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Daniels et al.

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(54) **PEBBLE BED BEAM CONVERTER**

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H01J 35/12 (2006.01)

(52) **U.S. Cl.**
CPC ***H01J 35/12*** (2013.01)

(58) **Field of Classification Search**
CPC H01J 35/12; H01J 2235/086; G21G 1/12
See application file for complete search history.

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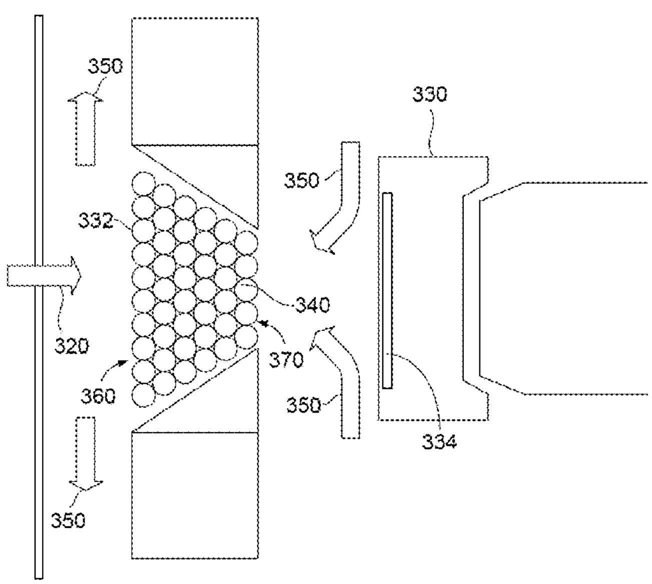
(57) **ABSTRACT**

A converter for converting an electron beam into photons is provided. The converter can include a plurality of spherical beads made of high atomic number (high-Z material) disposed within a coolant fluid. The converter can include an inlet and an outlet for the coolant fluid. The coolant fluid can flow in a opposite direction as a direction of an electron beam.

20 Claims, 8 Drawing Sheets



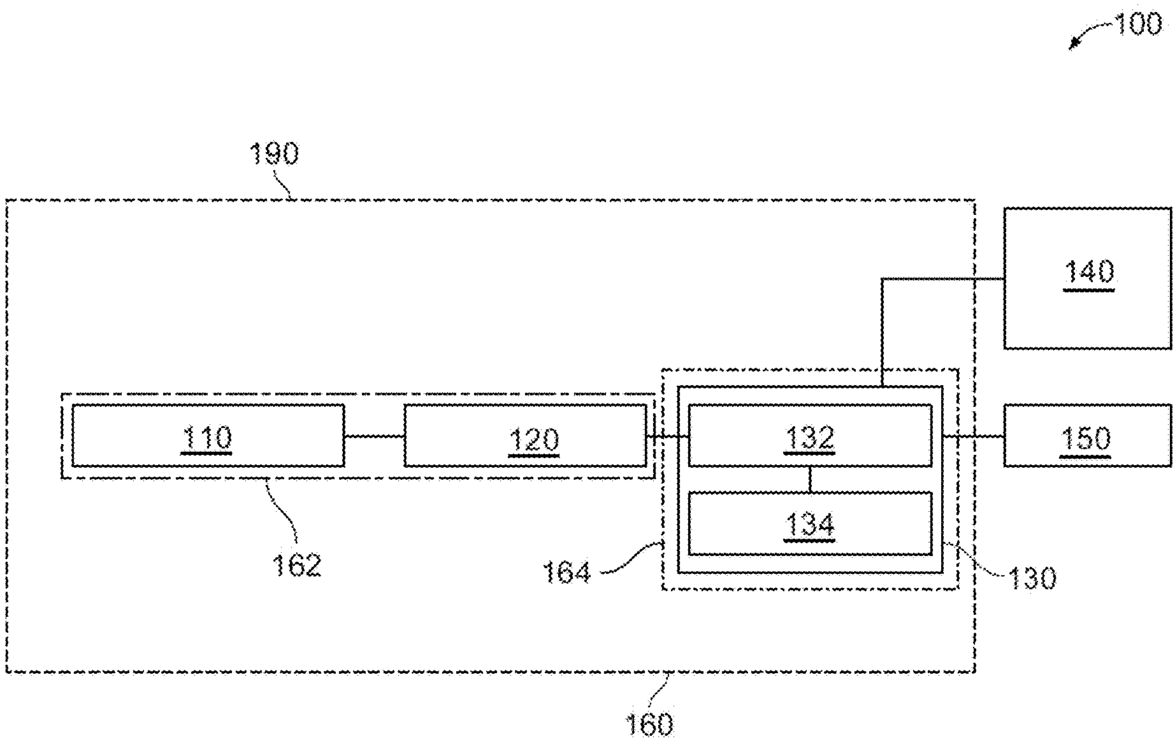


FIG. 1

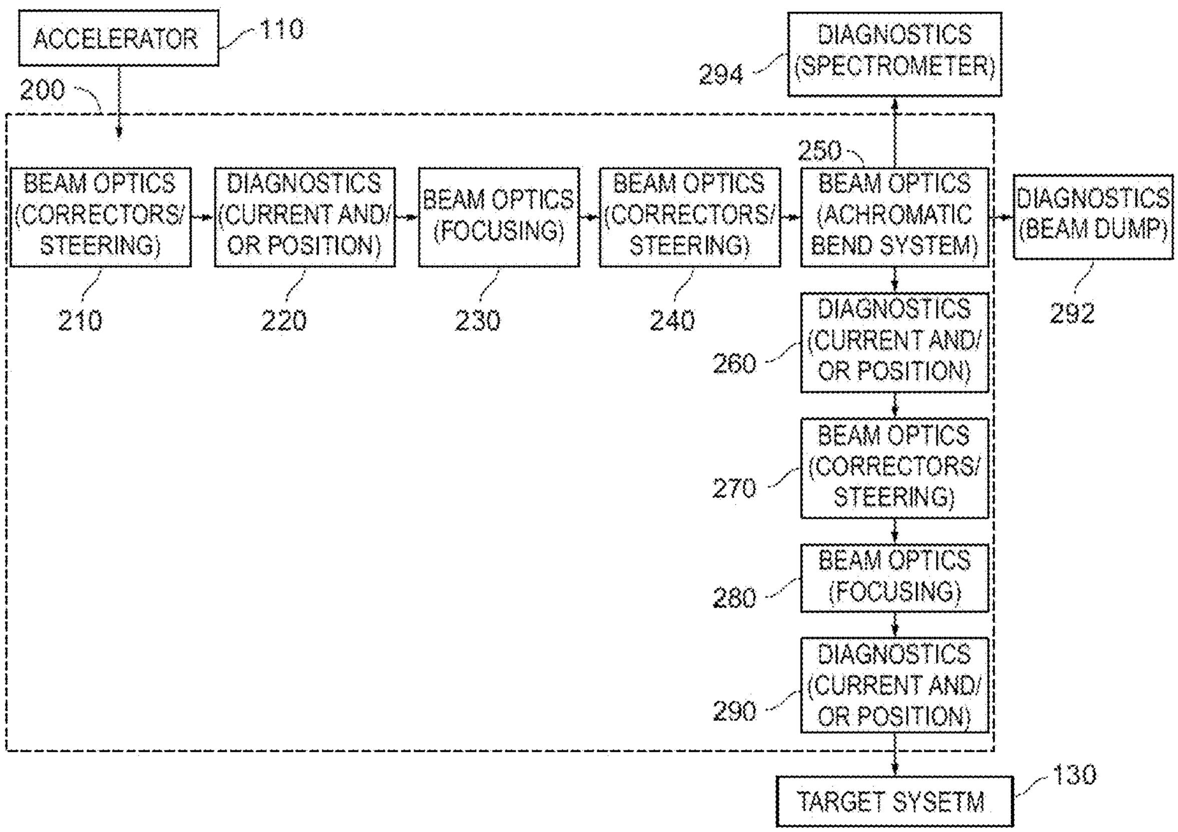

ACCELERATOR
110
200
BEAM OPTICS (CORRECTORS/ STEERING)
210
DIAGNOSTICS (CURRENT AND/ OR POSITION)
220
BEAM OPTICS (FOCUSING)
230
BEAM OPTICS (CORRECTORS/ STEERING)
240
250
BEAM OPTICS (ACHROMATIC BEND SYSTEM)
DIAGNOSTICS (SPECTROMETER)
294
DIAGNOSTICS (BEAM DUMP)
292
DIAGNOSTICS (CURRENT AND/ OR POSITION)
260
BEAM OPTICS (CORRECTORS/ STEERING)
270
BEAM OPTICS (FOCUSING)
280
DIAGNOSTICS (CURRENT AND/ OR POSITION)
290
TARGET SYSETM
130

FIG. 2

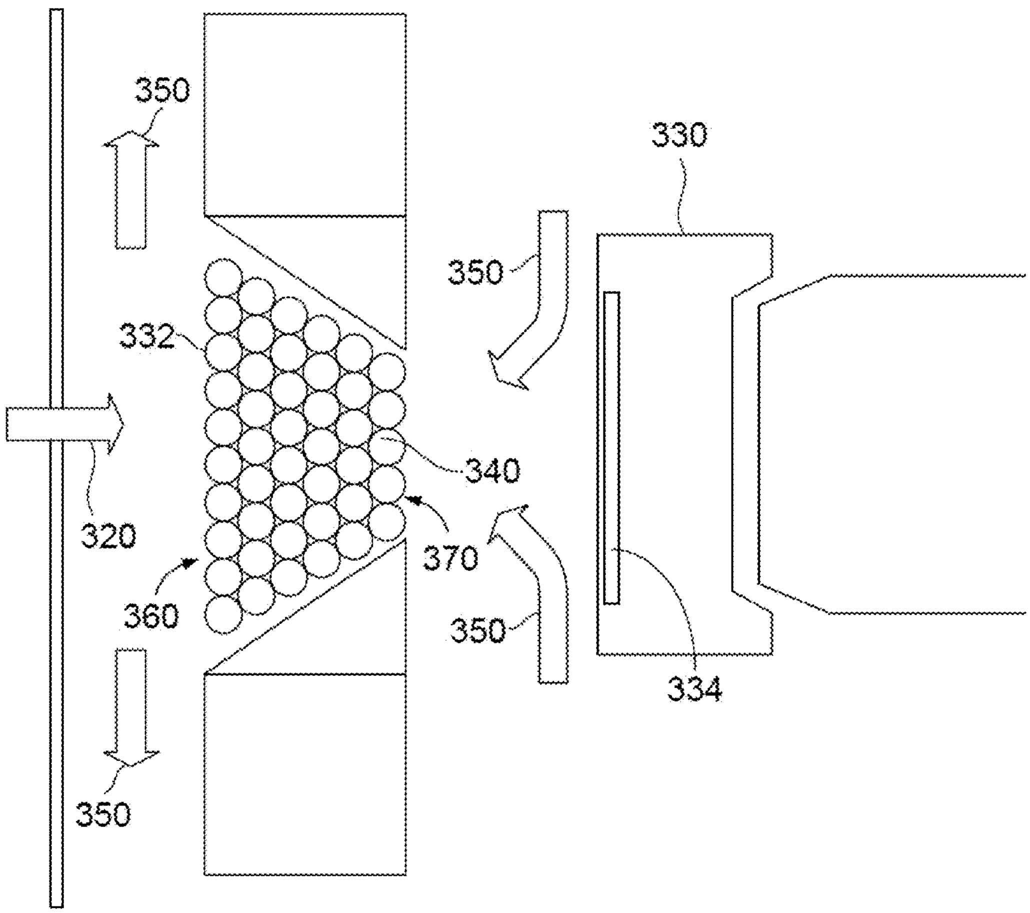


FIG. 3

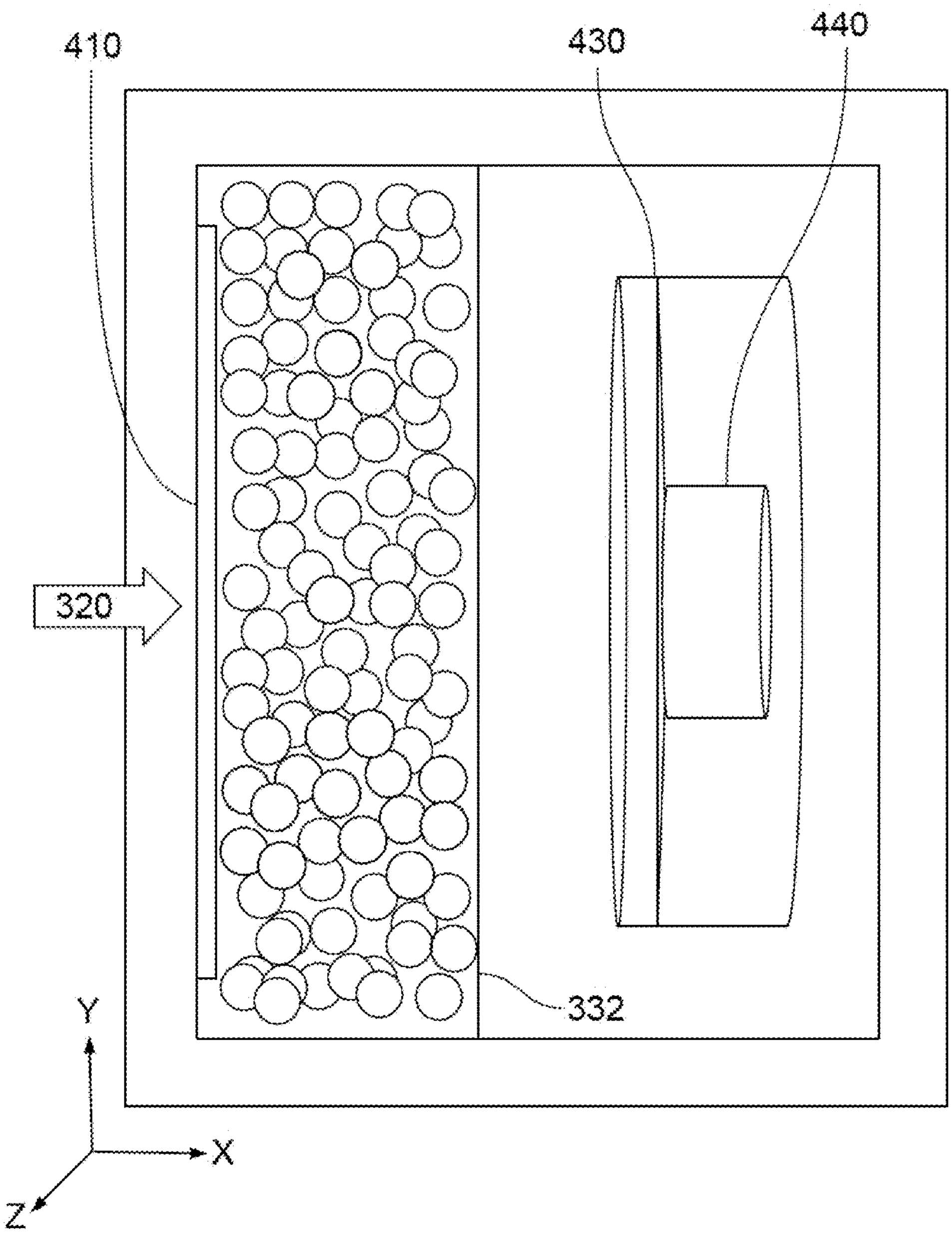
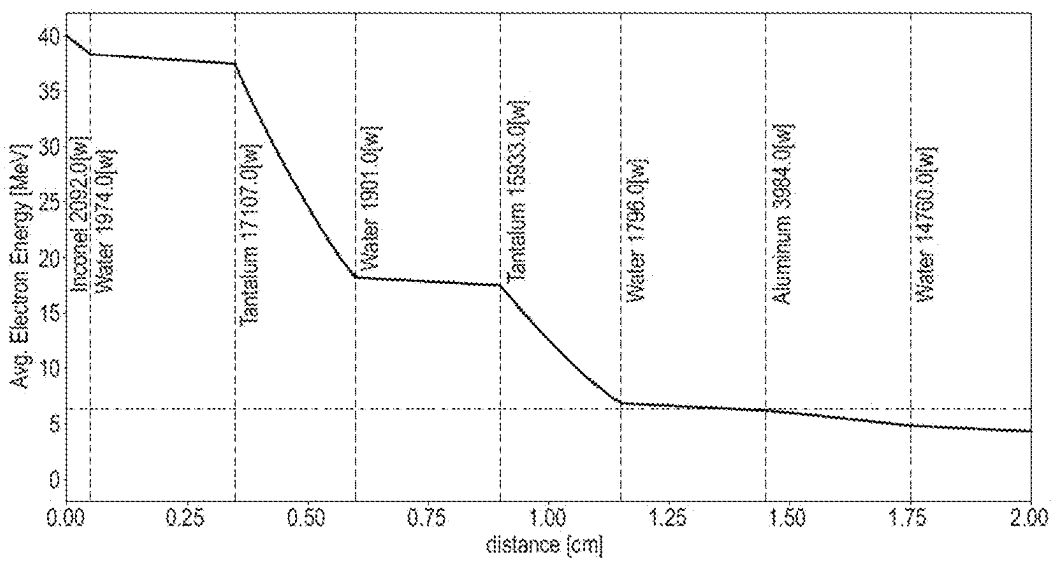


FIG. 4



Avg. Electron Energy [MeV]
40
35
30
25
20
15
10
5
0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
distance [cm]
Inconel 2092.0[w]
Water 1974.0[w]
Tantalum 17107.0[w]
Water 1901.0[w]
Tantalum 15933.0[w]
Water 1796.0[w]
Aluminum 3984.0[w]
Water 14760.0[w]

FIG. 5

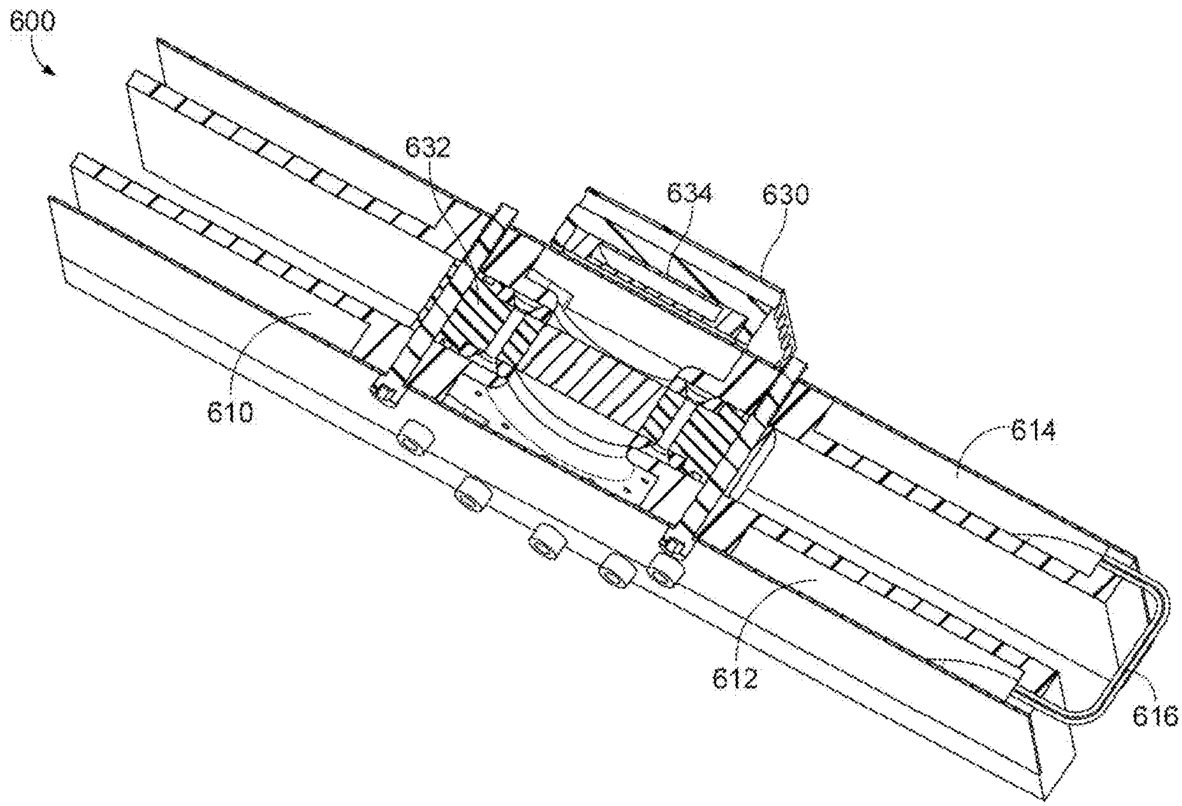


FIG. 6

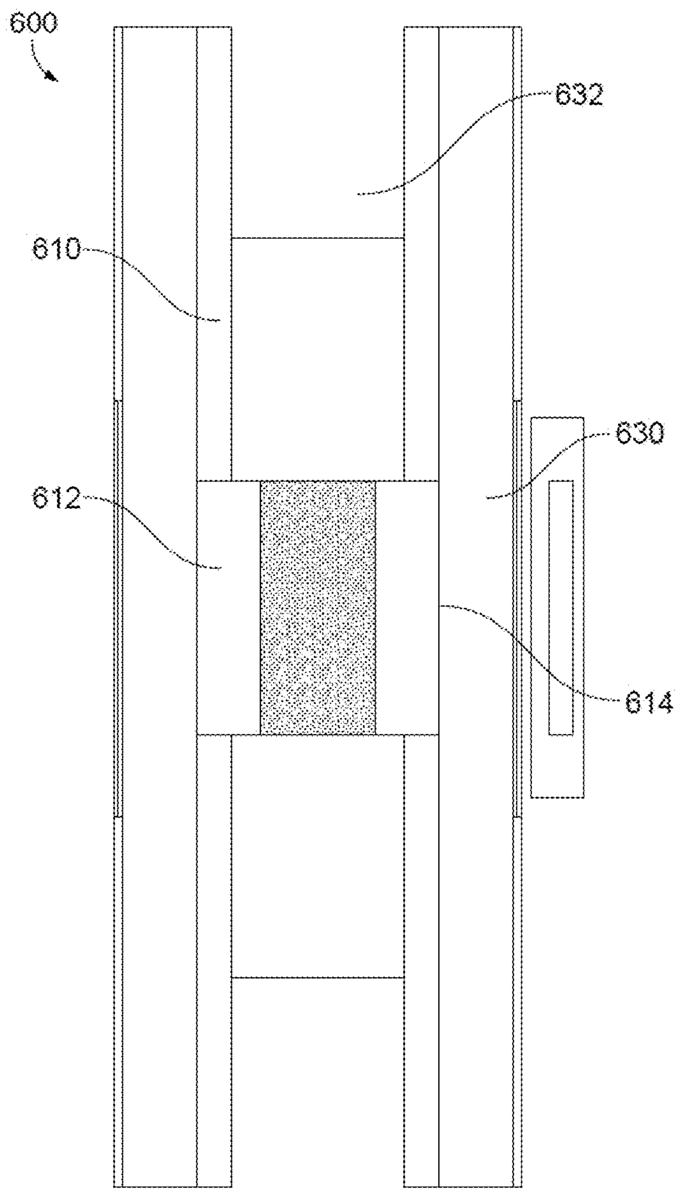


FIG. 7

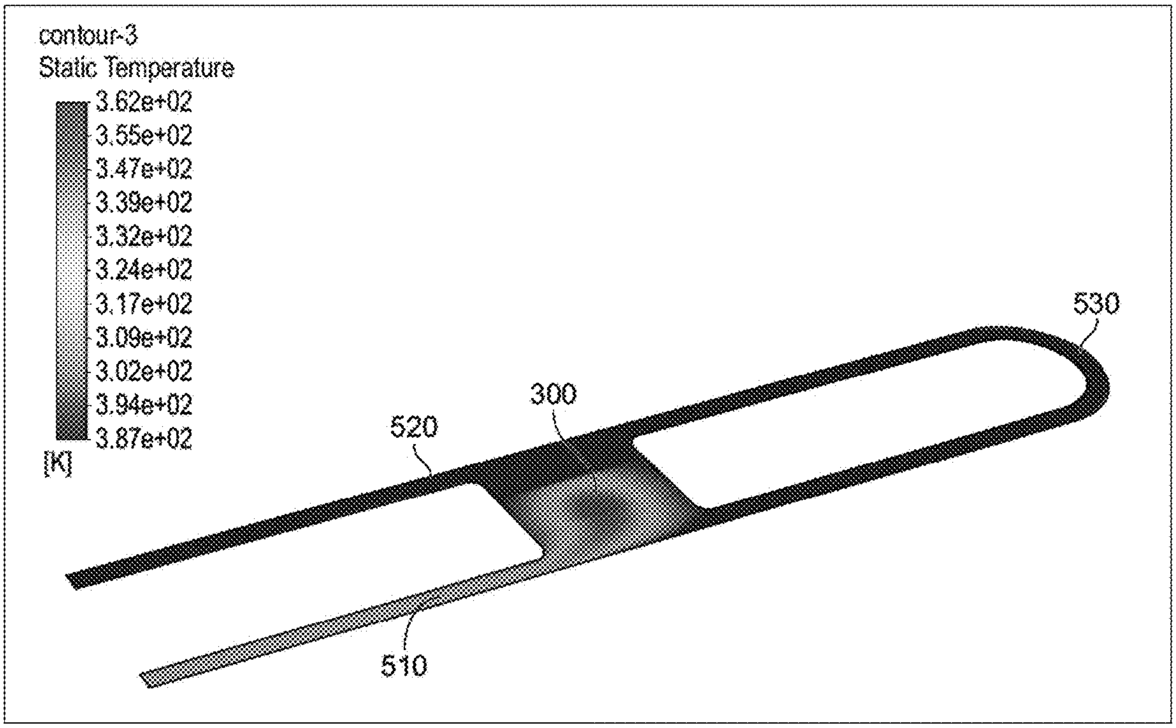

contour-3
Static Temperature
3.62e+02
3.55e+02
3.47e+02
3.39e+02
3.32e+02
3.24e+02
3.17e+02
3.09e+02
3.02e+02
3.94e+02
3.87e+02
[K]
530
300
520
510

FIG. 8

PEBBLE BED BEAM CONVERTER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of the filing date of U.S. provisional application Ser. No. 63/398,107, filed Aug. 15, 2022, entitled, "Pebble Bed Beam Converter," all of which is hereby incorporated by reference as if fully set forth herein.

FIELD OF THE INVENTION

This disclosure generally relates to a converter. Specifically, the disclosure relates to devices and apparatuses intended to produce high energy x-rays of a specific wavelength, intensity and duration from energetic electron beams, and more specifically, to a converter for generating a flux of high-energy photons from a high-energy electron beam.

BACKGROUND OF THE INVENTION

There is a need for a device to produce high energy x-rays from electron beams for radioisotope production. For example, the quest for bridging the gap between the severely constrained 225Ac supply and the large worldwide demand is a key factor in nuclear medicine. The demand for 225Ac stems from the use of that isotope in targeted alpha therapy (TAT). Radioisotope 225Ac and its daughter 213Bi are used in medicine for the treatment of prostate, brain, and neuroendocrine cancers. 213Bi has a half-life of about 45.61 months. However, 225Ac has a relatively short half-life ($T^{1/2}$) of about 9.92 days. Thus, it can be difficult to maintain a supply of 225Ac because it quickly decays.

In usual production, 225Ac is produced via the β^- decay of 225Ra, which is itself produced by the (γ,n) reaction on a high-purity 226Ra ($T^{1/2}$=1600 years) target. The high-energy photons are produced by a converter of high atomic number (high-Z) material, such as tantalum, via the braking-radiation (bremsstrahlung) mechanism that can result from slowing down very energetic accelerated electrons impinging on the converter material.

However, most existing converters are limited in beam power acceptance by the need to extract the thermal power deposited within the converter at sufficiently low temperatures to maintain the converter material's mechanical integrity. For example, typical existing converters are often limited to accept beam powers of less than 50 kilowatts (kW), limiting the photon creation potential to be a fraction of what a high-power converter could produce. As accelerators become more capable of producing higher power, there is a need for a converter suitable to accept higher beam powers.

Conventionally, converters suitable for high power regimes (such as greater than 100 kW up to about 500 kW or more) are exceedingly rare and mechanically complex. For example, existing high-power converters can utilize large rotating surfaces to reduce time-averaged thermal power deposition at a location on the disk surface, heating a point on a disk for a small fraction of its rotation and allowing cooling for the remainder. However, these types of converters can suffer from catastrophic and run-away failures due to their mechanical intricacies. As such, there is a need for a thermally and mechanically reliable converter suitable for high beam power regime that has low reliance on supplemental mechanics such as a motor.

BRIEF SUMMARY OF THE INVENTION

An aspect of this disclosure pertains to a converter capable of generating a high-flux of high-energy photons (such as greater than 5 MeV) from an electron beam. In some embodiments, the electron beam can be greater or equal to 40 MeV, with an effective beam power of greater or equal to 125 kW. In some embodiments, the converter can be utilized in applications up to about 500 kW.

Another aspect of this disclosure pertains to a converter including a structured or unstructured lattice of high-Z material in geometries of small spheres, irregular particles, meshes, or other porous arrangements. The converter is configured to accept electron beam from a first side and to generate photon out a second side opposite from the first side, and to allow simultaneous coolant flow through the converter in a direction parallel or perpendicular to the electron beam. A variety of coolant can be used. The coolant can be fluid such as water or gaseous such as helium, or other suitable materials.

Yet another aspect of this disclosure pertains to providing a converter having a plurality of spherical beads disposed in a coolant fluid; bombarding the converter with electron beams from a first side of the converter; and generating photons out of a second side of the converter opposite from the first side.

A further aspect of this disclosure pertains to providing the coolant fluid to a converter parallel to the direction of the electron beam bombardment.

In one embodiment, a converter for an electron beam is provided. The converter comprising a plurality of spherical beads disposed in a coolant fluid within the converter, wherein the converter is configured to accept the electron beam from a first side and to generate photons out a second side opposite from the first side.

In one embodiment, the plurality of spherical beads are made of high atomic number (high-Z) material.

In one embodiment, the plurality of spherical beads are packed and pseudo-randomly distributed within the converter.

In one embodiment, the coolant fluid enters the converter from an inlet on the second side and exits the converter from an outlet on the first side.

In one embodiment, a first screen is provided over the inlet and a second screen is provided over the outlet such that the plurality of spherical beads is contained within the converter through the first screen and the second screen.

In one embodiment, a system for producing isotopes is provided. The system comprising an accelerator; a beamline; and a target system comprising: a porous media converter comprising a plurality of spherical beads; and a target; an inlet designed to permit a flow of a coolant fluid to enter the porous media converter and surround the plurality of spherical beads; and an outlet designed to permit the coolant fluid to flow out of the porous media converter.

In one embodiment the accelerator is placed on a common axis with the target system.

In one embodiment, the accelerator is placed on a first axis and the target system is placed on a second axis, different than the first axis.

In one embodiment, the system comprises a target cooling system in fluid communication with the target system.

In one embodiment, the system comprises a hot cell in fluid communication with the target system.

In one embodiment, the system comprises an accelerator vault designed to house the accelerator, the beamline, and the target system.

In one embodiment, the system comprise a first irradiation zone located in the accelerator vault, the first radiation zone designed to house the accelerator and the beamline.

In one embodiment, the system comprises a second irradiation zone located in the accelerator vault, the second irradiation zone designed to house the target system.

In one embodiment, the system comprises a beamline window positioned in front of the porous media converter.

In one embodiment, the system comprises a passage designed to form a fluid passage between the inlet and the outlet to form a flow loop.

In one embodiment, a method of converting an electron beam into a photon is provided. The method comprising the steps of: providing a converter having a plurality of spherical beads disposed in a coolant fluid; bombarding the converter with one or more electron beams from a first side of the converter; and generating photons out of a second side of the converter opposite from the first side.

In one embodiment, the method comprises the plurality of spherical beads as being made of high atomic number (high-Z) material.

In one embodiment, the method comprises spherical beads being tightly packed and pseudo-randomly distributed within the converter.

In one embodiment, the method comprises providing the coolant fluid into the converter from an inlet on the second side; and allowing the coolant fluid to exit the converter from an outlet on the first side.

In one embodiment, the method comprises providing a first screen over the inlet and a second screen provided over the outlet such that the plurality of spherical beads is contained within the converter through the first screen and the second screen.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a schematic depiction of an exemplary system **100** for producing an isotope such as 225Ac according to an example embodiment;

FIG. **2** illustrates a block diagram of a beamline according to an example embodiment;

FIG. **3** illustrates a perspective view of a pebble bed converter according to an example embodiment;

FIG. **4** illustrates a cross-sectional view of a pebble bed converter according to an example embodiment;

FIG. **5** illustrates a diagram of average electron energy loss through materials;

FIG. **6** illustrates a cross-sectional view of a target region according to an example embodiment;

FIG. **7** illustrates another view of the target region of FIG. **6**;

FIG. **8** illustrates a heatmap of the target region of FIG. **6** as the target region is subjected to electron beam bombardment.

Before explaining the disclosed embodiment of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of the particular arrangement shown, since the invention is capable of other embodiments. Exemplary embodiments are illustrated in referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting. Also, the terminology used herein is for the purpose of description and not of limitation.

DETAILED DESCRIPTION

Although this invention is susceptible of embodiments in many different forms, that are shown in the drawings and will be described in detail herein in specific embodiments with the understanding that the present disclosure is an exemplification of the principles of the invention. It is not intended to limit the invention to the specific illustrated embodiments. The features of the invention disclosed herein in the description, drawings, and claims can be significant, both individually and in any desired combinations, for the operation of the invention in its various embodiments. Features from one embodiment can be used in other embodiments of the invention.

Referring to FIG. **1**, an exemplary system **100** for producing an isotope, particularly 225Ac, is shown. Specifically, the system **100** can comprise an accelerator **110** connected to a beamline **120**. The beamline **120** can impact on a target system **130**. The target system **130** can be an apparatus where a target isotope such as 226Ra is held for irradiation. The target system **130** can include a converter **132** and a target **134**. The target system **130** can further engage with a target cooling system **140** (also known as a process cooling system) and a hot cell **150**.

The accelerator **110**, the beamline **120**, and the target system **130** can be shielded within an accelerator vault **160**. In an exemplary embodiment, the accelerator vault **160** can further be separated into a first radiation zone **162** that houses the accelerator **110** and the beamline **120** therein and a second radiation zone **164** that houses the target system **130**.

In an exemplary embodiment, the accelerator vault **160** can include interior walls used to form the first radiation zone **162** and/or the second radiation zone **164**. The accelerator vault **160**, the interior walls, zones in the accelerator vault **160**, and other building rooms can be constructed out of high-density (HD) concrete blocks, such as that supplied by Veritas Medical Solutions, Harleysville, PA, USA. HD concrete is better per unit volume at shielding gamma rays, which are the primary source of radiation created in the process, than regular density concrete.

Although other materials such as steel or lead can also be used for the accelerator vault, these materials are more expensive, and are not as efficient in stopping prompt neutrons, which are also produced during the process, as borated HD concrete. Specifically, prompt radiation refers to radiation emitted instantaneously during an operation of the accelerator **110**, which is different from residual or induced radiation caused by activated components in the accelerator vault **160** or the beamline **120**.

The accelerator **110** can generate accelerated electrons to irradiate 226Ra held in the target system **130**. In an exemplary embodiment, the electron accelerator **110** is capable of supplying about 20 to about 250 kW of average power with about 25 to about 100 MeV electrons. Preferably the average power value is about 60 to about 200 kW, and more preferably about 80 to about 125 kW. Preferably, the electrons are at about 25 to about 55 MeV.

To irradiate the target system **130**, a specialized beamline can be used to bend a respective electron beam at an angle toward the target system **130**. In an exemplary embodiment, the beamline **120** bends the electron beam by 90 degrees toward the target system **130**. The invention is not limited to 90 degrees but can include other angles to result in beamlines irradiating the target **134** from different directions or degrees. As a result, the target system **130** can be placed on a different axis than the accelerator **110**. Instead, in an exemplary embodiment, accelerator **110** is offset from the target system **130** as shown in FIG. **1**. Accelerator **110** can also be placed on a common axis with target system **130**.

Further, a control system can be provided that integrates individual control systems of the accelerator **110**, the beamline **120**, the target cooling system **140**, the hot cell **170**, and other components of the system for producing a radioisotope such as 225Ac. For example, the combined control system can be used to time a production of beam pulses by the accelerator **110** such that the beam pulses arrive at the target **134**.

In operation, the beamline **120** can accept the electron beam from the accelerator **110**. Then the beamline **120** can bend the respective beam to hit the target system **130** to avoid backstreaming radiation. After the bend, the beamline **120** can aim the beam to a desired spot at the target system **130**, analyze the energy of the beam, or pass the beam straight through to a waiting beam analyzer and dump.

According to an exemplary embodiment, a Rhodotron® electron beam (E-beam) accelerator, produced by IBA Industrial, Louvain-La-Neuve, Belgium, can be used as the accelerator **110**. Unlike a conventional linear accelerator (linac), a Rhodotron® E-beam accelerator is a continuous wave electron beam accelerator combining high-power and high energy. The high-power high-energy property of a Rhodotron® E-beam accelerator helps to improve the production efficiency of 225Ac, previously unattainable using a linac. Moreover, a Rhodotron® E beam accelerator is more compact in size, allowing the accelerator setup to take up less square footage in an isotope production facility.

The preferred Rhodotron® E beam accelerator can provide an electron beam whose diameter is about 7 mm (Full Width at Half Max), about 12 mm FWHM, or about 25 mm FWHM. A Gaussian beam with 3 sigma of standard deviation corresponds to 8.9 mm and 15 mm of diameter, respectively. The accelerator's ability to operate at a larger FWHM decreases the maximum volumetric thermal power deposition into the converter **132** by distributing the energy of the beam over a larger volume of the converter material. The size of the target **134** can be about 25 mm in diameter, with about 0.060198 mm of thickness (RaBr2).

FIG. **2** illustrates an example beamline **200**. The beamline **200** can be the beamline **120** of FIG. **1**. As shown, the beamline **200** can include a first beam optics **210** that accepts an electron beam from accelerator **110**. The beam optics **210** can be used to correct and steer the electron beam received from the accelerator. The beam optics **210** can be coupled to a diagnostic component **220** that can be used to analyze a current or a position of the electron beam. The diagnostic component **220** can further be coupled with a second beam optics **230** used for focusing the electron beam. The second beam optics **230** can be coupled with a third beam optics **240** for further correcting and steering the electron beam. Therefrom, the third beam optics **240** can be coupled to a fourth beam optics **250** comprising an achromatic bend system. In an exemplary embodiment, to facilitate the bending of the electron beam, a pair of 270° magnets can be used for the achromatic bend system to bend the electron beam.

From the fourth beam optics **250**, the electron beam can travel down one of three paths. If the electron beam matches a predetermined criteria for production, the electron beam can be bent by the fourth beam optic **250** toward a second diagnostic component **260** for further analysis of the current or the position of the electron beam. The second diagnostic component **260** can be coupled with a fifth beam optics **270** for correction and steer, which can further be coupled with a sixth beam optics **280** for focusing. The sixth beam optics **280** can be coupled to a third diagnostic component **290** for further current and position analysis of the electron beam before transporting the electron beam to a target (such as 226Ra housed in the target system **130** described above in reference to FIG. **1**).

Alternatively, if the electron beam does not match the predetermined criteria for production, the fourth beam optics **250** can pass the electron beam to a fourth diagnostic component **292** and to a beam dump or beam stop. Lastly, if the electron beam is not used for production, the fourth beam optics **250** can pass the electron beam to a fifth diagnostic component **294** such as a spectrometer for further analyzing.

In an exemplary embodiment, the electron beam can enter the fourth beam optics **250** and exit the fourth beam optics **250** in substantially the same plane. That is to say, the achromatic bend system of the fourth beam optics **250** does not affect a vertical elevation of the electron beam. However, in other embodiments, the electron beam can exit the fourth beam optics **250** in a different plane than the plane at which the electron beam enters the fourth beam optics **250**.

It can be appreciated that the beamline **200** can include other variations such as addition or omission of certain components. Such variations are within the spirit of this disclosure.

FIG. **3** illustrates a beam converter system **300** suitable for high-power usage according to an example embodiment. The beam converter system **300** can include a converter **332**, which can be the converter **132** of FIG. **1**. The converter **332** can be positioned ahead of a target **334** in a target system **330** prior to a beamline **320** approaching the target **334**. The beamline **320**, the target system **330**, and the target **334** can be the beamline **120**, the target system **130**, and the target **134** of FIG. **1**, respectively.

As shown in FIG. **3**, the beam converter **332** can be configured as a volume of porous media **340** including a matrix of solid 'high-Z' beam converter material with a flowing coolant fluid **350**. Alternatively or additionally, the converter **332** can also include a matrix of solid "medium-Z" material such as silver or copper. Many geometries for such matrix can be possible, such as packed irregular particles, structured woven meshes of wires, or unstructured 'wool'-like fibers. In an exemplary embodiment, randomly packed spherical beads can be used as shown in FIGS. **3** and **4**.

In an example embodiment, the beads can be made out of a high-Z material such as tantalum, tungsten, gold, platinum, thorium, or other suitable materials. Other materials or compositions can also be utilized depending on the specific system requirements for coolant hydraulics, thermal power dissipation, mechanical strength, and photon yield of an implementing system. For example, gold-coated tungsten beads can be utilized for improved chemical compatibility with the water coolant, or lower-Z silver could be used to reduce local thermal power deposition. In some embodiments, the beads can have diameters less than about 2 millimeters (mm). In another embodiment, the diameters of the beads can be between about 0.1 mm and about 1 mm.

In some embodiments, the beads can be tightly packed and pseudo-randomly distributed. The beads can be contained in a "puck" with a diameter constrained by the FWHM (full width at half maximum) of the incident electron beam and a depth that correlates to the porosity and composition of the porous high-Z material. An encasement volume for the beads can be about 15 mm in diameter and about 9 mm in depth. The beads can be packed in place and secured at the flow inlet and flow exit by a fine woven stainless steel mesh with an opening size less than the converter sphere diameter.

The highly porous converter configuration can provide large convective heat transfer coefficients (at the interface to a water-based liquid or chemically inert gas coolant) and significant heat transfer surface area per unit converter volume for the converter material. This allows significantly higher volumetric thermal power deposition relative to non-porous converters constrained by equivalent material or thermal hydraulic properties such as converter material melting temperature, coolant boiling temperature, or critical boiling heat flux. Relative to a non-porous converter, a porous converter can therefore dissipate greater thermal power and high-efficiency photon generation. In some embodiments, the photon generation efficiency can be above 50% radiative power. More specifically, in some embodiments, the photon generation efficiency can be around 60% radiative power.

A coolant flow direction can be perpendicular or parallel to the electron beam. In some embodiments, porous media geometries, such as structured meshes, can allow the porosity of the media to be controlled independently of the solid feature size—using wire diameter and spacing. Such a configuration can increase heat transfer while minimizing coolant pressure drop.

A porous converter can operate at lower temperatures relative to conventional non-porous converter geometries due to its higher heat transfer coefficient and heat transfer surface area per unit volume, avoiding or minimizing thermal deformation of the converter material. Thermal deformations that do occur in a porous converter are less likely to incur thermal performance penalties than those occurring in a non-porous converter geometry. For instance, in a packed bed of spherical particles, individual spheres and the overall volume of the packed bed will expand as the temperature increases but the pores can remain open, allowing coolant to flow through the matrix of spheres in the expanded state.

In an example conventional converter, consisting of a set of solid parallel plates separated by cooling channels with the electron beam traveling perpendicular to the plate surface and coolant flow, buckling can occur as the electron beam produces a non-uniform temperature distribution in the plate, in turn changing the coolant channel geometry and potentially degrading the thermal performance of the overall converter structure.

Still referring to FIG. **3**, the converter **332** can include an inlet **360** and an outlet **370**. The inlet **360** and the outlet **370** can allow the coolant **350** to form a flow loop. As shown in FIG. **3**, in an embodiment, the beamline **320** can be directed at the converter **332** from a first direction, and the coolant **350** can flow through the converter **332** from a second direction opposite the first direction. In addition, the target system **334** can be aligned with the beamline **320** and the converter **332** such that the beam **320** can be converted into bremsstrahlung through the converter **332** as it approaches the target **334**.

As discussed above, in some embodiments, the porous media **340** can be allowed to expand and/or contract due to thermal expansion. In the case of porous media beads, the expansion and/or contraction of the beads can result in a slow migration of individual damaged beads as a consequence of the self-arranging phenomenon of the random spherical packing. In some embodiments, the beads can be held in place via fine screens of metal (such as stainless steel) placed over the inlet **360** and/or the outlet **370**. In some embodiments, the porous material can be sintered together.

Now referring to FIG. **4**, a pebble bed beam converter **400** is shown. The pebble bed beam converter **400** is similar to the beam converter system **300** of FIG. **3**. However, here, the pebble bed beam converter **400** can include a beamline window **410** that can direct the beamline **320** towards the converter **332**. Further, a target system **420** can include a target capture **430** and a target cavity **340**.

Now turning to FIG. **5**, a diagram of average electron energy versus distance as an electron beam traverses through a series of coolant (such as water) and high-Z material (such as tantalum) is shown.

FIGS. **6** and **7** illustrate a target region **600**. The target region **600** can include a target system **630** which contains a converter **632** and a target **634**. In some embodiments, the target system **630**, the converter **632**, and the target **634** can be the target system **130**, the converter **132**, and the target **134** of FIG. **1**, respectively. In some embodiments, the target system **630**, the converter **632**, and the target **634** can be the target system **330**, the converter **332**, and the target **334** of FIG. **3**, respectively.

The target region **600** can also include a cooling system **610**. The cooling system **610** can include an inlet coolant pipe **612** and an outlet coolant pipe **614**. The inlet coolant pipe **610** and the outlet coolant pipe **614** can be connected via a passage **616** to form a flow loop.

In embodiments utilizing a parallel flow of coolants, a flow loop with inlet and outlet streams can be provided such that the inlet stream and the outlet stream are perpendicular to the beam with the pass-through directed through the converter **632**. In some embodiments, a second pass-through between the inlet coolant pipe **612** and outlet coolant pipe **614** can be provided past the converter **632** to cause the coolant to continue to be driven forward as well as through the converter **632**.

The secondary pass through can be restricted, for example, by decreasing the cross-sectional area of the channel by adding an in-line adjustable valve. Such a configuration can prevent recirculation zones within the coolant in the vicinity of the converter **632** inlet and outlet regions (e.g., the inlet **360** and the outlet **370** of FIG. **3**) by allowing for a consistent coolant flow velocity at the surfaces of the containment structure (which are subject to thermal power deposition from the electron beam and must be cooled by the coolant fluid).

Referring specifically to FIG. **6**, the converter **632** can minimize a flow length of the coolant, and therefore reduce the pressure drop, by putting a coolant flow direction parallel to the beamline. In such a configuration, the width of the converter **632** can be unrestrained by thermal performance. For example, in an embodiment, only 9 mm of porous tantalum can be used to stop 40 MeV electrons, which is shorter than a width of conventional converters that can be made to accommodate the FWHM from an accelerator. Moreover, reducing the flow length can also decrease the total temperature change of the coolant, thus increasing cooling efficiency. This concept can be seen in FIG. **8**.

As shown in FIG. **8**, the photon flux produced by this model in MCNP [C. J. Werner, et al., "MCNP6.2 Release Notes", Los Alamos National Laboratory, report LA-UR-18-20808 (2018)] sees only a 3.7% drop in photon flux with 10-30 MeV energy compared to results from a model consisting of two solid tantalum converter disks similar to other academic papers' designs [Diamond, William & Ross, Carl. (2021). Actinium-225 production with an electron accelerator. *Journal of Applied Physics*. 129. 104901. 10.1063/5.0043509.].

Thus, the systems and methods disclosed herein can absorb and dissipate a high fraction of the beam power from a beamline and, in effect, shield a target from high thermal power deposition loads. This can alleviate the thermal design constraints on the target and add a passive safety function by placing the majority of the strain on the system on a non-radioactive component. Further, the target can be cooled via contact conduction cooling, rather than direct convection cooling in a fluid, as a benefit of the decreased thermal load on the target provided by the porous bed converter. This allows for simplified handling of the target and can reduce the risk that the accelerator cooling system becomes contaminated with target material by adding additional safety barriers to protect the system from causing groundwater contamination.

Each of the patents, patent applications and articles cited herein is incorporated by reference. The use of the article "a" or "an" is intended to include one or more.

The foregoing description and the examples are intended as illustrative and are not to be taken as limiting. Still other variations within the spirit and scope of this invention are possible and will readily present themselves to those skilled in the art.

Specific embodiments of a pebble bed beam converter according to the present invention have been described for the purpose of illustrating the manner in which the invention can be made and used. It should be understood that the implementation of other variations and modifications of this invention and its different aspects will be apparent to one skilled in the art, and that this invention is not limited by the specific embodiments described. Features described in one embodiment can be implemented in other embodiments. The subject disclosure is understood to encompass the present invention and any and all modifications, variations, or equivalents that fall within the spirit and scope of the basic underlying principles disclosed and claimed herein.

What is claimed is:

1. A converter for an electron beam comprising:
- a plurality of spherical beads disposed in a coolant fluid within the converter,
- wherein the converter is configured to accept the electron beam from a first side and to generate photons out a second side opposite from the first side.

2. The converter of claim **1**, wherein the plurality of spherical beads are made of high atomic number (high-Z) material.

3. The converter of claim **1**, wherein the plurality of spherical beads are packed and pseudo-randomly distributed within the converter.

4. The converter of claim **1**, wherein the coolant fluid enters the converter from an inlet on the second side and exits the converter from an outlet on the first side.

5. The converter of claim **4**, wherein a first screen is provided over the inlet and a second screen is provided over the outlet such that the plurality of spherical beads is contained within the converter through the first screen and the second screen.

6. A system for producing isotopes comprising:
- an accelerator;
- a beamline; and
- a target system comprising:
  - a porous media converter comprising a plurality of spherical beads; and
  - a target;
  - an inlet designed to permit a flow of a coolant fluid to enter the porous media converter and surround the plurality of spherical beads; and
  - an outlet designed to permit the coolant fluid to flow out of the porous media converter.

7. The system for producing isotopes of claim **6**, wherein the accelerator is placed on a common axis with the target system.

8. The system for producing isotopes of claim **6**, wherein the accelerator is placed on a first axis and the target system is placed on a second axis, different than the first axis.

9. The system for producing isotopes of claim **6**, comprising a target cooling system in fluid communication with the target system.

10. The system for producing isotopes of claim **6**, comprising a hot cell in fluid communication with the target system.

11. The system for producing isotopes of claim **6**, comprising an accelerator vault designed to house the accelerator, the beamline, and the target system.

12. The system for producing isotopes of claim **11**, comprising a first radiation zone located in the accelerator vault, the first radiation zone designed to house the accelerator and the beamline.

13. The system for producing isotopes of claim **11**, comprising a second radiation zone located in the accelerator vault, the second radiation zone designed to house the target system.

14. The system for producing isotopes of claim **6**, wherein the target system comprises a beamline window positioned in front of the porous media converter.

15. The system for producing isotopes of claim **6**, wherein the target system comprises a passage designed to form a fluid passage between the inlet and the outlet to form a flow loop.

16. A method of converting an electron beam into a photon, the method comprising the steps of:
- providing a converter having a plurality of spherical beads disposed in a coolant fluid;
- bombarding the converter with one or more electron beams from a first side of the converter; and
- generating photons out of a second side of the converter opposite from the first side.

17. The method of claim **16**, wherein the plurality of spherical beads are made of high atomic number (high-Z) material.

18. The method of claim **16**, wherein the plurality of spherical beads are tightly packed and pseudo-randomly distributed within the converter.

19. The method of claim **16** further comprising:
- providing the coolant fluid into the converter from an inlet on the second side; and
- allowing the coolant fluid to exit the converter from an outlet on the first side.

20. The method of claim **19**, wherein a first screen is provided over the inlet and a second screen is provided over the outlet such that the plurality of spherical beads is contained within the converter through the first screen and the second screen.

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