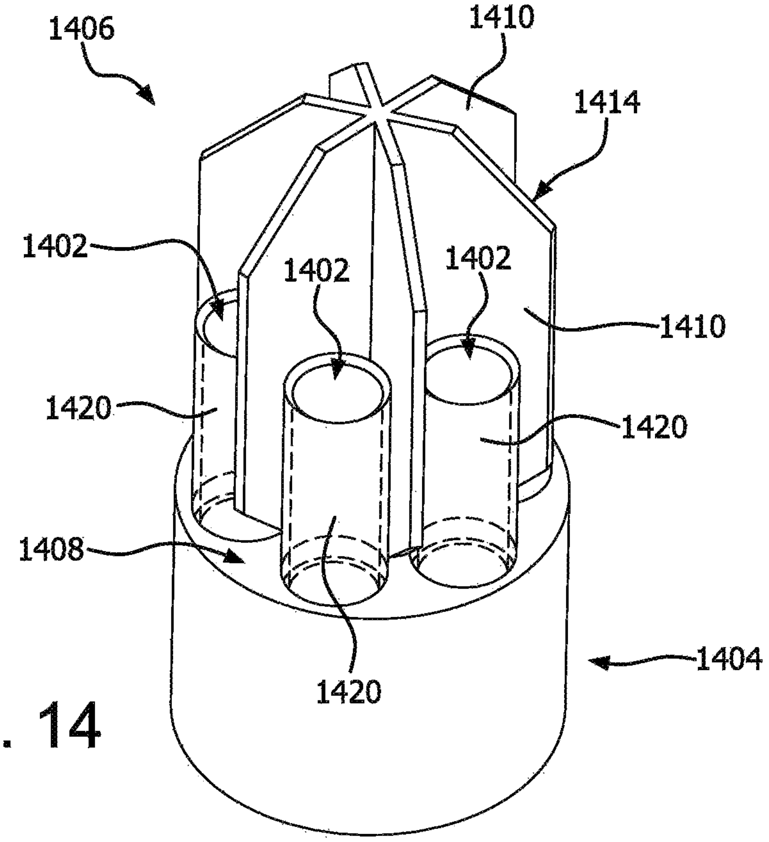
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FIG. 14

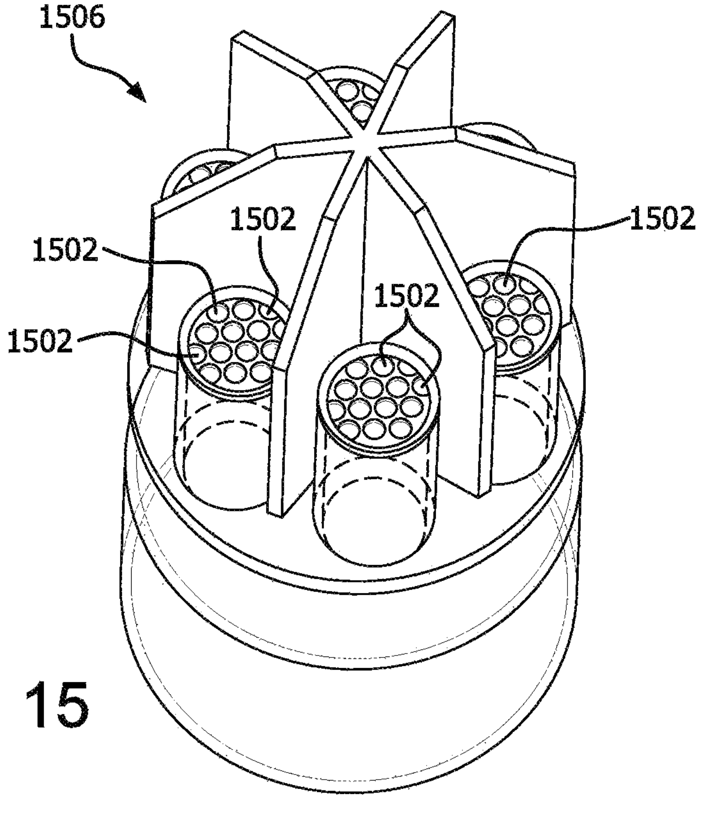
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FIG. 15

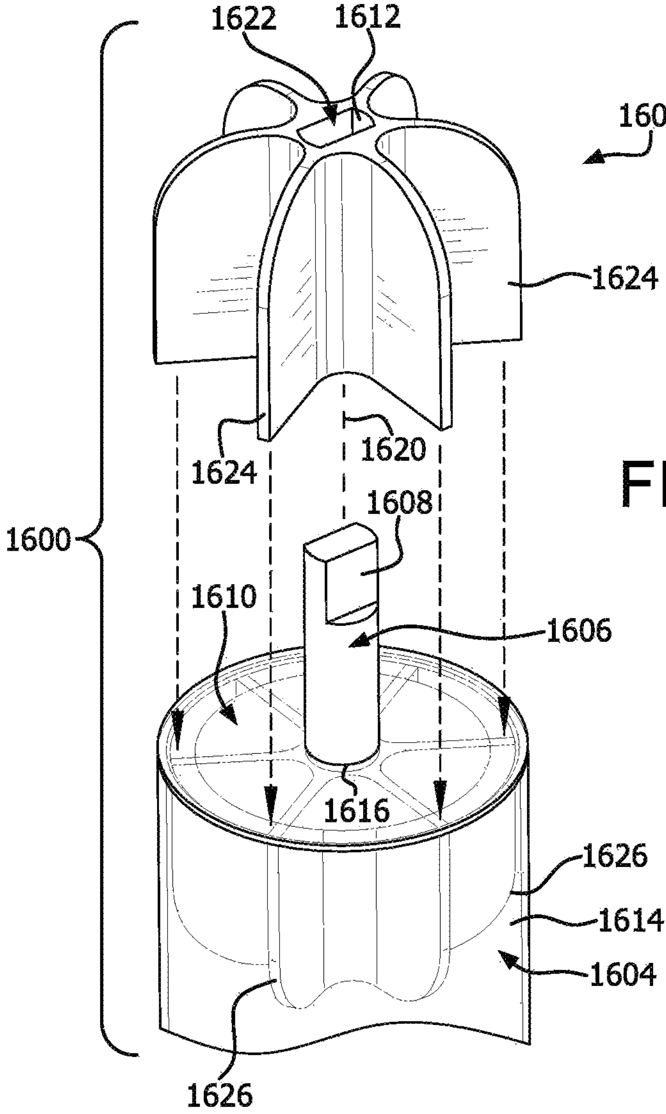
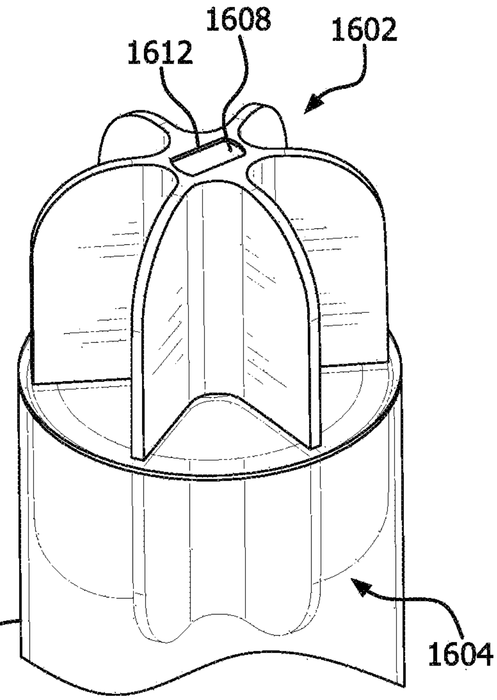


FIG. 16A



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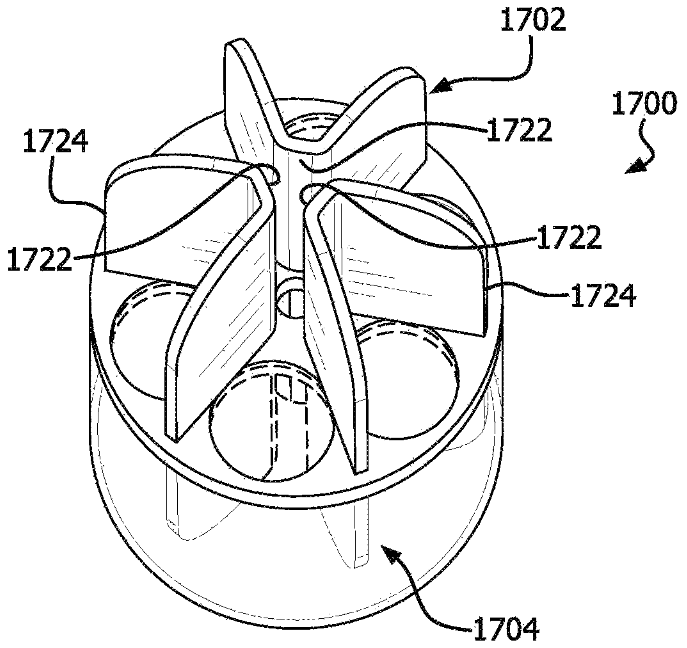


FIG. 17A

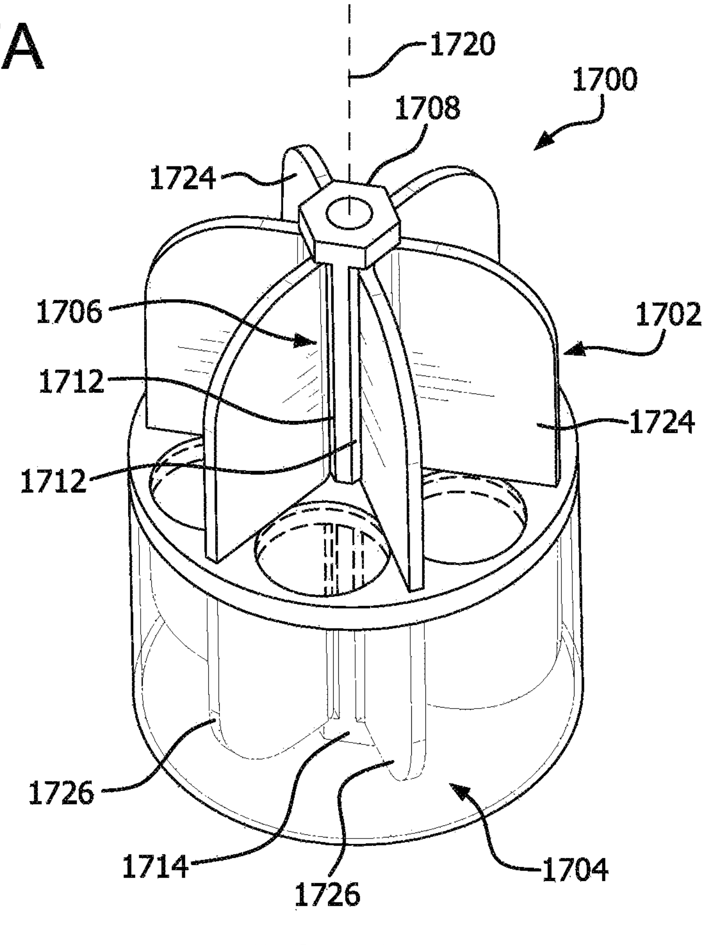
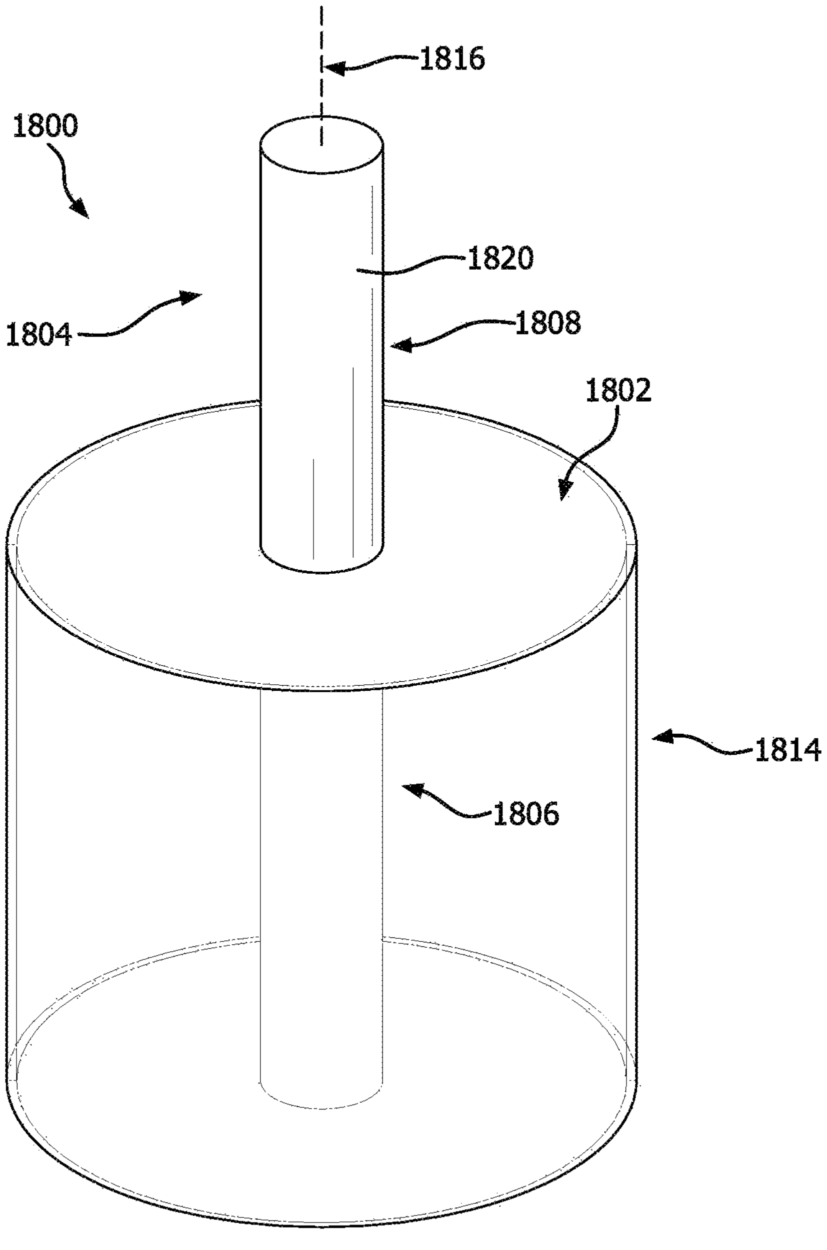


FIG. 17B



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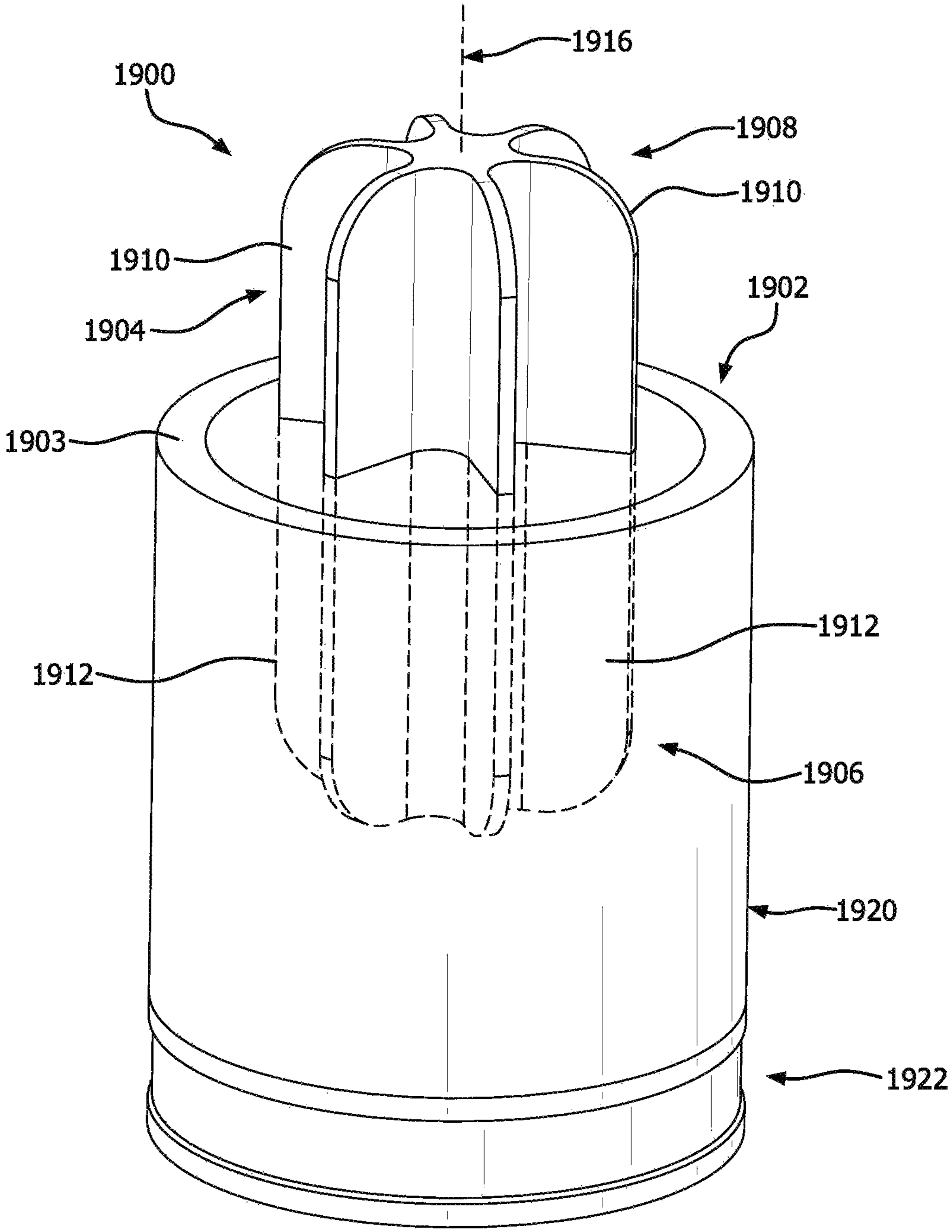
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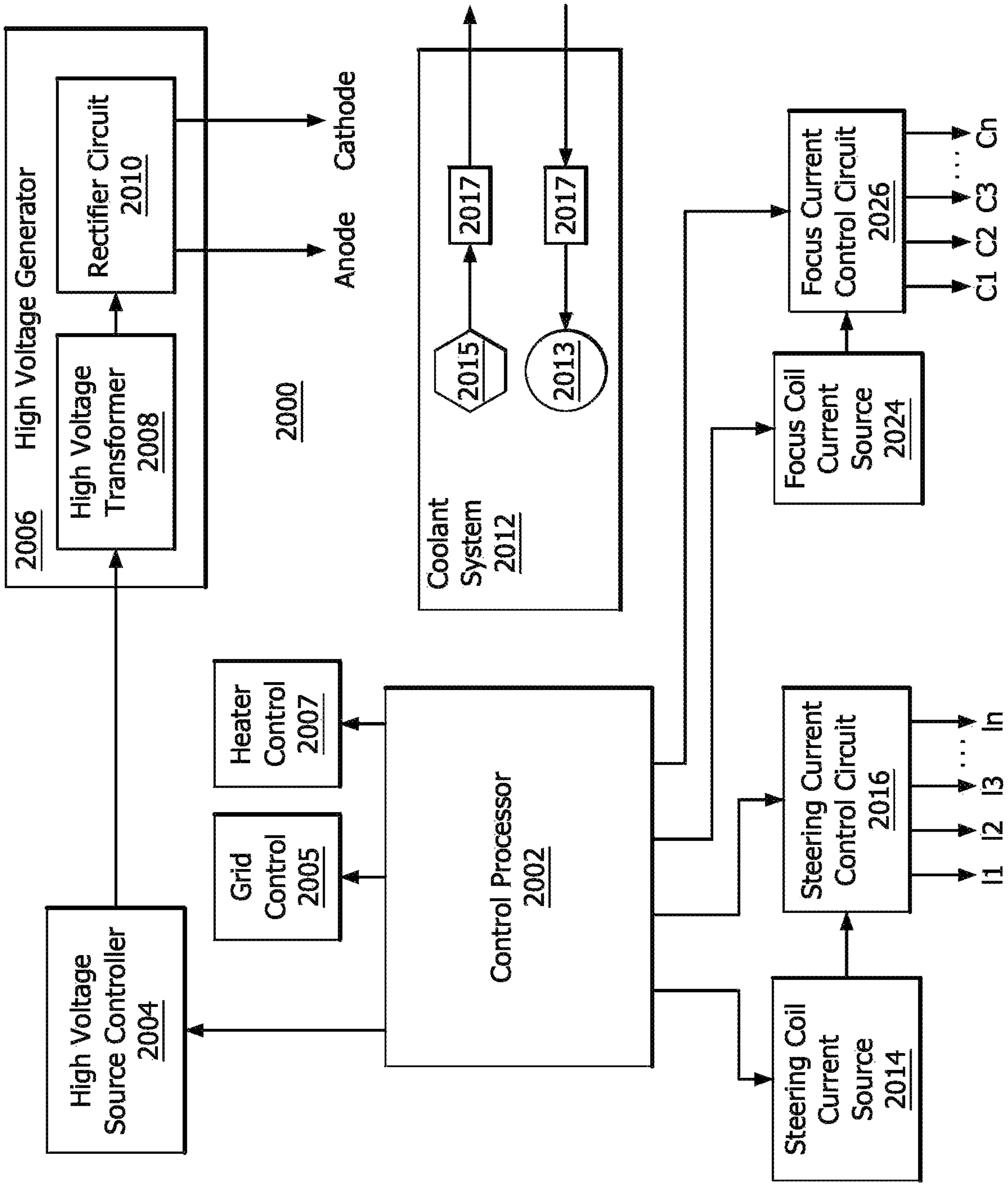
FIG. 19


2006 High Voltage Generator
High Voltage Transformer 2008
Rectifier Circuit 2010
Anode
Cathode
2000
Coolant System 2012
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2013
2017
2017
High Voltage Source Controller 2004
Grid Control 2005
Heater Control 2007
Control Processor 2002
Steering Coil Current Source 2014
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C1 C2 C3 . . . Cn

FIG. 20

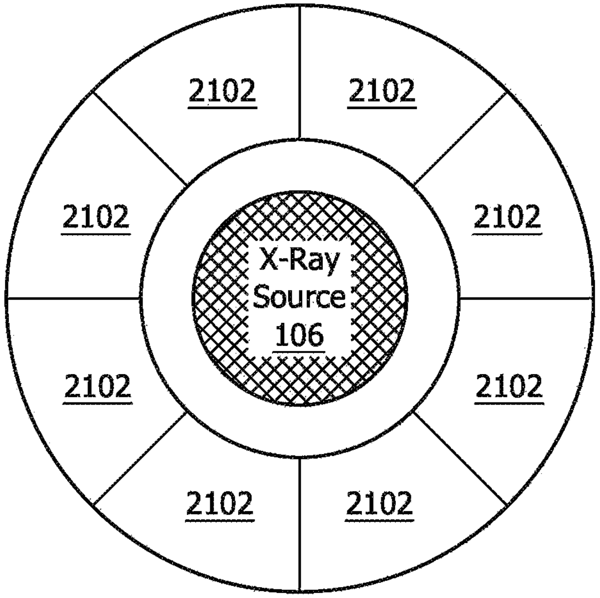


FIG. 21A

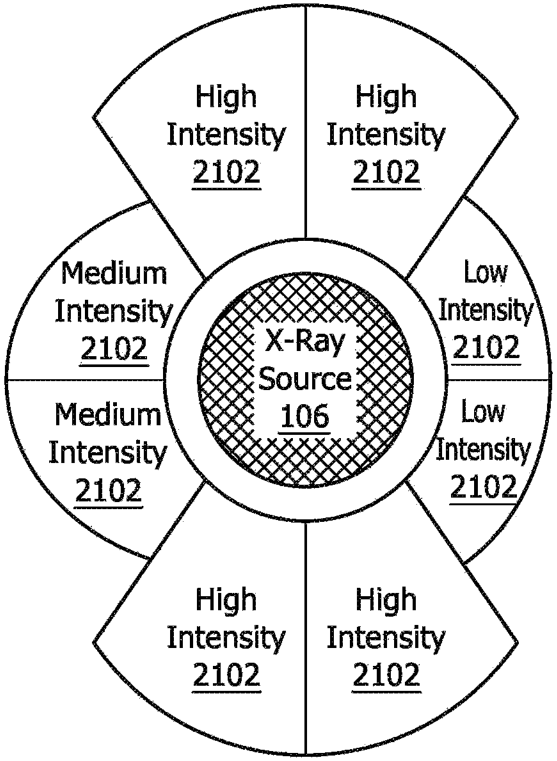


FIG. 21B

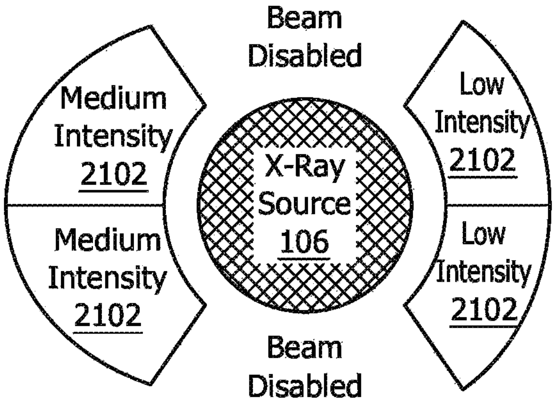
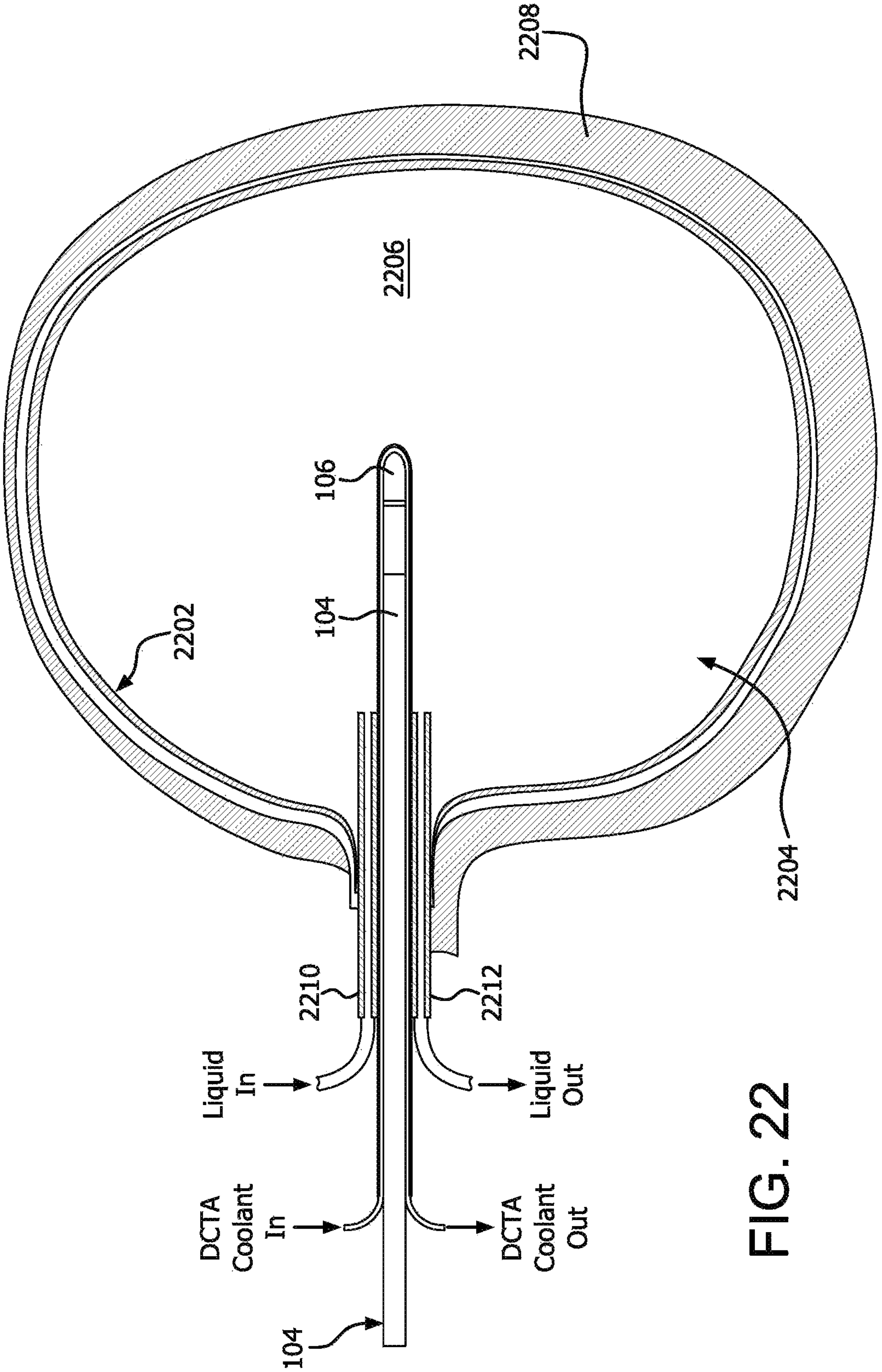


FIG. 21C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DCTA Coolant In
DCTA Coolant Out
104

FIG. 22

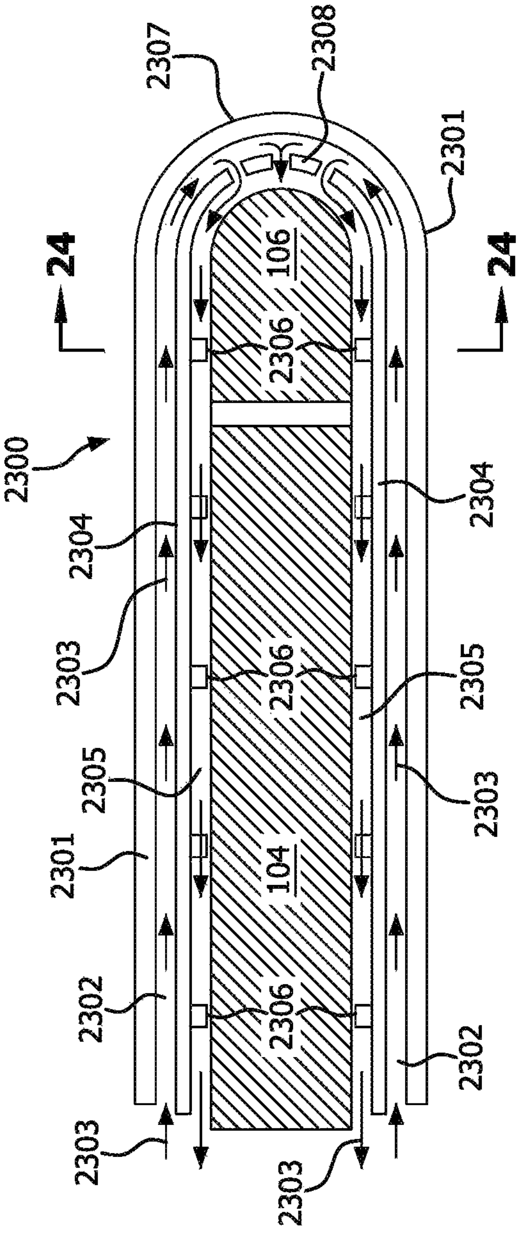
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FIG. 23

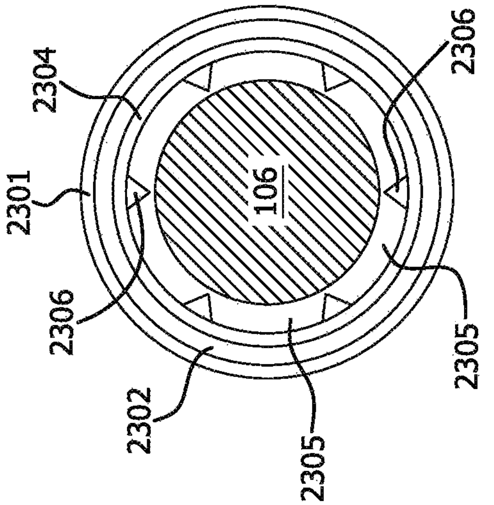
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FIG. 24

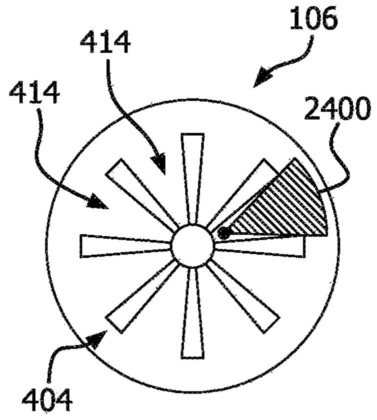

FIG. 25A

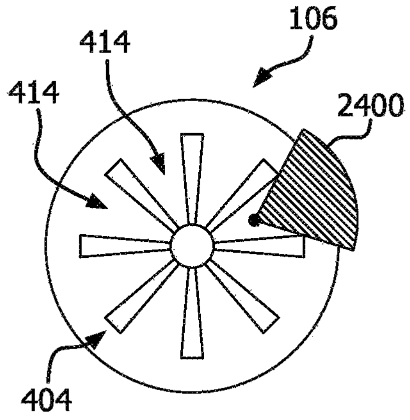

FIG. 25B

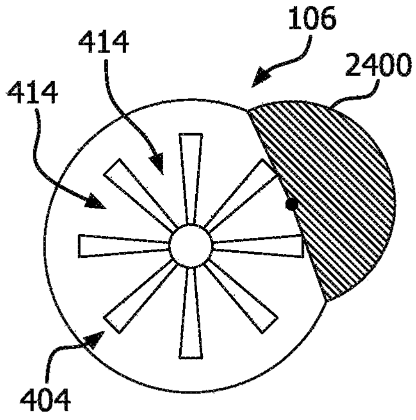

FIG. 25C

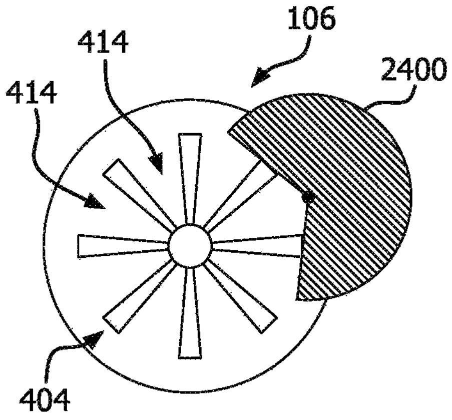

FIG. 25D

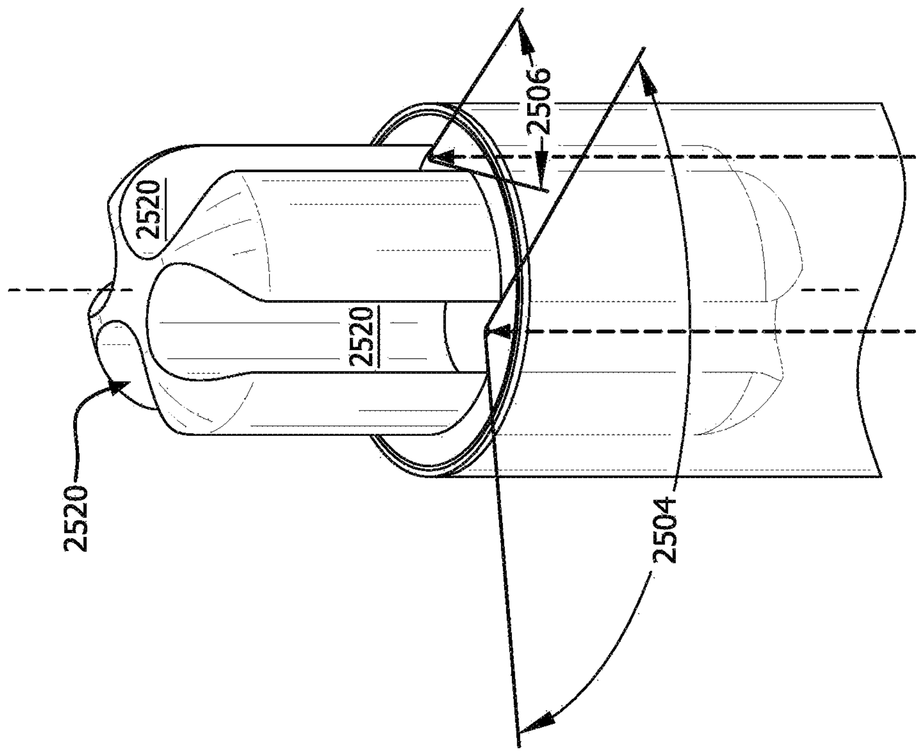

FIG. 26B

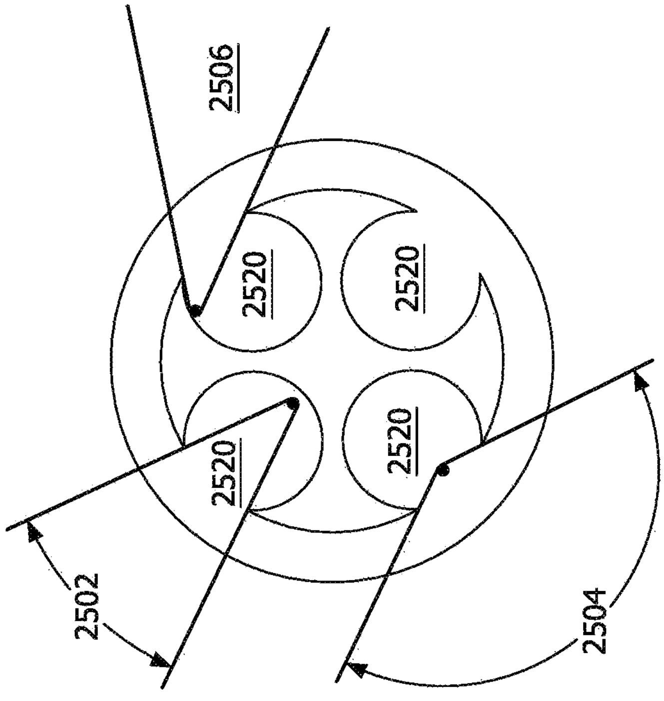

FIG. 26A

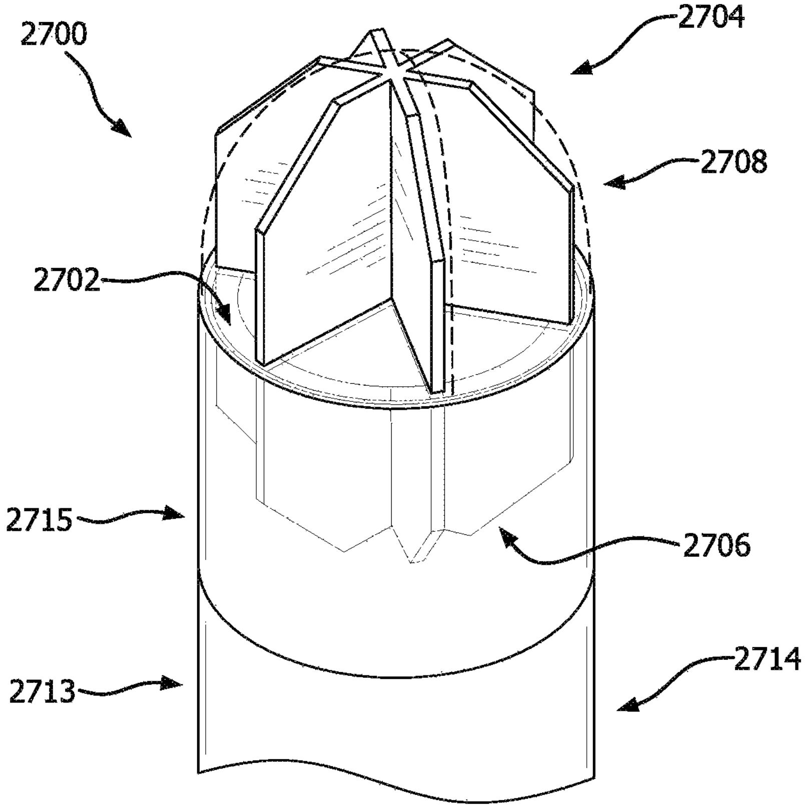

FIG. 27

THREE-DIMENSIONAL BEAM FORMING X-RAY SOURCE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/941,547, filed on Mar. 30, 2018, which claims the benefit of U.S. Patent Provisional No. 62/479,455, filed on Mar. 31, 2017, the contents of which are hereby incorporated by reference in their entireties.

BACKGROUND

Statement of the Technical Field

The technical field of this disclosure comprises sources of X-ray electromagnetic radiation, and more particularly to compact sources of X-ray electromagnetic radiation.

Description of the Related Art

X-rays are widely used in the medical field for various purposes, such as radiotherapy. A conventional X-ray source comprises a vacuum tube which contains a cathode and an anode. A very high voltage of 50 kV up to 250 kV is applied across the cathode and the anode, and a relatively low voltage is applied to a filament to heat the cathode. The filament produces electrons (by means of thermionic emission, field emission, or similar means) and is usually formed of tungsten or some other suitable material, such as molybdenum, silver, or carbon nanotubes. The high voltage potential between the cathode and the anode causes electrons to flow across the vacuum from the cathode to the anode with a very high velocity. An X-ray source further comprises a target structure which is bombarded by the high energy electrons. The material comprising the target can vary in accordance with the desired type of X-rays to be produced. Tungsten and gold are sometimes used for this purpose. When the electrons are decelerated in the target material of the anode, they produce X-rays.

Radiotherapy techniques can involve an externally delivered radiation dose using a technique known as external beam radiotherapy (EBRT). Intraoperative radiotherapy (IORT) is also sometimes used. IORT involves the application of therapeutic levels of radiation to a tumor bed while the area is exposed and accessible during excision surgery. The benefit of IORT is that it allows a high dose of radiation to be delivered precisely to the targeted area, at a desired tissue depth, with minimal exposure to surrounding healthy tissue. The wavelengths of X-ray radiation most commonly used for IORT purposes correspond to a type of X-ray radiation that is sometimes referred to as fluorescent X-rays, characteristic X-rays, or Bremsstrahlung X-rays.

Miniature X-ray sources have the potential to be effective for IORT. Still, the very small conventional X-ray sources that are sometimes used for this purpose have been found to suffer from certain drawbacks. One problem is that the miniature X-ray sources are very expensive. A second problem is that they have a very limited useful operating life. This limited useful operating life typically means that the X-ray source must be replaced after being used to perform IORT on a limited number of patients. This limitation increases the expense associated with IORT procedures. A third problem is that the moderately high voltage available to a very small X-ray source may not be optimal for the desired therapeutic effect. A fourth problem is that their radiation characteristics can be difficult to control in an IORT context such that they are not well suited for conformal radiation therapy.

SUMMARY

This document concerns a method and system for controlling an electron beam. The method involves generating an electron beam and positioning a target element in the path of the electron beam. X-ray radiation is generated as a result of an interaction of the electron beam with the target element. The X-ray radiation is caused to interact with a beam-former structure disposed proximate the target element to form an X-ray beam. At least one of a beam pattern and a direction of the X-ray beam is controlled by selectively varying a location where the electron beam intersects the target element so as to determine an interaction of the X-ray radiation with the beam-former structure.

The location where the electron beam intersects the target element can be controlled by steering the electron beam with an electron beam steering unit. According to one aspect the steered electron beam can be guided through an elongated length of an enclosed drift tube. The drift tube is maintained at a vacuum pressure to minimize attenuation of the electron beam. The electron beam is permitted to interact with the target element after it passes through the drift tube.

According to one aspect, certain operations associated with X-ray beam control are facilitated by absorbing a portion of the X-ray radiation with the beam-former structure. For example, the location where the electron beam intersects the target element can be varied or controlled to indirectly control the portion of the X-ray beam that is absorbed by the beam-former. In some scenarios disclosed herein, the beam former can include at least one shield wall. The shield wall can be arranged to at least partially divide the target element into a plurality of target element segments or sectors. Further, the one or more shield walls can be used to form a plurality of shielded compartments. Each such shielded compartment can be arranged to at least partially confine a range of directions in which the X-ray radiation is emitted when the electron beam intersects the target element sector or segment that is associated with the shielded compartment.

From the foregoing it will be understood that the method can involve controlling the beam direction and form by controlling the electron beam so that it selectively intersects the target element in one or more of the target element sectors. The beam pattern can be further controlled by selectively choosing the location where the electron beam intersects the target element within a particular one of the target element sectors. According to a further aspect, the method can involve selectively controlling an X-ray dose delivered by the X-ray beam in one or more different directions by selectively varying at least one of an EBG voltage and an electron beam dwell time used when the electron beam intersects one or more of the target element sectors.

This document also concerns an X-ray source. The X-ray source is comprised of an electron beam generator (EBG) which is configured to generate an electron beam. A target element is disposed at a predetermined distance from the EBG and positioned to intercept the electron beam. A drift tube is disposed between the EBG and the target element. The EBG is configured to cause the electron beam to travel through an enclosed elongated length of the drift tube maintained at a vacuum pressure.

The target element is formed of a material responsive to the electron beam to facilitate generation of X-ray radiation when the electron beam intercepts the target element. A beam former structure is disposed proximate to the target element and comprised of a material which interacts with the X-ray radiation to form an X-ray beam. An EBG control system selectively controls at least one of a beam pattern and a direction of the X-ray beam by selectively varying a location where the electron beam intersects the target element. In some scenarios disclosed herein, the EBG control system is configured to selectively vary the location where the electron beam intercepts the target by steering the electron beam with an electron beam steering unit.

The beam former is comprised of a high-Z material which is configured to absorb a portion of the X-ray radiation to facilitate formation of the X-ray beam. The EBG control system is configured to indirectly control the portion of the X-ray beam that is absorbed by the beam-former by selectively varying the location where the electron beam intersects the target element.

According to one aspect, the beam-former is comprised of at least one shield wall. The one or more shield walls are arranged to at least partially divide the target element into a plurality of target element sectors or segments. As such the one or more shield walls can define a plurality of shielded compartments. Each shielded compartment is configured to at least partially confine a range of directions in which the X-ray radiation can be radiated when the electron beam intersects the target element sector associated with the particular shielded compartment.

With the X-ray source described herein, the EBG control system can be configured to determine the direction of the X-ray beam by controlling which of the plurality of target element sectors is intersected by the electron beam. The EBG control system is further configured to control the beam pattern by selectively controlling the location within one or more of the target element sectors where the electron beam intersects the target element. According to a further aspect, the EBG control system is configured to selectively control an X-ray dose delivered by the X-ray beam in one or more different directions defined by the target element sectors. It achieves this result by selectively varying at least one of an EBG voltage and an electron beam dwell time which are applied when the electron beam intersects one or more of the target element sectors.

BRIEF DESCRIPTION OF THE DRAWINGS

This disclosure is facilitated by the following drawing figures, in which like numerals represent like items throughout the figures, and in which:

FIG. **1** is a perspective view of an X-ray source with some structures shown partially cut-away to facilitate improved understanding.

FIG. **2** is an enlarged view of a portion of FIG. **1** which shows certain details of an electron beam generator.

FIG. **3** is an enlarged view of a portion of FIG. **2** which shows certain details of an electron beam generator.

FIG. **4** is an enlarged perspective view of an X-ray emission directionally controlled target assembly (DCTA) which is useful for understanding the X-ray source of FIG. **1**.

FIG. **5** is an end view of the DCTA in FIG. **4**.

FIG. **6** is an enlarged view of the DCTA in FIG. **6** which is useful for understanding an X-ray beam-forming operation.

FIG. **7** is a drawing that is useful for understanding an X-ray beam-forming operation in the X-ray source of FIG. **1**.

FIG. **8** is a cross-sectional view showing certain details of an X-ray target disclosed herein.

FIGS. **9**, **10** and **11** are a series of drawings which are useful for understanding a first alternative X-ray DCTA configuration.

FIG. **12** is a second alternative DCTA configuration.

FIG. **13** is a third alternative DCTA configuration.

FIG. **14** is a fourth alternative DCTA configuration.

FIG. **15** is a fifth alternative DCTA configuration.

FIGS. **16**A-**16**B are a series of drawings which are useful for understanding a sixth alternative DCTA configuration and assembly process.

FIGS. **17**A and **17**B are a series of drawings which are useful for understanding a seventh alternative DCTA configuration and assembly process.

FIG. **18** is a drawing that is useful for understanding an eighth alternative DCTA configuration.

FIG. **19** is a drawing that is useful for understanding an ninth alternative DCTA configuration.

FIG. **20** is a block diagram that is useful for understanding a control system for the X-ray source in FIG. **1**.

FIGS. **21**A-**21**C are a series of drawings that are useful for understanding how an X-ray beam can be selectively controlled.

FIG. **22** is a drawing which is useful for understanding how the X-ray source described herein can be used in an IORT procedure.

FIG. **23** is a cross-sectional view showing a cooling arrangement for a DCTA.

FIG. **24** is a cross sectional view along line **24**-**24** in FIG. **23**.

FIGS. **25**A-**25**D are a series of drawings which are useful for understanding a technique for controlling beam width in a DCTA as described herein.

FIGS. **26**A-**26**B show a sixth alternative DCTA configuration and an associated beam steering method.

FIG. **27** is useful for understanding how a portion of a drift tube proximal to the DCTA can be formed from an X-ray transmissive material.

DETAILED DESCRIPTION

It will be readily understood that the solution described herein and illustrated in the appended figures could be arranged and designed in a wide variety of different configurations. Thus, the following more detailed description, as represented in the figures, is not intended to limit the scope of the present disclosure, but is merely representative of certain implementations in various different scenarios. While the various aspects are presented in drawings, the drawings are not necessarily drawn to scale unless specifically indicated.

A solution disclosed herein concerns an X-ray source which can be used for treating superficial tissue structures in various radiotherapy procedures, including IORT. Drawings useful for understanding the X-ray source **100** are provided in FIGS. **1**-**7**. With the arrangement shown in FIGS. **1**-**7**, X-rays can be selectively directed in a plurality of different directions around a periphery of a beam directionally controlled target assembly (DCTA) **106** comprising the X-ray source. Moreover, the pattern of relative X-ray intensity, which defines the shape of the beam, can be controlled to facilitate different treatment plans. For example, the intensity over a range of angles can be selected to vary an X-ray beam parameter such as beam width.

The source **100** is comprised of electron beam generator (EBG) **102**, a drift tube **104**, DCTA **106**, beam focusing unit **108**, and beam steering unit **110**. In some scenarios, a cosmetic cover or housing **112** can be used to enclose the EBG **102**, beam focusing unit **108** and beam steering unit **110**.

The DCTA **106** can facilitate a miniature source of steerable X-ray energy, which is particularly well suited for IORT. Accordingly, the dimensions of the various components can be selected accordingly. For example, the diameter d of the drift tube **104** and DCTA **106** can be advantageously selected to be about 30 mm or less. In some scenarios, the diameter of these components can be 10 mm, or less. For example the diameter of these component can be selected to be in the range of about 10 mm to 25 mm. Of course, the drift tube and DCTA **106** are not limited in this regard and other dimensions are also possible.

Similarly, the drift tube **104** is advantageously configured to have an elongated length L which extends some distance from the EBG **102**. The drift tube length is advantageously selected so that it is sufficiently long so as to extend from the cover or housing **112** and into a tumor cavity of a patient so that the DCTA can be selectively positioned inside of a portion of a human body undergoing treatment. Accordingly, exemplary values of drift tube length L can range from 10 cm to 50 cm, with a range of between 18 cm to 30 cm being suitable for most applications. Of course, the dimensions disclosed herein are provided merely as several possible examples and are not intended to be limiting.

Electron beam generators are well-known in the art and therefore the structure and operation of the EBG will not be described in detail. However, a brief description of various aspects of the EBG **102** is provided here to facilitate an understanding of the disclosure. The EBG **102** can include several major components which are best understood with reference to FIGS. **2** and **3**. These components can include an envelope **202** which encloses a vacuum chamber **210**. In some scenarios, the envelope **202** can be comprised of a glass, ceramic or metallic material that provides suitable freedom from air leaks. Within the vacuum chamber a vacuum is established and maintained by means of an evacuation port **216** and a getter **214**.

Inserted within the vacuum chamber is a high voltage connector **204** for providing high negative voltage to a cathode **306**. A suitable high voltage applied to the cathode for purposes of X-ray generation as described herein would be in the range of −50 kV and −250 kV. Also enclosed in the vacuum chamber is a field shaper **206** and a repeller **208**. The purpose of each of these components is well known in the electron beam generator art. However, a brief description is provided to facilitate understanding of the solution presented herein. The cathode **306**, when heated, serves as a source of electrons, which are accelerated by the high voltage potential between the cathode **306** and the anode. In FIG. **2**, the purpose of the anode is served by the envelope **202**, and the repeller **208**, where the envelope **202** is at ground voltage and the repeller is at a small positive voltage with respect to ground.

The function of the repeller **208** is to repel any positively charged ions that might be generated in the drift tube **104** or the DCTA **106**, thus preventing those ions from entering the region of the cathode **306** where they might cause damage. The function of the field shaper **206** is to provide smooth surfaces which control the shape and magnitude of the electric field caused by the high voltage. In the scenario of FIG. **3**, the grid **310** provides a desired shape to the electric field in the vicinity of the cathode **306**, as well as allowing the emission of electrons from the cathode **306** to be shut off. The cathode **306** is fixed to the legs of the heater **309***a* and **309***b*. The legs of the heater **309***a* and **309***b* are typically made from a metallic material that has both high electrical resistivity and high resistance to thermal degradation, thus allowing an electric current flowing through the heater legs to generate a high temperature that heats the cathode **306**. The electrical connections to the heater legs **309***a* and **309***b* are provided by the connector pins **308***a* and **308***b*, which connect the heater legs **309***a* and **309***b* to connections in the high voltage connector **204**. The insulating disk **302** is typically made of an insulating material such as glass or ceramic and provides electrical insulation between the connector pins **308***a* and **308***b* and is also resistant to heat generated by the heater legs **309***a* and **309***b*.

In a scenario disclosed herein, the drift tube **104** can be comprised of a material such as stainless steel. In other scenarios the drift tube can be partially comprised of Silicon Carbide (SiC). Alternatively, the drift tube **104** can be comprised of a ceramic material such as alumina or aluminum nitride. If the drift tube structure is not formed of a conductive material, then it can be provided with a conductive inner lining **114**. For example, the conductive inner lining can be comprised of copper, titanium alloy or other material, which has been applied (e.g., applied by sputtering, evaporation, or other well-known means) to the interior surface of the drift tube. The hollow inner portion of the drift tube is open to the vacuum chamber **210**, such that the interior **212** of the drift tube **104** is also maintained at vacuum pressure. A suitable vacuum pressure for purposes of the solution described herein can be in the range below about 10^{-5} torr or particularly between about 10^{-9} torr to 10^{-7} torr.

Electrons comprising an electron beam are accelerated by EBG **102** toward the DCTA **106**. These electrons will have significant momentum when they arrive at the entry aperture **116** to the drift tube **104**. The interior **212** of the drift tube is maintained at a vacuum and at least the inner lining **114** of the tube is maintained at ground potential. Accordingly, the momentum imparted to the electrons by EBG **102** will continue to ballistically carry the electrons down the length of the drift tube **104** at very high velocity (e.g., a velocity approaching the speed of light) toward the DCTA **106**. It will be appreciated that as the electrons are traveling along the length of the drift tube **104**, they are no longer electrostatically accelerated.

The beam focusing unit **108** is provided to focus a beam vortex of electrons traveling along the length of the drift tube. For example, such focusing operations can involve adjusting the beam to control a point of convergence of the electrons at the DCTA tip. As such, the beam focusing unit **108** can be comprised of a plurality of magnetic focusing coils **117**, which are controlled by selectively varying applied electric currents therein. The applied electric currents cause each of the plurality of magnetic focusing coils **117** to generate a magnetic field. Said magnetic fields penetrate into the drift tube **104** substantially in the region enclosed by the beam focusing unit **108**. The presence of the penetrating magnetic fields causes the electron beam to converge selectively in a manner well understood in the art.

A beam steering unit **110** is comprised of a plurality of selectively controllable magnetic steering coils **118**. The steering coils **110** are arranged to selectively vary a direction of travel of electrons traveling within the drift tube **104**. The magnetic steering coils achieve this result by generating (when energized with an electric current) a magnetic field. The magnetic field exerts a force selectively upon the electrons traveling within the drift tube **104**, thus varying the electron beam direction of travel. As a result of such deflection of the electron beam direction of travel, a location where the beam strikes a target element of the DCTA **106** can be selectively controlled.

As shown in FIGS. **4** and **5**, the DCTA **106** is disposed at an end portion of the drift tube **104**, distal from the EBG **102**. The DCTA is comprised of a target **402** and a beam shield **404**. The target **402** is comprised of a disk-shaped element, which is disposed transverse to the direction of electron beam travel. For example, the disk-shaped element can be disposed in a plane which is approximately orthogonal to the direction of electron beam travel. In some scenarios, the target **402** can enclose an end portion of the drift tube **104** distal from the EBG to facilitate maintenance of the vacuum pressure within the drift tube. The target **402** can be comprised of various different materials; however it is advantageously comprised of a material such as molybdenum, gold, or tungsten which has a high atomic number so as to facilitate the production of X-rays at relatively high efficiency when bombarded with electrons. The structure of the target **402** will be described in greater detail as the discussion progresses.

As shown in FIG. **4**, the beam shield **404** can include a first portion **406** which is disposed adjacent to one major surface of the target **402**, and a second portion **408**, which is disposed adjacent to an opposing major surface of the target. In some scenarios, the first portion **406** can be disposed internal of the drift tube **104** within a vacuum environment, and the second portion **408** can be disposed external of the drift tube. If a portion of the beam shield **404** is disposed external of the drift tube as shown in FIG. **4**, then an X-ray-transmissive cap member **418** can be disposed over the second portion **408** of the beam shield to enclose and protect the portions of the DCTA external of the drift tube. In FIG. **4**, the cap member is indicated by dotted lines only so as to facilitate an understanding of the DCTA structure. However, it should be understood that the cap member **418** would extend from the end of the drift tube **104** so as to enclose the first portion **406** of the DCTA.

The beam shield **404** is comprised of a plurality of wall elements **410**, **412**. The wall elements **410** associated with the first portion **406** can extend from a first major surface of the disk-shaped target which faces in a direction away from the EBG **102**. The wall shaped elements **412** associated with the second portion **408** can extend from the opposing major surface of the target facing toward the EBG **102**. The wall elements **410**, **412** also extend in a radial direction outwardly from a DCTA centerline **416** toward a periphery of the disk-shaped target **402**. Accordingly, the wall elements form a plurality of shielded compartments **420**, **422**. The wall elements **410**, **412** can be advantageously comprised of a material which interacts in a substantial way with X-ray photons. In some scenarios, the material can be one that interacts with the X-ray photons in a way which causes the X-ray photons to give up a substantial part of its energy and momentum. Accordingly, one type of suitably interactive material for this purpose can comprise a material that attenuates or absorbs X-ray energy. In some scenarios, the material chosen for this purpose can be advantageously chosen to be one that is highly absorbent of X-ray energy.

Suitable materials which are highly absorptive of X-ray radiation are well known. For example, these materials can include certain metals such as stainless steel, molybdenum (Mo), tungsten (W), tantalum (Ta), or other high atomic number (high-Z) materials. As used herein the phrase high-Z material will generally include those which have an atomic number of at least 21. Of course, there may be some scenarios in which a lesser degree of X-ray absorption is desired. In such scenarios, a different material may be suitable. Accordingly, a suitable material for the shield wall is not necessarily limited to high atomic number materials.

In the scenario shown in FIG. **4**, the plurality of wall elements extend radially outward from the centerline **416**. However, the configuration of the beam shield is not limited in this regard and it should be understood that other beam shield configurations are also possible. Several of such alternative configurations are described below in further detail. Each of the wall elements can further comprise rounded or chamfered corners **411** to facilitate beam formation as described below. These rounded or chamfered corners can be disposed at portions of the wall elements, which are distal from the target **402** and spaced apart from the centerline **416**.

As shown in FIG. **4**, wall elements **410** can be aligned with wall elements **412** to form aligned pairs of shielded compartments **420**, **422** on opposing sides of the target **402**. Each such shielded compartment will be associated with a corresponding target segment **414** which is bounded by a pair of wall elements **410** on one side of the target **402**, and a pair of wall elements **412** on an opposing side of the target.

As is known, X-ray photons are released in directions which are generally transverse to the collision path of the electron beam with the major surface of the target **402**. The target material is comprised of a relatively thin layer of target material such that electrons bombarding the target **402** produce X-rays in directions extending away from both major surfaces of the target. Each aligned pair of shielded compartments **420**, **422** (as defined by wall elements **410**, **412**) and their corresponding target segment **414** comprise a beam-former. X-rays which are generated when high energy electrons interact with a particular target segment **414** will be limited in their direction of travel by the wall elements defining the compartments **410**, **412**. This concept is illustrated in FIG. **6**, which shows that an electron beam **602** bombards a segment of target **402** to produce transmitted and reflected X-rays in directions that are generally transverse to the collision path of the electron beam. But it can be observed in FIG. **6** that the X-rays will only be transmitted over a limited range of azimuth and elevation angles α, β due to the shielding effect of the beam-former. By selectively controlling which target segment **414** is bombarded with electrons, and where within the target segment **414** that the electron beam actually strikes the target segment, the X-ray beams in a range of different directions and shapes can be selectively formed and sculpted as needed.

Accordingly, the X-ray beam direction (which is defined by a main axis of transmitted X-ray energy), and a pattern of relative X-ray intensity, which comprises the shape of the beam, can be selectively varied or controlled to facilitate different treatment plans. FIG. **7** illustrates this concept by showing that a direction of maximum intensity of X-ray beam **700** can be aligned in a plurality of different directions **702**, **704** by selectively controlling the electron beam **706**. The exact three-dimensional shape or relative intensity pattern of the X-ray beam **700** will vary in accordance with several factors described herein. In some scenarios, the electron beam can be rapidly steered so that different target segments are successively bombarded with electrons so that the electron beam intersects different target segments for predetermined dwell times. If more than one target segment **414** is bombarded by the electron beam, then multiple beam segments can be formed in selected directions defined by the associated beam-formers and each can have a different beam shape or pattern.

Referring now to FIG. **8** it can be observed that the target **402** is formed of a very thin layer of target material **802**, which can be bombarded by an electron beam **804** as described herein. The target material is advantageously chosen to be one which has a relatively high atomic number. Exemplary target materials which can be used for this purpose include molybdenum, tungsten and gold. The thin layer of target material **802** is advantageously disposed on a thicker substrate layer **806**. The substrate layer is provided to facilitate a target that is more robust for added strength, and to facilitate thermal energy transfer away from the metal layer. Exemplary materials that could be used for the substrate layer **806** can include Beryllium, Aluminum, Sapphire, Diamond or ceramic materials such as alumina or boron-nitride. Among these, Diamond is particularly advantageous for this application as it is relatively transmissive of X-rays, non-toxic, strong, and offers excellent thermal conductivity.

A diamond substrate disk, which is suitable for substrate layer **804** can be formed by a chemical vapor deposition technique (CVD) that allows the synthesis of diamond in the shape of extended disks or wafers. In some scenarios, these disks can have a thickness of between 300 to 500 μm. Other thicknesses are also possible, provided that the substrate has sufficient strength to contain the vacuum within the drift tube **104** and is not so thick as to attenuate X-rays passing through it. In some scenarios a CVD diamond disk having a thickness of about 300 μm can be used for this purpose. A thin layer of a target material **802**, which has been sputtered on one side of the CVD diamond disks as described herein can have thickness of between 2 to 50 μm. For example, the target material can in some scenarios have a thickness of 10 μm. Of course, other thicknesses are also possible and the solution presented herein is not intended to be limited by these values.

FIGS. **9**, **10** and **11** are a series of drawings which are useful for understanding a first alternative DCTA configuration. The DCTA **906** is similar to the DCTA **106** but includes an additional ring element mounted to a periphery of the beam shield **914** to facilitate attachment of the DCTA to an end portion of the drift tube **904**. More particularly, each of a first and second portion **916**, **918** of the beam shield **914** can respectively include a ring **908***a*, **908***b*. The target **914** can be disposed between the two rings. One or both of the rings can then be secured to the end of the drift tube (e.g., secured by brazing) as shown in FIG. **11**.

FIG. **12** is useful for understanding a second alternative DCTA configuration. In this scenario, the single disk-shaped X-ray target **402** shown in FIG. **4** is replaced by a plurality of individual smaller wedge-shaped targets **1202**, which are respectively aligned with each of the compartments as shown. In such a scenario, the wall elements **1210**, **1212** corresponding to two portions **1216** and **1218** and medial base plate **1220** can be optionally made of a single piece of material. The segmented wedge-shaped targets **1202** can be positioned in the medial base plate **1220** between the wall elements as shown, after which the entire assembly can be fixed to an end portion of the drift tube. It can also be observed in FIG. **12** that wall elements **1210** have curved or rounded corners rather than the chamfered corners shown in FIGS. **4**-**6**. FIG. **13** is a third alternative DCTA **1306** which is similar to the arrangement shown in FIG. **12**, but is comprised of a plurality of separate circular or disk shaped targets **1302** which are provided in place of the wedge-shaped targets **1202**.

FIG. **14** is a fourth alternative DCTA configuration **1406** in which an entire beam shield **1414** is disposed externally of the drift tube. The target elements **1402** in this scenario are end faces of hollow tubular pedestals **1420**. The wall elements **1410** extend from a face of a base plate **1408** which mounts to the drift tube at an end distal from the EBG **102**. The end faces defined by the target elements **1402** are spaced apart from the base plate on which the wall elements **1410** are disposed. In some scenarios, the tubular pedestals can have a cylindrical geometry as shown. However, other tubular configurations are also possible. The tubular pedestals can advantageously have a length that is sufficient to position the target elements **1402** at a medial location along the length of the DCTA. As such, the positioning of the target elements can be selected optimally for beam forming operations. The hollow interior portion of each of the pedestals is open to the vacuum defined by the interior of the drift tube **1404**. Consequently, an electron beam directed at a particular one of the target elements **1402** will travel in a vacuum environment through the drift tube and through the interior of the pedestal **1420** before striking the target element **1402**. FIG. **15** is a fifth alternative DCTA **1506** which is similar to the arrangement shown in FIG. **14**. However, in DCTA **1506** each individual target element **1402** shown in FIG. **14** is replaced with a plurality of smaller diameter target elements **1502**.

FIGS. **16**A and **16**B are a series of drawings which are useful for understanding a sixth alternative DCTA configuration and assembly process. As will be appreciated from the discussion herein, proper alignment of first and second portions **1602**, **1604** of a beam shield **1600** is important to ensure correct functioning of each X-ray beam-former. This problem is compounded because the second portion **1604** of the beam shield may not be visible to an assembly technician once inserted into the drift tube **1614**. Further, it is important that the first and second portions **1602**, **1604** remain aligned after assembly.

To facilitate these alignment concerns a post **1606** is provided in alignment with a central axis **1620** of the second portion **1604**. The post **1606** can extend through an aperture **1616** in the target **1612**. The post can include a notch element or key structure **1608**. A bore **1622** is defined within the first portion **1602** in alignment with the central axis **1620**. At least a portion of the bore can have a complimentary notch element or key structure **1612**. This complimentary notch element or key structure will correspond to the geometry and shape of the notch or keyed structure **1608**. Accordingly, the first and second portions **1602**, **1604** can only be mated in a manner shown in FIG. **16**B, whereby the wall elements **1624** of the first portion **1602** are aligned with the wall elements **1626** of the second portion **1604**.

An alignment similar to that described in FIGS. **16**A and **16**B can alternatively be achieved by means of a profiled pin in a seventh alternative DCTA configuration shown in FIGS. **17**A and **17**B. As illustrated therein, a beam shield **1700** can comprise first and second portions **1702**, **1704**. Each of the first and second portions can comprise wall elements **1724**, **1726** which define a plurality of guide faces **1722**. These guide faces **1722** can engage a plurality of corresponding pin faces **1712** formed on the profiled pin **1706**. When the guide faces and pin faces are properly aligned, the profiled pin can be inserted through the first and second portions along a central axis **1720**. A pin head **1714** limits the insertion of the pin into the first and second portions. Once inserted, the pin

1706 can be secured in place with a suitable securement device. For example, the pin **1706** can comprise a threaded end on which a threaded nut **1708** can be disposed to hold the pin in place.

An eighth alternative DCTA **1800** is shown in FIG. **18**. The DCTA **1800** is comprised of a target **1802** and a beam shield **1804**. The beam shield **1804** has a structure which is comprised of a post **1820**. In some scenarios, the post **1820** can be in alignment with a centerline **1816** of the target **1802** and the drift tube **1814**. The post can include a first portion **1806** which is disposed adjacent to (and extends from) one major surface of the target **1802**, and a second portion **1808** which is disposed adjacent to (and extends from) an opposing major surface of the target. As such, the first portion **1806** can be disposed internal of the drift tube **104** within the vacuum environment, and the second portion **1808** can be disposed external of the drift tube as shown.

The post **1820** can be comprised of a cylindrical post as shown. However, acceptable configurations of the structure are not limited in this regard and the post can also have a different cross-sectional profile to facilitate beam forming operations. For example, the post can have a cross-sectional profile that is square, triangular, or rectangular. In some scenarios the cross-sectional profile can be chosen to be an n-sided polygon (e.g., an n-sided regular polygon). Like the wall elements of the other configurations described herein, the post **1820** is advantageously comprised of a material which greatly attenuates X-ray energy. For example, the post can be comprised of a metal such as stainless steel, molybdenum, or tungsten, tantalum, or other high atomic number (high-Z) materials.

A ninth alternative DCTA **1900** is shown in FIG. **19**. The configuration of the DCTA **1900** can be similar to that of DCTA **106**. As such the DCTA can include a beam shield **1904** comprised of a first portion **1906** which is disposed adjacent to one major surface of the target **1902**, and a second portion **1908** which is disposed adjacent to an opposing major surface of the target. In some scenarios, the first portion **1906** can be disposed within a portion of the DCTA exposed to a vacuum environment associated with the drift tube **104**. The second portion **1908** can be disposed external of the drift tube as shown. The beam shield **1904** is comprised of a plurality of wall elements **1910**, **1912**. The wall elements **1910** associated with the first portion **1906** can extend from a first major surface of the disk-shaped target which faces in a direction away from the EBG **102**. The wall shaped elements **1912** associated with the second portion **1908** can extend from the opposing major surface (e.g., a target surface facing toward the EBG **102**). The wall elements **1910**, **1912** also extend in a radial direction outwardly from a DCTA centerline **1916** toward a periphery of the disk-shaped target **1902**. Accordingly, the wall elements form a plurality of shielded compartments.

The DCTA **1900** is similar to many of the other DCTA configurations disclosed herein. However, it can be observed in FIG. **19** that the wall elements **1910**, **1912** of DCTA **1900** do not fully extend to the peripheral edge **1903** of the target element **1902**. Instead, the wall elements extend only a portion of a radial distance from a DCTA centerline **1916** to the peripheral edge **1903** of target element **1902**. The configuration shown in FIG. **19** can be useful to facilitate different beam patterns as compared to other DCTA configurations shown herein.

Turning now to FIG. **20**, there is illustrated an exemplary control system **2000** for controlling the X-ray source shown in FIGS. **1-7**. The control system can include a control processor **2002**, which controls a high voltage source controller **2004**, a high voltage generator **2006**, a coolant system **2012**, a focusing coil current source **2024**, a focusing current control circuit **2026**, a steering coil current source **2014** and a steering current control circuit **2016**. The high voltage source controller **2004** can be comprised of control circuitry which is designed to facilitate control of the high voltage generator **2006**. A grid control circuit **2005** and a heater control circuit **2007** can also be provided as part of the exemplary control system.

The high voltage generator **2006** can be comprised of a high voltage transformer **2008** for stepping up relatively low voltage AC to a higher voltage, and a rectifier circuit **2010** for converting the high voltage AC to high voltage DC. The high voltage DC can then be applied to the cathode and the anode in the X-ray source devices described herein.

Coolant system **2012** can include a coolant reservoir **2013** which contains an appropriate fluid for cooling the DCTA **106**. For example, water can be used for this purpose in some scenarios. Alternatively, an oil or other type of coolant can be used to facilitate cooling. In some scenarios a coolant can be selected, which minimizes the potential for corrosion of certain metal components comprising the DCTA. A pump **2015**, electronically controlled valves **2017**, and associated fluid conduits can be provided to facilitate a flow of coolant for cooling the DCTA.

A plurality of electrical connections (not shown) can be provided in association with each of the one or more focusing coils **117** in FIG. **1**. These one or more focusing coils can be independently controlled using the control circuitry in FIG. **20**. More particularly, the focusing coil current source **2024** can comprise a power supply which is capable of supplying DC electric current to each of the one or more focusing coils **117**. This source of electric current can be connected to a focusing coils control circuit **2026** which is comprised of an array of current control elements which are under the control of the control processor. Accordingly, the focusing current control circuit **2026** can selectively direct one or more focusing currents C**1**, C**2**, C**3**, . . . Cn to one or more of the focusing coils **117** for controlling a focus of an electron beam. Methods for focusing an electron beam are known in the art and therefore will not be described here in detail. However, it should be understood that a magnitude of the electric current applied to each of the one or more focusing coils can be selectively controlled to vary the beam focus.

Similarly, a plurality of electrical connections (not shown) can be provided in association with each of the one or more steering coils **118** in FIG. **1**. These steering coils can also be independently controlled using the control circuitry in FIG. **20**. More particularly, the steering coil current source **2014** can comprise a power supply which is capable of supplying DC electric current to each of the plurality of steering coils. This source of current can be connected to a steering coils control circuit **2016** which is comprised of an array of current control elements which are under the control of the control processor. Accordingly, the steering current control circuit can selectively direct steering currents I**1**, I**2**, I**3**, . . . In to one or more of the steering coils **118** for controlling a direction of an electron beam. Methods for controlling electron beam steering coils are known in the art and therefore will not be described here in detail. For example, electron beam steering is commonly performed in conventional cathode ray tube. Still, it should be understood that a magnitude of the current applied to each of the steering coils can be selectively controlled to vary a position where the electron beam strikes a target.

It should be understood that the arrangements are not limited to magnetic deflection of the electron beam as described herein. Other methods of electron beam steering are also possible. For example, it is well known that applied electric fields can also be used to deflect the electron beam. In such scenarios, high voltage deflection plates could be used to control the electron beam in place of the steering coils and the voltage applied to the plates would be varied rather than the current.

The control processor **2002** can be comprised of one or more devices, such as a computer processor, an application specific circuit, a field programmable gate array (FPGA) logic device, or other circuits programmed to perform the functions described herein. As such, the controller may be a digital controller, an analog controller or circuit, an integrated circuit (IC), a microcontroller, or a controller formed from discrete components.

FIGS. **21**A-**21**C are a series of drawings which are useful for understanding the operation of an DCTA as described herein. For convenience, the explanation will proceed with respect to the DCTA disclosed herein with respect to FIGS. **1**-**8**. However, it should be understood that these concepts are similarly applicable to many or all of the DCTA configurations disclosed herein.

FIG. **21**A conceptually shows a composite X-ray beam pattern viewed along DCTA centerline **416** in which X-rays can be understood as being uniformly generated in a plurality of radially directed beams beam segments **2102**. Such a beam pattern can be produced when the electron beam is diffused or steered to excite all of the segments **414** associated with a target **402**. Each of the radial beam segments **2102** is generated by a corresponding beam-former comprising a portion of the DCTA **106**. In the scenario illustrated in FIG. **21**A, the beam generator is controlled (e.g., with a control system **2000**) so that each of the beam segments results in substantially the same X-ray dosage to the treated areas in different azimuth directions relative to the DCTA centerline **416**. Further, it can be observed in FIG. **21**A that the beam segments **2102** are arranged so that X-ray photons are directed at a plurality of different angles around the DCTA **106** in an arc of about 360 degrees.

The total intensity of the X-ray radiation produced by a DCTA, such as DCTA **106**, is approximately proportional to the square of the accelerating voltage. So, in some scenarios, the intensity of an X-ray beam produced at the can be respectively controlled by controlling a voltage potential of the cathode relative to the anode. Independent control over the intensity and direction of each X-ray beam segment **2102** can facilitate selective variations in the composite beam pattern to achieve composite beam patterns, such as the one which is shown in FIG. **21**B. The electron beam intensity and/or dwell time can be selectively varied when impinging on different segments of the target to facilitate a desired radiation treatment plan. FIG. **21**C illustrates that in some scenarios, beams intensity in certain radial or azimuth directions can be reduced to substantially zero. In other words, the X-ray beam in a particular radial or azimuth direction can be essentially disabled to facilitate a particular radiation treatment plan. Control over the beam generators can be facilitated by a control system (such as control system **2000**).

It should be noted that the beam patterns in FIGS. **21**A-**21**C are simplified patterns which are presented in two-dimensions to facilitate a conceptual understanding of the manner in which the beam pattern can be controlled in different radial directions by varying the electron beam intensity and dwell times at different locations on the target. Actual beam patterns produced using this technique are considerably more complex and would naturally comprise a three-dimensional radiation pattern as generally illustrated in FIG. **7**. Still, it will be understood that electron beams produced using higher voltage potentials can result in greater X-ray beam intensity in a particular radial or azimuth direction, and electron beams produced using lower voltage potentials will result in lower X-ray beam intensity in a particular radial or azimuth direction. Naturally, the total length of time the X-ray beam is applied in a particular direction will affect the total radiation dose that is delivered in that direction.

The intensity of X-rays emitted by a focused electron beam depends strongly on the distance away from the focus. To control the distance of the tissue treatment volume, and to modify the penetrating power of the X-ray beam, it can be advantageous in the case of IORT at least to fill an interstitial space between the X-ray source and a wound cavity with saline fluid. Such an arrangement is illustrated in FIG. **22** which shows that a DCTA **106** can be disposed within a fluid bladder **2202**. The fluid bladder can be an elastic balloon-like member which is inflated with a fluid **2206**, such as saline, so as to fill an interstitial space **2204** between the X-ray source and a tissue wall **2208** (e.g., a tissue wall comprising a tumor bed). Fluid conduits **2210**, **2212** can facilitate a flow of fluid to and from the interior of the fluid bladder. Such an arrangement can help enhance the uniformity of irradiation of the tumor bed by positioning the entire tissue wall a uniform distance away from the X-ray source to facilitate a more consistent radiation exposure.

The generation of X-rays at DCTA **106** can generate substantial amounts of heat. So, in some scenarios, in addition to the fluid **2206** which fills the interstitial space **2204**, a separate flow of coolant can be provided to the DCTA. One example of such an arrangement is shown in FIGS. **23** and **24**. FIG. **23** shows a portion of the drift tube **104** and the DCTA **106**. A cooling jacket **2300**, which surrounds the drift tube and the DCTA is shown in cross-section to reveal a plurality of coaxial cooling channels **2302**, **2305**. FIG. **24** is a cross-sectional view of the assembly shown in FIG. **23**, taken along line **24**-**24**. It may be understood from FIGS. **23** and **24** that the plurality of coaxial cooling channels can be configured as a sheath which surrounds the DCTA (and portions of the drift tube) and provides a flow of coolant to carry heat away from the DCTA.

More particularly, an outer coaxial cooling channel **2302** is defined by an interstitial space between an outer sheath **2301** and an inner sheath **2304**. An inner coaxial cooling channel **2305** is defined by the inner sheath and an outer surface comprising portions of the drift tube **104** and DCTA **106**. The inner coaxial cooling channel **2305** is maintained in part by nubs **2306**. The nubs maintain a gap between the inner sheath **2304** and outer surfaces of the drift tube **104** and the DCTA **106**. When the X-ray source is in operation, coolant **2303** is flowed under a positive pressure toward the DCTA **106** through the outer coaxial cooling channel **2302**.

As indicated by the arrows in FIG. **23**, the coolant **2303** flows to an end portion **2307** of the cooling jacket where a nozzle part **2308** is provided. In some scenarios the nozzle part **2308** can be integrated with the inner sheath **2304** as shown. Alternatively, the nozzle part can comprise a separate element. The nozzle part **2308** includes a plurality of ports which are arranged to permit coolant **2303** to flow from the outer coaxial cooling channel **2302** to the inner coaxial cooling channel **2305**. The nozzle part also serves to direct the flow or spray of coolant onto and around the DCTA **106** so as to provide a cooling effect. This flow, which is indicated by the arrows in FIG. **23** can be in the form of a continuous flow, a spray or a dripping action depending on the coolant flow pressure and the exact configuration of the nozzle part. After cooling the DCTA tip, the coolant **2303** flows along a return path defined by the inner coaxial cooling channel **2305** in the space maintained by the nubs **2306**. The coolant **2303** will then exit the inner coaxial cooling channel through an exhaust port (not shown in FIG. **23**).

It will be appreciated that a cooling jacket **2300** as shown and described herein is one possible configuration that facilitates cooling of the DCTA. In this regard it should be understood that other types of cooling sheaths are also possible and can be used without limitation. Also, it should be understood that there can be some scenarios where the X-ray source can be operated at reduced voltage levels such that a cooling jacket may not be needed.

Additional control over the X-ray radiation pattern can be obtained by selectively varying where the electron beam impinges upon a particular target segment **414**. For example, it can be observed in FIGS. **25**A-**25**D that a beam width of an X-ray beam produced by each beam-former can be adjusted by varying the location where the electron beam strikes a particular target segment. When the electron beam strikes the target segment closest to a centerline of the beam shield **404**, a relatively narrow beam is produced by the beam forming compartment. But when the beam is progressively moved radially outward from the centerline in FIGS. **25**B-**25**D, the resulting X-ray beam becomes progressively wider in the azimuth direction. Accordingly, the direction and shape of the resulting X-ray radiation intensity pattern can be selectively controlled. It should be noted that the beam patterns in FIGS. **25**A-**25**D are simplified two-dimensional patterns which are presented primarily to facilitate a conceptual understanding of the manner in which the beam width can be controlled by varying the location where the electron beam striges a particular target segment. Actual beam patterns produced using this technique are considerably more complex and would naturally comprise a three-dimensional radiation pattern similar to that illustrated in FIG. **7**.

FIGS. **26**A-**26**B illustrate a similar concept but with a beam shield having a different configuration. In FIGS. **26**A-**26**B a beam shield **2504** is comprised of a plurality of compartments **2520** which are semi-circular in profile rather than wedge shaped. As illustrated in FIG. **26**A, selectively controlling the location where the electron beam intersects the target can help control whether a relatively narrow X-ray beam **2502** is produced by the beam forming compartment or a relatively wide beam **2504** is produced. As the beam moves radially outward from the centerline of the beam shield **2504**, a wider beam is produced.

A further effect shown in FIG. **26**A can involve varying the location where the electron beam intercepts the target relative to the wall elements to effectively providing a further method to steer the direction of the X-ray beam produced. As the electron beam is rotated around the periphery of the compartment, the direction of the X-ray beam will be varied.

Referring now to FIG. **27**, a DCTA **2700** can include a beam shield **2704** including a first portion **2706** which is disposed adjacent to one major surface of the target **2702**, and a second portion **2708** which is disposed adjacent to an opposing major surface of the target. The first portion **2706** can be disposed internal of the drift tube **2714** within a vacuum environment, and the second portion **2708** can be disposed external of the drift tube. But in some scenarios, a main portion **2713** of the drift tube **2714** can be comprised of a material that absorbs or attenuates X-rays. In such instances it can be desirable to select a material comprising an end portion **2715** of the drift tube to be one that is more highly transmissive to X-ray radiation as compared to the main portion **2713** of the drift tube. In such a scenario, the material comprising the end portion **2715** can be chosen so that it is transparent to X-rays. This arrangement can allow those X-rays which are emitted within the drift tube **2714** to escape the interior without attenuation, thereby providing a desired therapeutic effect.

Alternatively, a DCTA as disclosed herein can be arranged to have a configuration similar to DCTA **1900** which is shown in FIG. **19**. The DCTA **1900** includes a tubular main body portion **1920**. The tubular main body portion can support at a first end a target **1902** and at an opposing end a coupling ring **1922**. The first portion **1906** of the beam shield **1904** extends from a face of the target such that it is disposed within the tubular main body portion **1920**. The coupling ring is configured to allow the DCTA **1900** to be secured to the end of a drift tube (e.g., drift tube **104**). The coupling ring can facilitate a vacuum seal with a distal end of the drift tube. Accordingly, the interior of the tubular main body portion **1920** can be maintained at the same vacuum pressure as the interior of the drift tube.

The tubular main body portion **1920** can be comprised of an X-ray transmissive material. Consequently, an X-ray beam part which is formed interior of the tubular main body portion is not substantially absorbed or attenuated by the structure of the tubular main body portion **1920**. An example of an X-ray transmissive material which can be used for this purpose would include Silicon Carbide (SiC). If SiC is used for this purpose, it can be advantageous to form the coupling ring **1922** from a material such as Kovar, a nickel-cobalt ferrous alloy. Use of Kovar for this purpose can facilitate brazing of the coupling ring to the main body portion. Of course, there may be some scenarios in which it is desirable to attenuate the portion of the X-ray beam which is generated interior of the tubular main body portion **1920**. In that case, the tubular main body portion can instead be formed of a material which is highly absorbent to X-ray photons. An example of such a material that is highly absorbent to X-ray photons would include copper (Cu).

Although the invention has been illustrated and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In addition, while a particular feature of the invention may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application.

The terminology used herein is for the purpose of describing particular aspects of the systems and methods described herein and is not intended to be limiting of the disclosure. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. Furthermore, to the extent that the terms “including”, “includes”, “having”, “has”, “with”, or variants thereof are used in either the detailed description and/or the claims, such terms are intended to be inclusive in a manner similar to the term “comprising.”

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

We claim:

1. A method for generating X-ray photons, comprising:
- generating an electron beam;
- positioning a planar target element wafer in the path of the electron beam;
- generating X-ray radiation as a result of an interaction of the electron beam with a target layer of the target element wafer;
- causing the X-ray radiation to interact with a beam shield comprising a plurality of wall elements extending transversely from a face of the target element wafer;
- variably controlling at least one of a beam shape and direction of the X-ray radiation by selectively controlling a location where the electron beam intersects the target layer; and
- facilitating transfer of thermal energy away from the target layer using a substrate layer on which the target layer is disposed.

2. The method according to claim **1**, wherein the substrate layer is selected to comprise diamond.

3. The method according to claim **1**, wherein the substrate layer is selected to comprise at least one material selected from the group consisting of beryllium, aluminum, and sapphire.

4. The method according to claim **1**, wherein the substrate layer is selected to comprise a ceramic material.

5. The method according to claim **1**, wherein the target layer is applied to the substrate layer using a sputtering method.

6. The method according to claim **1**, further comprising forming the target layer of a material selected from the group consisting of molybdenum, gold and tungsten.

7. The method according to claim **1**, further comprising facilitating X-ray photon emission in directions extending away from opposing major faces of the planar target element wafer by forming the substrate layer of a material that is transmissive of X-ray photons.

8. The method of claim **1**, wherein the substrate layer, the target layer and the beam shield comprise a directionally controlled target assembly (DCTA) and the method further comprises enclosing the DCTA within a drift tube and an X-ray transmissive cap disposed at an end portion of the drift tube.

9. The method of claim **8**, further comprising cooling the DCTA by transferring thermal energy from the substrate layer to the drift tube and the X-ray transmissive cap through a peripheral portion of the substrate layer.

10. The method of claim **9**, further comprising cooling the drift tube and the X-ray transmissive cap with a coolant fluid flowing along an elongated length of the drift tube through a plurality of cooling channels arranged coaxial with the drift tube.

11. A method for generating X-ray photons, comprising:
- generating an electron beam;
- positioning a planar target element wafer in the path of the electron beam;
- generating X-ray photons as a result of an interaction of the electron beam with a target layer of the target element wafer;
- causing the X-ray photons to interact with a beam shield comprising a plurality of wall elements extending transversely from a face of the target element wafer;
- variably controlling at least one of a beam shape and direction formed by the X-ray photons by selectively controlling a location where the electron beam intersects the target layer; and
- facilitating transfer of thermal energy away from the target layer using a substrate layer formed of diamond on which the target layer is disposed.

12. An X-ray target, comprising:
- a planar wafer comprising a target layer and a substrate layer;
- the target layer comprised of an element having a relatively high atomic number;
- the substrate layer transmissive of X-ray photons and configured to support the target layer;
- a beam shield comprising a plurality of wall elements extending transversely from a face of the planar wafer;
- wherein the substrate layer is comprised of a material which has high thermal conductivity to facilitate transfer of thermal energy away from the target layer, and the beam shield is configured to facilitate variable control of at least one of a shape and direction of an X-ray beam produced by the X-ray target responsive to an electron beam intersecting the target layer at a plurality of different locations.

13. The X-ray target of claim **12**, wherein the relatively high atomic number is 21 or greater.

14. The X-ray target of claim **13**, wherein the target layer is comprised of a material selected from the group consisting of molybdenum, gold and tungsten.

15. The X-ray target of claim **12**, wherein the substrate layer is formed of a material selected from the group consisting of beryllium, aluminum, sapphire, ceramic and diamond.

16. The X-ray target of claim **12**, wherein the substrate layer has a thickness of between about 300 μm to 500 μm.

17. The X-ray target of claim **12**, wherein the target layer has a thickness of between about 2 μm to 50 μm.

18. An X-ray target, comprising:
- a planar wafer comprising a target layer and a substrate layer;
- the target layer comprised of an element having an atomic number greater than 21;
- the substrate layer comprised of diamond;
- a beam shield comprising a plurality of wall elements extending transversely from a face of the planar wafer;
- wherein the substrate layer is configured to support the target layer and facilitate transfer of thermal energy away from the target layer, and the beam shield is configured to facilitate variable control of at least one of a shape and direction of an X-ray beam produced by the X-ray target responsive to a location where an electron beam intersects the target layer.

19. The X-ray target according to claim **18** wherein the substrate layer has a thickness of between 300 to 500 μm.

20. The X-ray target according to claim **19**, wherein the target layer has a thickness of between about 2 μm to 50 μm.

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