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(54) HIGH POWER POINT-SOURCE CONVERTER TARGET ASSEMBLY, RELATED FACILITY AND METHOD TO PRODUCE BREMSSTRAHLUNG FOR PHOTONUCLEAR REACTIONS USING AN ELECTRON LINEAR ACCELERATOR OR AN ELECTRON ACCELERATOR WITH SIMILAR TIME STRUCTURE OF THE BEAM

(57) The invention relates to a facility for the production of radionuclides, in particular diagnostic and therapeutic radionuclides, based on the principle of photonuclear irradiation, comprising
• an electron accelerator (1), producing an electron beam (2) with a time structure characteristic for a linear electron accelerator (1),
• a converter target assembly (21) with a converter target (20) that converts the electron beam (2) to Bremsstrahlung photons (15),
• a number of production targets (17), irradiated by the Bremsstrahlung photons (15) and thereby producing said radionuclides,
wherein the converter target assembly (21) comprises a sealed housing (9), the housing (9)
• enclosing a cavity (19) which holds the converter target (20),
• comprising an entry window holder (8) with a mounted vacuum window disk (23) for the electron beam (2) and an exit window (22) for the Bremsstrahlung photons (15),
• comprising cooling medium ports (10), these ports being part of a cooling circuit (11) for establishing a cooling flow through the cavity (19), thereby cooling the converter target (20) and the vacuum window disk (23),
wherein
• the converter target (20) comprises a number of rotatable converter disks (12),
• the electron beam (2) is set off-center with respect to the respective converter disk (12),
and wherein the respective converter disk (12) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of the electron beam (2) over an annular area (14) of the converter disk (12) over numerous revolutions.

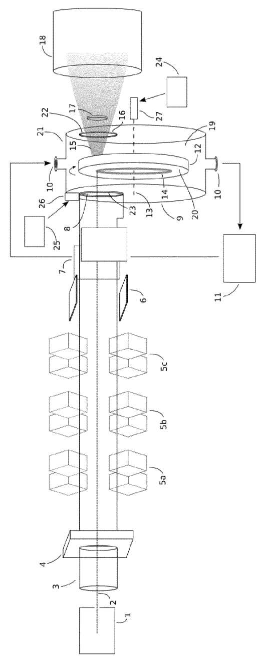

FIG. 1

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Description

[0001] The invention relates to a facility for the production of radionuclides, in particular diagnostic and therapeutic radionuclides, based on the principle of photonuclear irradiation. The invention also relates to a converter target assembly for usage in such a facility. The invention further relates to a method of operating such a facility and to a method of producing radionuclides.

[0002] Photonuclear reactions have been identified as very suitable for the production of diagnostic and therapeutic radionuclides for applications in nuclear medicine. With high energy photons (≥ 8 MeV) nuclear reactions of the type (γ,n), (γ, 2n), (γ,p), and (y, pn) can be induced. Photonuclear reactions show significant cross section in the giant dipole resonance (GDR) region, which, in certain cases are not significantly smaller than for charged particle induced reactions (such as protons, deuterons, ^{3}He and ^{4}He). Due to the penetrating properties of high energy photons compared to charged particles, the overall production yield of radionuclides with high energy photons can be very high since the missing cross section compared to charged particle reactions can be overcompensated by much thicker targets. In general, the photonuclear reaction cross sections scale roughly with atomic number.

[0003] Promising candidates of radionuclides that are high in demand and can be produced using photonuclear reactions are ^{99}Mo (for ^{99}Mo/^{99m}Tc radionuclide generators) produced in a $^{100}Mo(\gamma,n)$ reaction or the positron emitter ^{64}Cu for positron emission tomography, produced in a $^{66}Zn(\gamma,np)$ reaction. Furthermore, significant activities of ^{111}In can be produced in the photonuclear reaction $^{112}Sn(\gamma,n)^{111}Sn \xrightarrow{ec} {}^{111}In$.

[0004] Promising candidates of radionuclides used for radionuclide therapy which are presently not easily available, but which are in high demand and can be produced with high yields are the alpha-particle emitter ^{225}Ac (from decay of ^{225}Ra that is formed in the photonuclear reaction $^{226}Ra(\gamma,n)$), the beta-minus emitters ^{67}Cu (produced in the reaction $^{68}Zn(\gamma,p)$) and ^{47}Sc (produced in the reaction $^{48}Ti(\gamma,p)$). Furthermore, the beta-minus emitter ^{149}Pm with 53.1 h half-life produced in the photonuclear reaction $^{150}Nd(\gamma,n)$) has promising chemical and decay properties as therapeutic radionuclide. Also, the commonly used beat-minus emitter ^{90}Y or ^{177}Lu can be produced in a $^{91}Zr(\gamma,p)$ or a $^{178}Hf(\gamma,p)$ reaction, respectively.

[0005] The objective underlying the present invention is to provide a facility that allows for an industrial-scale production of rare but highly demanded radionuclides, in particular diagnostic and therapeutic radionuclides, such as, for example, ^{225}Ac or ^{99}Mo. The facility shall be cost-efficient to erect and operate, with high reliability, high safety margins, and minimal consumption of raw materials during operation. Furthermore, a converter target assembly for usage in such a facility shall be provided. Corresponding methods of operation and for the production of radionuclides shall be given as well.

[0006] According to the invention, the first-mentioned objective is met by a facility according to claim 1.

[0007] The invention provides a facility for the production of radionuclides, in particular diagnostic and therapeutic radionuclides, based on the principle of photonuclear irradiation, comprising

- an electron accelerator, producing an electron beam, and, if necessary, a beam transfer line,
- a converter target assembly with a converter target that converts the electron beam to Bremsstrahlung photons,
- a number of production targets, irradiated by the Bremsstrahlung photons and thereby producing said radionuclides,

wherein the converter target assembly comprises a sealed housing, the housing

- enclosing a cavity which holds the converter target,
- comprising an entry window for the electron beam and an exit window for the Bremsstrahlung photons,
- comprising cooling medium ports, these ports being part of a cooling circuit for establishing a cooling flow through the cavity, thereby cooling the converter target and the entry window,

wherein

- the converter target comprises a number of rotatable converter disks,
- the electron beam is set off-center with respect to the respective converter disk,

and wherein the respective converter disk is designed to rotate during operation of the facility, thereby, in the course of time, spreading or distributing the focal spot of the electron beam over an annular area of the converter disk.

[0008] In an aspect of the invention, the electron accelerator is chosen such that it generates an electron beam with a time structure characteristic for a linear electron accelerator. Such a linear electron accelerator typically generates a pulsed electron beam, wherein the pulsed electron beam has impulse times ("beam-on time") in the range of microseconds and period times ("beam-off time") in the range of milliseconds or longer. In other words: "a time structure characteristic for a linear electron accelerator" in the scope of the invention is to be understood as a pulsed time structure, in which the overall period times are significantly longer than the actual pulse times, providing a significant "pulse"-like beam structure.

[0009] The invention is based on the consideration that a high yield of radionuclides of the kind mentioned above can be produced according to the principle of photonuclear irradiation if an electron beam with relatively high electron energy and high beam power is directed onto a suitable point-source, high-power converter target to produce Bremsstrahlung, which is then used to irradiate a suitable production target. One key element to enable the converter target to withstand the heat-load associated with such a high-intensity electron beam while at the same time maintaining a point-source characteristic of the emerging photon radiation, is to distribute the beam energy over a relatively large area of the converter target by rotating a number of stacked converter disks during irradiation, and at the same time to remove excess heat by a flow of cooling medium, in particular a cooling gas or liquid, being in direct contact with the surface of the converter disks. The impact or focal point of the electron beam is essentially fixed in space - albeit some small (as compared to the target size) wobbling may be allowed or even forced - while the respective converter disk moves relative to this fixed point.

[0010] The other mentioned objectives are met by a converter target assembly according to claim 21 and by corresponding methods defined in claims 23 et seqq.

[0011] Further features, embodiments, objectives, and related advantages are associated with the co-pending independent and the dependent claims and the corresponding description in connection with the accompanying drawings.

[0012] In view of the foregoing and subsequent description, the following non-limiting examples are contemplated, many of which are considered inventive in their own right.

1. Facility for the production of radionuclides, in particular diagnostic and therapeutic radionuclides, based on the principle of photonuclear irradiation, comprising

- an electron accelerator (1), producing an electron beam (2), and, if necessary, a beam transfer line (3),
- a converter target assembly (21) with a converter target (20) that converts the electron beam (2) to Bremsstrahlung photons (15),
- a production target (17), irradiated by the Bremsstrahlung photons (15) and thereby producing said radionuclides,

wherein the converter target assembly (21) comprises a sealed housing (9), the housing (9)

- enclosing a cavity (19) which holds the converter target (20),
- comprising an entry window holder (8) with a mounted window disk (23) for the electron beam (2) and an exit window (22) for the Bremsstrahlung photons (15),
- comprising cooling medium ports (10), these ports being part of a cooling circuit (11) for establishing a cooling flow through the cavity (19), thereby cooling the converter target (20) and the entry window holder (8) with its mounted window disk (23),

wherein

- the converter target (20) comprises a number of rotatable converter disks (12),
- the electron beam (2) is set off-center with respect to the respective converter disk (12),

and wherein the respective converter disk (12) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of the electron beam (2) such that over multiple irradiation cycles and rotations of the converter disk the series of irradiation spots form a homogeneously irradiated annular area of the converter disk (12).

2. Facility according to example 1, wherein the electron accelerator (1) is designed to generate electron energies in excess of 20 MeV.

3. Facility according to example 1 or 2, wherein the electron accelerator (1) is designed to generate beam powers in excess of 20 kW.

4. Facility according to any of the preceding examples, wherein the electron accelerator (1) generates a pulsed electron beam (2).

5. Facility according to example 4, wherein the pulsed electron beam (2) has impulse times of microseconds and period times in the range of milliseconds or longer.

6. Facility according to example 4 or 5, wherein the electron accelerator (1) is a linear accelerator or a microtron or other type of accelerator with similar beam structure as described in example 3 and 5.

7. Facility according to example 4 to 5, wherein the electron accelerator (1) is a superconducting linear accelerator.

8. Facility according to any of examples 4 to 7, comprising a control unit (24) which keeps the rotation speed of the respective converter disk (12) synchronized with the time structure of the electron accelerator.
The control unit preferably comprises suitable sensors, actors, and controllers for this task.

9. Facility according to example 8, wherein the area on the respective converter disk exposed to a single beam pulse describes a near to circular area, wherein the ratio of the revolution time of the converter disk to the period time is preferably chosen such that the beam spot on the converter disk is rotated or displaced by at least one spot diameter. According to this aspect of the invention, the system is designed and engineered such that thermal load deposited into the converter disk is limited to an amount acceptable for the converter material. In order to facilitate this, in a preferred embodiment the segment of the converter disk exposed to the respective beam pulse during the time interval of the respective period is moved such that in the subsequent pulse it is not further exposed, or in other words the segment is shifted or moved far enough that the subsequent electron pulse irradiates a different segment. This concept according to one aspect of the invention allows an exposure of a cooled-off section of the converter disk for each pulse, and, therefore, over multiple irradiation cycles the series of irradiation spots form a more or less homogeneously irradiated annular area of the converter disk. Depending on the deposited energy per unit surface area on the converter disk, even a slight overlap of deposition spots of subsequent beam pulses may be considered permissible.
In yet another aspect of the invention, the converter disk may be rotated around two or more rotational axes, each more or less parallel to the beam direction. Rotational speed around these various axes may be different, resulting in a broadened ring area for the irradiated area on the converter disk. In particular, instead of providing only one, single rotation axis, the design in a preferred embodiment may be extended with additional rotational or linear movement of the main rotation axis of the converter disks. In this way the photon field can be held stationary while additional area (compared to the single axis design) of the converter disc is irradiated.

10. Facility according to example 8 or 9, wherein the rotation speed of the respective converter disk (12) is set in the range from a few hundreds to several thousands of revolutions per minute.

11. Facility according to any of the preceding claims, wherein the entry window holder (8) comprises a rotatable window disk (23), the electron beam (2) is set off-center with respect to the window disk (23), and wherein the window disk (23) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of the electron beam (2) over multiple irradiation spots of the window disk (23).

This is another key embodiment of the invention, allowing for efficient heat distribution over a larger area of the entry window, analogously to the converter disks. In one aspect of the invention, and depending on the deposited energy per unit surface area on the window disk (23), even a slight overlap of deposition spots of subsequent pulses may be considered permissible.

The window disk (23) is preferably mounted in/on/at a hollow shaft (30). The rotation of the hollow shaft (30) is preferably facilitated by a rotary drive (26).

12. Facility according to example 11, wherein the entry window holder (8) is coupled to a rotary drive (26).
The rotary drive could be a stepping motor mounted outside of the housing, whereby the hollow vacuum feedthrough is driven by a gear drive.

13. Facility according to example 11 or 12, wherein the entry window holder (8) comprises a window disk (23), which in a preferred embodiment is a Beryllium foil, preferably of a thickness between 50 and 500 micrometers, or any other high strength material of low atomic number. In an alternative embodiment the window disk (23) may be made of Havar™, preferably of a thickness between 50 and 250 micrometers.

14. Facility according to any of examples 11 to 13, wherein the entry window holder (8) is mounted on/in/at a hollow

shaft, which is part of a rotary vacuum feedthrough. In a preferred embodiment, the entry window holder (8) and the mounted window disk (23) or the rotary vacuum feedthrough are sealed with respect to the beam transfer line (3) by appropriate feedthrough technology in order to separate the vacuum of the accelerator section from the gaseous or liquid cooling medium, preferably by a magnetofluid sealing (31).

15 Facility according to example 14, wherein the entry window holder (8) and the mounted window disk (23) is sealed with respect to the beam transfer line (3) by a magnetofluid sealing. Alternatively, the sealing may be effected by any other feedthrough technology to separate the vacuum of the accelerator section from the gaseous or liquid cooling medium.
Due to the required thin thickness of the entry vacuum window and the mechanical and thermal stress it is exposed to, a preferred diameter of 40 mm was considered. Commercially available hollow shaft magnetofluid sealed vacuum feedthroughs allow for maximum rotation speeds of 3’100 rpm. Provisions on the hollow shaft to drive it with a gear drive are commercially available.

16. Facility according to any of examples 11 to 15, wherein a control unit (25) keeps the rotation speed of the entry window holder (8) and the mounted window disk (23) synchronized with the time structure of the electron accelerator.

17. Facility according to example 16, wherein the area on the respective converter disk (12) exposed to a single beam pulse describes a near circular area, wherein the ratio of the revolution time of the converter disk (12) to the period time is preferably chosen such that the beam spot on the converter disk is rotated by at least one spot diameter to allow an exposure of a cooled-off section of the converter disk (12) and that over multiple irradiation cycles and rotations of the converter disk the series of irradiation spots form a homogeneously irradiated annular area of the converter disk (12).

18. Facility according to example 16 or 17, wherein the rotation speed of the window disk (23) is set in the range from several hundreds to several thousands of revolutions per minute.

19. Facility according to any of the preceding examples, wherein the beam transfer line (3) comprises a beam optical element (5a-c) that allows for focusing or defocusing of the electron beam (2) to different FWHM.

20. Facility according to example 19, wherein a FWHM of at least 2 mm is set.

21. Facility according to any of the preceding examples, wherein the beam transfer line (3) comprises a beam wobbler (6, 7) that allows for periodical movement of the focal spot of the electron beam (2) on the entry window foil (23) and on the respective converter disk(s) (12).

22. Facility according to example 21, wherein the wobble amplitude is in the range of millimeters on the converter disk(s) (12).

23. Facility according to example 21 or 22, wherein the wobble frequency is in the range of 10^1 to 10^6 Hz.

24. Facility according to any of the preceding examples, wherein the beam transfer line (3) comprises a slammer valve (4) triggered by a downstream pressure sensor in order to protect the electron accelerator (1) from a vacuum breach in the converter target assembly (21).

25. Facility according to any of the preceding examples, wherein the converter target (20) comprises a plurality of converter disks (12).

26. Facility according to example 25 wherein the converter disks (12) are stacked on a common shaft (13).
Preferably, the converter disks are stacked or placed one after another (concentrically) on the shaft with gaps in between them, to allow a flow of cooling medium to cool any of the disks from both sides. On the other hand, the gaps are small enough in order to keep the converter target compact and not to destroy the essential point-source characteristic of the emerging photon radiation.

27. Facility according to any of the preceding examples, wherein the respective converter disk (12) is coupled to a rotary drive (27).
The rotary drive is preferably mounted outside of the housing in a shielded position. The converter disks are preferably driven by a stepping motor via a gear drive and a rotary feed through.

28. Facility according to to any of the preceding examples, wherein the converter disks (12) are arranged to form a Tesla pump.

29. Facility according to any of the preceding examples, wherein the converter disks (12) are predominantly made of Tantalum or Tungsten.

30. Facility according to any of the preceding examples, wherein the respective converter disk (12) has a number of radially aligned slots or indentations at its outer circumference.

31. Facility according to any of the preceding examples, wherein the exit window comprises a flattening filter (22) that absorbs most of the photons with photon energy $\leq$ 8 MeV and preferably absorbs and/or slows down residual electrons.
In one aspect of the invention, and in a preferred embodiment, water is used as cooling medium. In this embodiment, the water itself will act as such flattening filter.

32. Facility according to example 33, wherein the flattening filter (22) comprises a water-cooled Aluminum column.

33. Facility according to any of the preceding examples, wherein the exit window comprising a flattening filter (22) comprises a neutron absorber (16).
In one aspect of the invention, and in a preferred embodiment, water is used as cooling medium. In this embodiment, boric acid can be added to the cooling water to enhance neutron absorption.

34. Facility according to any of the preceding examples, wherein the cooling medium is a liquid, preferably water.
In one aspect of the invention, gas may be used as cooling medium, preferably gaseous Helium.

35. Facility according to any of the preceding examples, wherein a massive and preferably water-cooled beam stop (18) is arranged behind the production target (17).

36. Facility according to any of the preceding examples, wherein the region of origin of the emerging Bremsstrahlung photons is fixed in space.

37. Facility according to any of the preceding examples, wherein the production target (17) is predominantly made of one of the following isotopes: ^{226}Ra, ^{178}Hf, ^{150}Nd, ^{112}Sn, ^{100}Mo, ^{91}Zr, ^{66}Zn, ^{68}Zn, ^{48}Ti, ^{48}Ca.

38. Converter target assembly (21) for a facility according to any of the preceding claims, comprising a sealed housing (9), the housing (9)

- enclosing a cavity (19) which holds the converter target (20),
- comprising an entry window holder (8) with a mounted entry window disk (23) for an electron beam (2) and an exit window (22) for Bremsstrahlung photons,
- comprising cooling medium ports (10), these ports being designated to be connected to a cooling circuit (11) for establishing a cooling flow through the cavity (19), thereby cooling the converter target (20) and the entry window holder (8) with its mounted entry window disk (23),

wherein the converter target (20) comprises a number of rotatable converter disks (12), and wherein the respective converter disk (12) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of an incoming electron beam (2) over multiple irradiation cycles. The series of irradiation spots form a homogeneously irradiated annular area of the converter disk (12).

39. Converter target assembly (21) according to example 38, wherein the entry window holder (8) comprises a rotatable window disk (23), wherein the window disk (23) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of an incoming electron beam (2) over multiple irradiation cycles. The series of irradiation spots form a homogeneously irradiated annular area of the window disk (23).

40. Method of operating a facility according to any of the preceding examples, wherein at least of the following radionuclides is produced: ^{225}Ra, ^{224}Ra, ^{225}Ac, ^{213}Bi, ^{212}Pb, ^{177}Lu, ^{149}Nd, ^{149}Pm, ^{111}Sn, ^{111}In, ^{90}Y, ^{99}Mo,^{99m}Tc, ^{67}Cu, ^{64}Cu, ^{47}Ca, ^{47}Sc.

41. Method of producing radionuclides, wherein an an electron beam (2) is directed onto a converter target (20) with a number of rotating converter disks (12), in particular about one or more axes, such that, in the course of time, the focal spot of the electron beam (2) is spread over multiple irradiation cycles. The beam spot on the converter disk is rotated by at least one spot diameter to allow an exposure of a cooled-off section of the converter disk (12) and that over multiple irradiation cycles and rotations of the converter disk, the series of irradiation spots form a homogeneously irradiated annular area of the converter disk (12). Depending on the deposited energy per unit surface area on the converter disk (12), even a slight overlap of deposition spots is permissible. The produced beam of Bremsstrahlung photons is used for the irradiation of production targets (17), wherein the converter target (20) is cooled by a flow of cooling medium, in particular gaseous Helium or, preferably, liquid water.

42. Method according to example 41, wherein the converter target (20) is arranged inside a housing (9), and wherein the electron beam (2) is lead through a rotating entry window holder (8) with a mounted entry window disk (23) of the housing (9), such that over multiple irradiation cycles the series of irradiation spots form a homogeneously irradiated annular area of the entry window disk (23).

[0013] A detailed description of the invention is subsequently set out with respect to the accompanying drawings.

Figure 1 schematically shows an assembly of a photonuclear irradiation set-up.

Figure 2 shows a schematic of a rotating hollow shaft vacuum feedthrough with magnetofluid sealing. The vacuum window disk is mounted on the upstream side of the rotating shaft. The beam axis is off-center to the rotation axis.

Figure 3 shows a comparison between the time structures of electron beams produced by a linear accelerator and a rhodotron with similar beam power.

Figure 4 shows an exemplary illustration of a series of beam-spots deposited on a rotating converter disk (e.g. 0.5 mm thick Tungsten), where the time structure of the electron beam has beam-on periods in the range of microseconds and beam-off periods in the range of milliseconds. The converter disks are rotated on a common shaft wit an angular velocity that displaces the applied beam spot by at least one spot diameter. This way, the available cooling time is maximized before a previously irradiated beam spot is irradiated again. Over time an annular section of the converter disk is irradiated.

Figure 5 shows a proposed scheme of irradiation of a rotating, e.g. Beryllium (Be), vacuum window foil and the rotating converter disks, as viewed in the direction of the beam axis. The window disk and the converter disks have minimal areal overlap and rotate in opposite directions. The tangential velocity of both disks is similar in order to avoid excessive shear forces on the cooling medium, e.g. water.

Figure 6 shows an illustration of a rotating disk converter design of a Tesla pump type.

Figure 7 illustrates the approach with an additional linear movement of the main axis. In the figure, the gray dots represent exemplary beam pulses. The blue line describes the central location of the beam pulse hits on the disc. In sub-figure a), the one-axis design is shown. Here the center spot line is a circle with radius Rc. Due to the mis-tune of rotational frequency and the beam repetition rate, the band in between the virtual circles of radius Rc + R_{Beam} and Rc - R_{Beam} (dotted gray lines in the figure) is irradiated after several revolutions. In sub-figure b) an additional vertical movement of the main axis is introduced. This results in an up- and downward amplitude to the center line spot, expanding the irradiated area. The path of the centerline describes an oscillating motion with amplitude A_{lin} around the mean radius Rc. The figure depicts the path for approximately 3 revolutions. Care must be taken to detune the frequencies of the rotation and linear movement. Otherwise, a stable orbit is achieved and only parts of the full area in between the virtual boundaries (dotted gray lines) are irradiated.

[0014] According to the invention, key to the industrial implementation of photonuclear reactions for medical radionuclide production are the following components:

1.) A high-power electron accelerator with available electron energies in excess of about 20 MeV and beam powers in excess of about 20 kW.

2.) A high-power converter target that converts the electron beam to Bremsstrahlung (braking radiation) photons that can absorb the power delivered by the high intensity electron beam. The higher the photon flux in the GDR region, the higher the specific activity that can be reached (i.e. for ^{99}Mo production), or the less target material for production targets must be employed, which mostly are valuable isotopically enriched materials (i.e. ^{68}Zn for ^{67}Cu production) or hazardous, highly radioactive materials (i.e. ^{226}Ra), preferably for ^{225}Ac production.

3.) Production target designs that can withstand the high energy, high intensity photon flux while at the mean time safely encapsulating hazardous and/or radioactive target materials (i.e. ^{226}Ra).

4.) Automated chemical procedures to extract the desired radionuclides in quality and quantity suitable for medical applications.

Ad 1): Several designs of electron accelerators have been developed in the past mainly for generating Bremsstrahlung up to 10 MeV for the sterilization of medical equipment or curing of polymers. Currently, accelerators with 30-40 MeV beam energy and beam powers of 100 kW or more are commercially available.

Ad 2): No high-power, point source converter targets have been developed that could convert electron beams in excess of 20 MeV and in excess of 100 kW beam power to Bremsstrahlung. This fact has effectively prevented the use of photonuclear reactions for the large-scale production of medical radionuclides. The description of such a converter target is the main topic of the current application.

Ad 3): As target materials can be encapsulated in relatively thick, high strength and high temperature materials, existing methods can be adapted to the task.

Ad 4): For many of the above-mentioned radionuclides, chemical separation procedures to separate the desired product from the target material have already been developed or can be adapted from existing procedures.

[0015] Based on the above presented assessment, the design and construction of a high-power converter target to produce Bremsstrahlung for photonuclear reactions is essential. Essential and preferred components, their function and their technical realization are sketched in the accompanying Figure 1 and described below.

[0016] Figure 1 schematically shows a preferred assembly of a photonuclear irradiation set-up comprising a high-power electron beam 2 provided by a conventional (not continuous wave) linear electron accelerator or an electron accelerator with similar time structure of the beam (i.e. microtron) 1, a vacuum beam line 3, a fast acting vacuum valve 4 (slammer valve) arranged within the beam line 3, a number of beam optical elements (5a-c) for focusing or defocusing the beam 2 to different full width at half maximum (FWHM), a rotating vacuum window holder 8 comprising a rotatable vacuum window disk 23, a rotary drive 26 for the vacuum window with associated control unit 25, a housing 9 for a rotating converter target 20, provisions, i.e. inlet and outlet ports 10 for providing a cooling medium flowing through the housing 9, and a converter target 20 with a number of (shown here: one) rotating converter disks 12 enclosed by the housing 9. Further indicated are a distributed beam spot 14 (trace over time) on the rotating converter disk(s) 12, the rotation axis 13 of the converter disk(s) 12 coupled to a rotary drive 27 with associated control unit 24, an emerging cone 15 of Bremsstrahlung photons, a flattening filter and neutron absorber 16, production target(s) 17, and a massive high-density beam stop 18.

[0017] As will be apparent from Figure 1 and from the detailed description below, the vacuum window holder 8 with its mounted vacuum window disk 23 arranged in the housing 9 acts as an inlet or entry window for the electron beam 2, entering a cavity 19 enclosed by the housing 9. The electron beam 2 impinges on the converter target 20 located in the cavity 19 and generates Bremsstrahlung photons 15. The flattening filter 22 and neutron absorber 16 arranged in the housing 9 acts as outlet or exit window 22 for the photon cone 15 leaving the cavity on the other side. The photon cone 15 is centered around the prolongation of the electron beam axis. The cavity 19 is sealed by the housing 9 in a liquid-tight manner with respect to the outer environment. That is, the entry window 8 and the flattening filter exit window 22 provide a liquid-tight barrier but are largely transparent for electron radiation or photon radiation, respectively. A flow of cooling medium, in particular cooling water, within the cavity 19 provides cooling for the converter target 20 - and also for the vacuum window holder 8 comprising a rotating vacuum window disk 23, by flowing over its inner surface inside the cavity 19. This cooling flow enters and leaves the cavity 19 through according cooling medium inlet and outlet ports 10 arranged in the housing wall. The housing wall may be further cooled by a flow of cooling liquid, in particular cooling water, through suitable channels.

[0018] The cooling flow through the cavity 19 is part of a cooling circuit 11, which is indicated only schematically in Figure 1. Advantageously, liquid water is used as a cooling medium. The pressure of the coolant in inside the cavity 19 is preferably in the range of atmospheric pressure in order to keep the differential pressure on the entry window 8 and the flattening filter exit window 22 in a manageable range.

[0019] As will be appreciated in more detail below, the rotation axis 13 of the converter disks 12 is arranged off-center (parallelly shifted) with respect to the axis of the electron beam 2.

[0020] Furthermore, the entry window holder 8 for the electron beam 2 preferably comprises a rotatable window disk 23, the rotation axis of which is also arranged off-center (parallelly shifted) with respect to the axis of the electron beam 2.

[0021] The unit comprising the housing 9 with the cooling inlet port and outlet port 10, the vacuum window holder 8 with a mounted vacuum window disk 23 for the entry of the electron beam 2, the flattening filter 22 and neutron absorber 16 at the exit of the photon cone 15, and the integrated converter target 20 - if necessary, with a related rotary drive for the vacuum window holder 8 comprising a vacuum window disk 23 and/or the converter target 20 - may be called converter target unit or converter target assembly 21.

[0022] Instead of a single flattening filter 22 and neutron absorber 16, there may be two (or more) separate filters, one for the purpose of flattening (see below), and one for the purpose of neutron absorption. While it is convenient that these functions are integrated into a single exit window 22 of the housing 9, there might be an exit window 22 for high-energy photons plus a number of additional filters of the kind described above, either integrated in one assembly or realized as separate components. For example, there may be a simple exit window 22, sealing the housing 9 in a tight manner with respect to the outer environment, and then a flattening filter and a neutron absorber in arbitrary order (as viewed in the direction of the passing photons), or just one or even none of the latter.

[0023] When using a cooling liquid, particularly flowing water as cooling agent, the coolant itself will already serve as flattening filter, absorbing mainly low energy Bremsstrahlung (< 8 MeV) which does not contribute to the photonuclear production process. Furthermore, addition of boric acid to the cooling water will enhance its neutron absorption properties.

[0024] More specifically, an industrial radionuclide production facility using photonuclear reactions preferably comprises:

- A high-power electron linear accelerator or an electron accelerator with a similar time structure of the beam.
- An evacuated beam transfer line transporting the extracted electron beam in vacuum.
- Preferably a fast-acting valve with a downstream pressure sensor (slammer valve) that protects the accelerator from a vacuum breach.
- Preferably a beam optical element that allows focusing or defocusing of the beam to different FWHM, e.g. in the form of a quadrupole triplet.
- Preferably, a beam optical element that allows a fast movement of the beam in x- and y-axis direction with high frequency, called a "beam wobbler".
- A vacuum window that separates the vacuum of the accelerator and beam line from the converter target assembly.
- A housing containing the converter target assembly.
- Provisions and connections for cooling gases and/or cooling liquids.
- A cooled converter target assembly that (ideally fully) stops the electron beam and converts it to Bremsstrahlung photons of various energies. The converter target preferably comprises several disks, thereby reducing the individual thermal load and arranged in an optimal way for efficient cooling.
- By rotating the converter disks, preferably synchronized with the time structure of the beam, the incoming beam packets are equally distributed over a large area of the converter disks.
- Preferably a flattening filter that absorbs most of the low energy photons that contribute only to heating of the production targets while not inducing photonuclear reactions. This task can concurrently be fulfilled by using a cooling liquid as cooling medium.
- Preferably a neutron filter for low energy and high energy photoneutrons that contribute to the production of undesired side products, thus enhancing radionuclidic purity of the desired products.
- A cooled assembly holding at least one preferably a stack of multiple production targets, and preferably provisions to remotely add or retrieve production targets.
- A cooled block of Beryllium (optional) for generating photoneutrons.
- A cooled massive beam stop with auxiliary (optional) irradiation positions for gemstone coloration.
- A cooling loop preferably with pump, reservoir, heat exchangers and filters to cool the converter target assembly.

[0025] Figure 2 shows schematically a rotating vacuum window assembly. The electron beam 2 is impinging on the Beryllium vacuum window disk 23 off-center. The Beryllium vacuum window disk is mounted in a ring-like holder 8 attached to a rotating hollow shaft vacuum feedthrough 30. Alternatively, the holder 8 may be an integral part of the hollow shaft 30. On the left, the rotating vacuum window assembly is connected to the beam transfer line 3. On the right, there is the cavity 19. The hollow shaft 30 with its magnetofluidic seals 31 and bearings 32 separates the vacuum of the accelerator 1 and the beam transfer line 3 from the cooling liquid in the housing 9. If using a cooling liquid any appropriate technology separating the cooling liquid from the vacuum of the beam line can be used. The hollow shaft is driven by rotary drive 26 and a corresponding control unit 25 (a indicated schematically in FIG. 1).

[0026] In the following paragraphs preferred embodiments of the individual components and underlying concepts are described in more detail.

1) Electron beam accelerators and specifications

[0027] An electron accelerator suitable to induce photonuclear reactions has to fulfill a number of requirements concerning electron beam energy, beam intensity (beam power), time structure of the beam and spatial width of the beam. Currently several types of accelerators are commercially available which are able to deliver electron beams with energies larger than 20 MeV and beam powers in excess of 20 kW, which are a prerequisite for a profitable radionuclide production for medical applications.

[0028] Linear accelerators with electron energies between 35 and more than 100 MeV and max. beam powers between 35 and 120 kW are commercially available. Peak current intensities of 200 to 300 mA are available at variable repetition rates of e. g. 800 Hz resulting in average beam currents of up to 4 mA. The length of one pulse can be up to 16 μs [1a]. The electron beam can be shaped to different FWHM with the use of beam optical elements. The beam profile can be selected to be non-Gaussian (i.e. flat-top profile).

[0029] Rhodotron type accelerators with electron energies of 40 MeV and a max. beam power of 125 kW are commercially available. The rhodotron accelerator operates at 10 up to 50 Hz with a duty cycle of 1 to 12.5%, resulting in pulse lengths of up to 2.5 ms with maximum peak current intensities of 25 mA and 3.125 mA average beam current [1b]. The electron beam can be shaped to different FWHM with the use of beam optical elements. The beam profile can be selected to be non-Gaussian (i.e. flat-top profile).

[0030] Compared to a rhodotron, a conventional linear accelerator offers an advantage if operated in conjunction with a point source converter target. Due to the different beam structure, the beam pulses are much shorter compared to a rhodotron. Therefore, the beam power cannot be significantly spread over a larger area of quickly moving components of the vacuum window and converter assembly. However, due to the short beam-on pulse, the energy deposited of one pulse translates to approximately the same areal energy density (energy deposited per cm^2 of the vacuum window or the converter disk assembly). Specifically, for a flat-top beam profile with 5 mm diameter (delivered by a 40 MeV, 800 Hz, 125 kW linear accelerator) the energy density deposited in a 0.5 mm thick Tungsten converter disk, amounts to about 10-15 J/cm^2, similar to the energy density delivered by a rhodotron (40 MeV, 50 Hz, 125 kW) beam-on pulse of 2.5 millisecond duration, 5 mm diameter flat-top beam profile, spread over an area of 1/3 of a rotating 0.5 mm thick converter disk at a radius of 15 cm (about 10 J/cm^2). Therefore, the peak temperatures per beam pulse induced by the passage of the intense electron beam are similar. This situation is schematically exemplified in Figure 3.

[0031] More specifically, Figure 3 shows a comparison between the time structures of electron beams produced by a linear accelerator and a rhodotron. In this example the linear accelerator was assumed to produce beam pulses of 15 μs duration and 200 mA peak current at a pulse repetition rate of 800 pps. This results in an average beam current of 2.4 mA with a 1.2% duty cycle. A rhodotron is operated at 50 Hz and produces beam pulses of 2.5 ms duration at 25 mA peak current. This results in an average beam current of 3.125 mA with a 12.5% duty cycle.

2) Fast acting valve (slammer valve)

[0032] In order to protect the accelerator and the beam line from a breach of the vacuum window and the transport of materials into the accelerator cavity(-ies) a fast-acting valve is installed which is triggered by a pressure sensor located downstream of the beam line in front of the vacuum window. In case of a breach of the vacuum window, the fast-acting valve physically closes the cross-sectional area of the beam line within milliseconds before the front of the intruding shock wave reaches the accelerator.

3) Synchronization of rotating vacuum window and converter target to the beam structure

[0033] In the presented approach, the fixed beam spot is directed onto a rotating disk (vacuum window and converter target). To distribute the heat load on the disk, the revolution time of these components are synchronized to the beam structure. In particular, the beam structure of an linear electron accelerator is characterized by very short beam-on pulses of the order of microseconds, followed by a beam-off period of the order of milliseconds. The beam-on period is characterized by very high beam currents of the order of hundreds of milliamperes, but for very short time periods, whereas the beam-off period of the order of milliseconds allows rotation of the vacuum window and converter disks in a manner that a previously cooled down area of the vacuum window or the converter disk is irradiated. This means, that the window disk and the converter disks have to be rotated in the beam-off period by at least one beam diameter to expose a new, cool section of the window disk or the converter disks to the next beam pulse. This way, the rotation speed of the window disk and the converter disks can be significantly reduced from thousands of rotations per minute required for a rhodotron time structure of the beam to hundreds of rotations per minute for a conventional linear accelerator time structure of the beam. As an example the irradiation patterns are depicted in Figure 4 .

[0034] More specifically, Figure 4 shows an exemplary illustration of the pattern generated by applying short beam pulses of microseconds with a frequency of several hundred Hz on a rotating disk. Under the assumption that the beam pulses are applied on a converter disk at a radius of 15 cm, with a repetition rate of 800 Hz and a beam diameter of 5 mm, a maximum of 188 positions are generated it the wheel is rotated with 255 rotations per minute. This results in a maximum cooling time of one deposition spot of 235 milliseconds, significantly longer than for a irradiated segment of 1/3 of the circumference with a rhodotron where the cooling time is only 60 milliseconds. Depending on the beam diameter, the rotation speed can be adjusted to faster rotation speeds, to prevent overheating of adjacent deposition spots of the beam. Or also slightly lower rotation speeds, if an overlap of deposition spots is acceptable, i.e. due to a Gaussian beam profile. The generally decreased rotation speeds (hundreds of rpm vs. thousands of rpm in the case of irradiations with a rhodotron) allow the use of liquid cooling media, such as water.

4) Vacuum window

[0035] The electron beam from the accelerator has to pass through a vacuum window that separates the vacuum of the accelerator from the cooling circuitry of the converter. This window must withstand the electron beam intensity without being compromised in its mechanical stability. Therefore, this window must consist of a material with a high melting point, good mechanical strength and of low atomic number in order to allow the passage of the electron beam with insignificant energy degradation. Furthermore, the material of the vacuum window should be chemically relatively inert and not react with components or trace components of the cooling circuitry. A suitable material for a vacuum window is a foil made from Beryllium or some high strength alloy (e.g. Havar™). The vacuum window and the converter target material have to be cooled, due to the energy deposited by the intense electron beam. Blackbody radiation is by far insufficient to dissipate the deposited energy.

[0036] A vacuum window made from Beryllium foil with thickness of > 0.1mm was considered. The energy deposited in the foil is dependent on the foil thickness but does not exceed 80 Watts for a window of 100 μm thickness.

[0037] Assuming a beam diameter of 5 mm (flat-top profile), the temperature increase for one beam-pulse of a conventional linear electron accelerator (40 MeV, 800 Hz, 125 kW) passing a 0.1 mm thick Beryllium window was calculated as only 1.5 °C. In order to further reduce temperature variations the entrance vacuum window is allowed to rotate (see Figure 6). That is, the vacuum window is coupled to a rotary drive. By way of example, a Be foil of 4 cm diameter is mounted on a hollow shaft, which is part of a rotary vacuum feedthrough, preferably with magnetofluid sealing. Commercially available rotary vacuum feedthroughs of 4 cm can be rotated with max. speeds of about 3100 rpm. For our considerations, the beam was hitting the periphery of the 4 cm diameter disk at a distance of 0.5 cm from the rim, resulting in an annular impact zone of 3 cm diameter.

[0038] Assuming a 5 mm deposition spot, about 18 spots can be applied to the rotating vacuum window disk. With a beam-off period of 1.25 milliseconds, the vacuum window disk needs to be rotated with about 2600 rpm. This rotation speed may be lowered if smaller beam diameters or an overlap of deposition spots can be tolerated. This aspect becomes important when cooling by liquids is considered. The resulting cooling period is of the order of 20 milliseconds before a new beam spot is applied, which should be sufficiently long to essential allow for a complete cool down of the applied beam spot. Since the temperature increase per beam spot is relatively low, also thicker Beryllium windows providing higher mechanical strength, smaller beam diameters or an overlap of deposition spots can be tolerated.

[0039] More specifically, Figure 6 shows a schematic of a Be-foil of 4 cm diameter mounted on a hollow shaft of a rotary vacuum feedthrough. One side is cooled by flowing He gas or water.

[0040] The rotation speed was chosen as 2'600 rpm. This way about 18 deposition spots are formed, each spot is irradiated for microseconds, followed by a beam-off period of 1.25 ms in which the disk is rotated by about one diameter of the beam spot. This results in a cooling period of 20 ms, before the same spot is irradiated again.

[0041] More specifically, Figure 5 shows a proposed scheme of irradiation of a rotating Be foil vacuum window. The foil is rotating in opposite direction compared to the rotation direction of the converter disks (counter clockwise). With the proposed scheme of irradiation with a beam structure of 800 Hz and 1.2% duty cycle, the cooling period of the irradiated section is maximized. By minimizing the areal overlap between the window disk and the converter disks as much as possible (as viewed in the direction of the beam axis) and by rotating the window disk and the converter disks in opposite direction, the occurrence of shear forces on the cooling medium, particularly water, is minimized, since the tangential velocity of the rotating window disk and the converter disks are similar.

5) Electron to photon converter, housing, and cooling

[0042] The electron beam impinges then on a converter material. The converter must be a material with a high melting point and good mechanical stability. Furthermore, the material must consist of a high atomic number and be of high density to effectively convert the electron beam to Bremsstrahlung. The high atomic number and the high density contribute to a optimal point source origin of the Bremsstrahlung. For reasons of maintenance and radioactive waste management, the converter material should only marginally be activated by the electron beam. Furthermore, the material of the converter should be chemically relatively inert and not react with components or trace components of the cooling circuitry. The thickness of the converter must be adjusted to the range of the electrons in the converter material. Good converter materials are Tungsten or Tantalum of 4 to 5 mm thickness.

[0043] The interaction of the electrons with the converter material can be described by a multitude of physical processes and is rather complicated. For the production of radionuclides in photonuclear reactions Bremsstrahlung photons with an energy in excess of about 8 MeV are important. However, in order to consider the energy deposited in the converter material all physical processes have to be included. Of importance is the arrangement of the converter materials in relation to the target materials to be irradiated. Bremsstrahlung photons larger than 8 MeV are mainly emitted in forward direction (the beam direction) in the form of a cone with a certain opening angle.

[0044] The vacuum window and the converter target material have to be cooled, due to the energy deposited by the intense electron beam. Blackbody radiation is by far insufficient to dissipate the deposited energy. Therefore, the vacuum window and the converter have to be cooled by a gas or liquid. In our considerations we suggest a cooling by flowing Helium gas. Helium has the advantage of being a material with low atomic number with high viscosity that cannot be activated or degraded by Bremsstrahlung photons. In case of using water as cooling liquid, photonuclear reactions on Oxygen isotopes are taking place. Most noteworthy is the production of the relatively short-lived isotope ^{15}O with a half-life of 122.24s in a $^{16}O(\gamma,n)^{15}O$ reaction. Other conceivable reaction products are ^{13}N ($T_{1/2}$ = 9.97 m), ^{11}C ($T_{1/2}$ = 20.364 m) or ^{14}C ($T_{1/2}$ = 5730 a). With the exception of ^{14}C these products are short-lived and can be filtered out of the cooling water (with the exception of ^{15}O).

[0045] A similar principle as applied for the construction of the vacuum window assembly can be applied to the converter target. As discussed above the converter must be a high Z, high melting point material and provide good heat conductivity. It must provide mechanical stability for fast rotation and must only be marginally activated. In our considerations we chose Tantalum as converter material for its high melting point of 3017 °C and its machinability. Furthermore, natural Tantalum consists only of 2 isotopes: ^{181}Ta with a natural abundance of 99.98799% natural abundance and ^{180m}Ta with 0.01201% natural abundance. In (γ,n) or (y, 2n) reactions on ^{181}Ta will form either very ^{180}Ta or ^{179}Ta with 665 d half-live to stable ^{179}Hf, respectively. The latter nuclide decays by an electron-capture without the emission of gamma-rays. The formation of ^{180}Ta with 8.15 h half-life needs to be investigated, but its decay leads to either stable ^{180}W or stable ^{180}Hf. In (y, pxn)-reactions on Ta stable Hf isotopes are being formed. The formation of ^{182}Ta from neutron-capture reactions is estimated to contribute only to a minor activation of the Ta converter material.

[0046] Also, Tungsten can be considered as a good converter material because of its high melting point of 3422 °C. Furthermore, natural Tungsten consists of 5 isotopes: ^{180}W with a natural abundance of 0.12%, ^{182}W with 26.50% natural abundance, ^{183}W with 14.31% natural abundance, ^{184}W with 30.64% natural abundance and ^{186}W with 28.43% natural abundance. In (γ,n) or (y, 2n) reactions on ^{180}W either ^{179}Ta with 665 d half-live that decays to stable ^{179}Hf, or relatively short-lived ^{178}W ($T_{1/2}$ = 22 d) that decays to ^{178}Ta is formed, respectively. In (γ,n) or (y, 2n) reactions on ^{182}W and ^{183}W, ^{181}W with a half-life of 121,2 d is formed, which decays by electron capture to stable ^{181}Ta under the emission of X-rays and a very low energy gamma-ray. In (γ,n) reactions on ^{186}W, ^{185}W with a half-life of 75.1 d is formed that decay by beta-minus emission (0.4 MeV) and gamma-ray of 125 keV with low branching ratio to stable ^{185}Re. The formation of ^{182}Ta with 114.43 d half-life in (γ,p) or (y, pn) reactions on ^{183}W and ^{184}W needs to be investigated, its dose rate may contribute significantly to the total dose rate even after an extended decay period. Of no big concern are (n, y) reactions on the various W isotopes. In general, W has many favorable properties as converter material, but its activation is expected to be much higher than for Ta.

[0047] The converter target assembly should be very compact as to allow a high photon flux with a minimal opening angle. The ideal thickness for the formation of gamma-rays in the energy window from 8 to 30 MeV lies between 4 to 5 mm.

[0048] In order to distribute the energy deposition of about 45 kW in a 4.5 mm thick W converter slab, the converter target is divided into a plurality of disks. The energy of the beam pulse of several microseconds in length is distributed around the circumference of the rotating disks assuming a radius of 15 cm. As discussed above, the rotation speed of the disks is preferably synchronized with the time structure of the beam which results in a rotation speed of >255 rpm for a beam diameter of 5 mm and a deposition radius of 15 cm.

[0049] The number of disks can be increased while adjusting the total thickness to the optimum value between 4.5 to 5 mm.

[0050] Maximum temperatures reached depend on the FWHM of the electron beam. The energy deposited in the actual converter amounts to about 45 kW. To remove this heat a flow of Helium gas of about 250 L/s at standard temperature and pressure (STP) is required assuming an exit temperature of the Helium gas, which is 200 °C higher than the entrance temperature. This rather high flow rate of He can be provided by a commercially available medium sized pump. Alternatively, a flow of water can be considered for cooling. The energy deposited in the window, the converter disks and the cooling water amounts to about 50 kW. Assuming an inlet temperature of 20 °C and an exit temperature of 80 °C a minimum cooling flow of 200 ml/s (12 L/min) of water is required, which is easily achieved with a commercially available water pump. In addition the rotating converter disks support the cooling flow by acting as a Tesla pump.

[0051] The converter disks are stacked on a common shaft separated by a small gap (in the order of (sub-) millimeters).

The number of disks and their thickness is optimized to the electron beam energy to achieve maximal Bremsstrahlung conversion efficiency. As discussed above, the disks preferably rotate at a speed which moves the deposited beam spot within the beam-off period by at least one diameter of the spot. Depending on the diameter of the converter disks and the beam spot diameter, rotation speeds of several hundred to several thousand rpm are resulting. The disks are tightly enclosed in a water-cooled housing with a small gap between disk and wall. To cool the disks, which are heated by the particle beam as described above, a cooling gas (e.g. Helium) is circulated through the gaps in between the disks. Due to the low rotation speeds also water can be used as cooling medium. In this case, water cooling of the housing is no longer required. Co-centric to the shaft, orifices are foreseen to facilitate axial gas or liquid flow along the shaft. The housing incorporates openings to allow gas or liquid circulation from the outer edge of the disks. This configuration describes a cohesion-type pump, also called Tesla pump, as originally described in U.S. Patent 1,061,206, hereby incorporated by reference.

[0052] The gas or liquid flow in between the disks describes a spiraling flow (vortex) due to the interplay of the gas or liquid, its adhesion to the disks and internal viscosity.

[0053] Due to the rotation, the contact time of the gas or liquid with the surfaces of the disks is prolonged and the heat transfer to the coolant is optimized. In pump configuration, the shaft is externally driven, and the gas or liquid are flowing from the shaft towards the outer rim of the disks.

[0054] The outward flow of the cooling gas or liquid enables homogenous cooling of the disks. Furthermore, with an increase of the number of disks, comes an increase in the total surface area available for cooling. Although the total heat load of the system in this configuration will remain constant the load per disk can be lowered.

[0055] More specifically, Figure 6 shows an illustration of the Tesla converter design. On the left the full disk assembly is shown with a shaft and multiple disks, the particle beam (in blue) impinges on the disk near the outer edge (the heated area, corresponding to the circular trace of the electron beam is indicated). On the right, a sketch of the coolant flow pattern on a single disk is depicted for a converter in pump configuration.

6) Energy Density Reduction

[0056] A further reduction of the energy density in the converter disks can be achieved by an additional movement of the main axis or by an additional movement of the electron beam (wobbling). While the first approach maintains the essentially point-like character of the emerging photon beam, the wobbling of the electron beam leads to a degraded photon density at the position of the production targets. Figure 7 illustrates the approach with an additional linear movement of the main axis (or a vertical wobbling of the beam). In the figure, the gray dots represent exemplary beam pulses. The blue line describes the central location of the beam pulse spots on the disc. In sub-figure a), the one-axis design is shown. Here the center spot line is a circle with radius Rc. Due to the mis-tune of rotational frequency and the beam repetition rate, the band in between the virtual circles of radius Rc + R_{Beam} and Rc - R_{Beam} (dotted gray lines in the figure) is irradiated after several revolutions. The irradiated area is given by

$$A_{rot} = \pi[(R_C + R_{Beam})^2 - (R_C - R_{Beam})^2].$$

[0057] In sub-figure b) an additional vertical movement of the main axis is introduced (or a vertical wobbling of the beam). This results in an up- and downward amplitude to the center line spot, expanding the irradiated area. The path of the centerline describes an oscillating motion with amplitude A_{lin} around the mean radius Rc. The figure depicts the path for approximately 3 revolutions. Care must be taken to detune the frequencies of the rotation and linear movement. Otherwise, a stable orbit is achieved and only part of the full area in between the virtual boundaries (dotted gray lines) is irradiated. The irradiated area is quantified by

$$A_{rot/lin} = \pi[(R_C + R_{Beam} + A_{lin})^2 - (R_C - R_{Beam} - A_{lin})^2].$$

[0058] The linear actuation of the main rotation axis (or a vertical wobbling of the beam) is the simplest extension of the approach. It is certainly possible to achieve a circular movement of the main axis.

7) Production target(s)

[0059] Target materials must be placed in the emerging cone of photons to be effectively irradiated. If the amount of target material is limited i.e. ^{226}Ra, or isotopically highly enriched materials such as, but not limited to ^{48}Ca, ^{48}Ti, ^{68}Zn, ^{100}Mo, ^{112}Sn, or ^{150}Nd, the target needs to be placed as close as possible to the converter. Due to the close geometrical arrangement of the converter, a high as possible photon flux density is achieved. The production of ^{99}Mo from ^{100}Mo in a (y,n)-reaction results in a "carrier added" ^{99}Mo that cannot be chemically separated from the target material ^{100}Mo. In order to produce easy to use ^{99m}Tc radionuclide generators from this material, the specific activity of the ^{99}Mo should exceed about 5 Ci/g of Mo. This can only be accomplished by irradiations of highly enriched ^{100}Mo with a high photon flux density, where the photons emerge from a point like converter source. Since photons of 8 MeV or higher energies are very penetrating, a stack of target materials can be irradiated simultaneously. During irradiation, the target materials absorb photons and energy is deposited in the targets. Therefore, the targets have to be cooled, e.g. by flowing cooling water. The high photon energies have the advantage that target materials, which are difficult to handle i.e. because of their radioactivity, toxicity, or chemical reactivity can be safely encapsulated in suitable materials for irradiation. Therefore, a breach of target materials into the cooling water circuit can be avoided. Furthermore, the simultaneous irradiation of multiple production targets with the same photon beam is possible, allowing the simultaneous production of several radionuclides. As an example, the relatively thin ^{226}Ra would be loaded in the positions closest to the converter assembly, where the photon flux is highest, followed by targets of e.g. ^{112}Sn or ^{150}Nd, which allow high production rates, but are relatively expensive as enriched materials, followed by massive targets of ^{68}Zn or ^{48}Ti, where chemical separation and reclamation procedures already exist in dealing with the large amounts of target material. Preferably, provisions to remotely load, unload and transport the targets to the processing hot-cells are made.

8) Massive beam stop

[0060] Since most of the high energy photons will penetrate all target materials, they must be stopped by a massive, preferably water-cooled beam stop made from i.e. Lead. According to Table 1, the energy deposited in the beam stop amounts to about 68 kW [2]. For reasons of shielding, a vertical arrangement of electron beam, converter and production targets could be envisaged, using the ground as additional shielding around the massive beam stop. Otherwise, additional shielding (i.e. concrete) must be put in place to reduce the gamma-ray dose to acceptable levels.

[0061] Inside the massive beam stop, provisions to irradiate artificial gemstones can be foreseen. The high energy gamma radiation is inducing defects in the lattice of artificially produced gemstones that act as color centers and thereby allow permanent coloring of artificially produced gemstones such as Topaz.

9) Cooling circuitry

[0062] Due to the low rotation speeds preferably water can be used as cooling agent, which massively facilitates the construction of an appropriate cooling circuit. The required flow of water is modest and most components are commercially available. Therefore, the technological simplicity outweighs its activation by the particle beam by far. Assuming an inlet temperature of 20 °C and an exit temperature of 80 °C a minimum cooling flow of 200 ml/s (12 L/min) of water is required, which is easily achieved with a commercially available water pump. In addition, the rotating converter disks support the cooling flow by acting as a Tesla pump. Chillers, that are able to remove heat of the order of 100 kW or more are available in air conditioning units of buildings.

[0063] Alternatively, as cooling medium Helium gas may be chosen due to its low atomic number and density, its chemical inertness and its reasonable heat capacity. Furthermore, He is not reacting with the high energy Bremsstrahlung photons. Assuming a temperature increase of 200 °C, about 250 L/s of He at STP are required to remove the energy deposited in the converter target assembly. The Helium gas is foreseen to enter the converter assembly at room temperature. The Helium gas is preferably circulated in a gas loop. Therefore, the cooling circuitry preferably comprises a high flow pump, high flow heat exchangers, a reservoir tank, filters for trace components such as Oxygen, water vapor and particles, and for provisions to fill and empty the circuitry with Helium gas. The pressure in the He tank (high pressure side) can be adjusted by a butterfly valve connected to pressure sensors. Several components of the cooling circuit can be sourced from the automotive industry, such as high-flow interchillers or radial compressors.

Calculated yields of radionuclides (examples):

[0064] With the point source high power converter target assembly as described above and production targets exposed to the resulting photon field, the following yields can be obtained, assuming an electron energy of 40 MeV and 125 kW of beam power:

Production of ^{225}Ra from ^{226}Ra:

[0065] With a target thickness of 100 mg/cm^2 and a target diameter of 2 cm a production rate of 10.65 GBq ^{225}Ra / day of irradiation was calculated. This corresponds to about 5 GBq of ^{225}Ac after an ingrowth period of 14 to 15 days. In order to limit the number of chemical separation procedures, it is advantageous to select longer irradiation times, for example 2 weeks. After few days waiting time a first batch of ^{225}Ac can be separated from the irradiated target. From thereon, with an optimum waiting time of about 17 days, so-called 2nd and 3rd chance ^{225}Ac can be separated from the irradiated target due to the ingrowth of ^{225}Ac from decay of ^{225}Ra with a half-life of 14.9 d. Assuming such a production regime and a patient dose of 10 MBq about 500 patient doses can be produced per day from one ^{226}Ra target.

Production of ^{99}Mo from ^{100}Mo:

[0066] With a target thickness of 1 g/cm^2 and a target diameter of 2 cm a production rate of about 650 GBq ^{99}Mo / day was calculated. This corresponds to about 17.5 Ci/day/target. With 1 g/cm^2 the target thickness is still relatively thin.

[0067] The calculated yields show that photonuclear reactions are a viable production method for medical radionuclides. The above-described point source high power converter target assembly is capable of absorbing enormous beam powers of up to 125 kW and make routine radionuclide production with the use of a linearelectron accelerator possible.

References:

[0068] The following reference are hereby incorporated by reference:

[1a] MEVEX The accelerator technology company. High Power Linacs for Isotope Production. http://www.mevex.com/Brochures/Brochure_High_Energy.pdf [accessed May 17, 2019]

[1b] Ion Beam Applications, IBA Industrial, Rhodotron® TT300-HE High Energy Electron Generator, www.iba-industrial.com [accessed June 26, 2018]

[2] M. Vagheian, "A Point Source High Power Converter Target to Produce Bremsstrahlung for Photonuclear Reaction", PhD thesis, University of Bern, Switzerland, February 25, 2022.

List of reference numerals

[0069]

1	electron beam source (electron accelerator)
2	electron beam
3	electron beam transfer line (vacuum pipe)
4	vacuum valve (slammer valve)
5a-c	beam optical elements (quadrupole triplet)
8	entry window holder for a vacuum window
9	housing
10	cooling medium ports (inlet and outlet port)
11	cooling loop (cooling circuit)
12	converter disk
13	rotation axis
14	projected focal beam spot (trace in time)
15	cone of Bremsstrahlung photons (photon field)
16	neutron absorber
17	production target
18	beam stop
19	cavity
20	converter target
21	converter target assembly
22	flattening filter / exit window
23	vacuum window disk
24	vacuum window control unit
25	converter disk control unit
26	vacuum window rotary drive
27	converter disk rotary drive
30	hollow shaft
31	magnetofluid seal
32	bearings
33	rotational axis

Claims

1. Facility for the production of radionuclides, in particular diagnostic and therapeutic radionuclides, based on the principle of photonuclear irradiation, comprising

   - an electron accelerator (1), producing an electron beam (2) with a time structure characteristic for a linear electron accelerator (1),
   - a converter target assembly (21) with a converter target (20) that converts the electron beam (2) to Bremsstrahlung photons (15),
   - a number of production targets (17), irradiated by the Bremsstrahlung photons (15) and thereby producing said radionuclides,

   wherein the converter target assembly (21) comprises a sealed housing (9), the housing (9)

   - enclosing a cavity (19) which holds the converter target (20),
   - comprising an entry window with a window disk (23) for the electron beam (2) and an exit window (22) for the Bremsstrahlung photons (15),
   - comprising cooling medium ports (10), these ports being part of a cooling circuit (11) for establishing a cooling flow through the cavity (19), thereby cooling the converter target (20) and the window disk (23),

   wherein

   - the converter target (20) comprises a number of rotatable converter disks (12),
   - the electron beam (2) is set off-center with respect to the respective converter disk (12),

   and wherein the respective converter disk (12) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of the electron beam (2) over an annular area (14) of the converter disk (12) over numerous revolutions.

2. Facility according to claim 1, wherein the electron accelerator (1) generates a pulsed electron beam (2), wherein the pulsed electron beam (2) has impulse times in the range of microseconds and period times in the range of milliseconds or longer.

3. Facility according to claim 1 or 2, comprising a control unit (24) which keeps the rotation speed of the respective converter disk (12) synchronized with period time structure of the electron beam.

4. Facility according to claim 3, wherein the area on the respective converter disk (12) exposed to a single beam pulse describes a near circular area, wherein the ratio of the revolution time of the converter disk (12) to the period time of the electron beam (2) is preferably chosen such that the beam spot on the converter disk between subsequent pulses is rotated by at least approximately one spot diameter.

5. Facility according to any of the preceding claims, wherein the rotation speed of the respective converter disk (12) is set in the range from a few hundreds to several thousands of revolutions per minute.

6. Facility according to any of the preceding claims, wherein the window disk (23) is rotatable and held or supported by an entry window holder (8), the electron beam (2) is set off-center with respect to the window disk (23), and wherein the window disk (23) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of the electron beam (2) over multiple irradiation spots of the window disk (23).

7. Facility according to claim 6, wherein the entry window holder (8) comprises or holds a preferably circular window disk (23), which is preferably a Beryllium foil or any other high strength material with low atomic number, wherein the entry window holder (8) is mounted on/in/at or is part of a hollow shaft (30), which is part of a rotary vacuum feedthrough.

8. Facility according to claim 7, wherein the entry window holder (8) and the mounted window disk (23) or the rotary vacuum feedthrough are sealed with respect to the beam transfer line (3) by a magnetofluid sealing (31).

9. Facility according to any of claims 6 to 8, wherein a control unit (25) keeps the rotation speed of the entry window

holder (8) and the mounted window disk (23) synchronized with the time structure of the electron beam period times.

10. Facility according to claim 9, wherein the area on the window disk (23) exposed to a single beam pulse describes a near circular area, wherein the ratio of the revolution time of the window disk (23) to the beam period time is preferably chosen such that over multiple irradiation cycles the series of irradiation spots form a homogeneously irradiated annular area of the window disk (23).

11. Facility according to any of claims 6 to 10, wherein the rotation speed of the window disk (23) is set in the range from several hundreds to several thousands of revolutions per minute.

12. Facility according to any of claims 6 to 11, wherein the overlap of the window disk and the rotating converter disks is minimal when viewed along the beam axis.

13. Facility according to any of claims 6 to 12, wherein the rotation direction of the window disk (23) is contrary to the rotation direction of the rotating converter disks.

14. Facility according to any of the preceding claims, wherein the beam transfer line (3) comprises a beam optical element (5a-c) that allows for focusing or defocusing of the electron beam (2) to different FWHM ("full width half maximum"), and wherein a FWHM of at least 2 mm is set.

15. Facility according to any of the preceding claims, wherein the converter target (20) comprises a plurality of preferably circular converter disks (12).

16. Facility according to claim 15, wherein the converter disks (12) are stacked on a common shaft (13).

17. Facility according to any of the preceding claims, wherein the respective converter disk(s) (12) is/are coupled to a rotary drive (27).

18. Facility according to any of the preceding claims, wherein the converter disks (12) are arranged to form a Tesla pump.

19. Facility according to any of the preceding claims, wherein the cooling medium is a cooling liquid, in particular water.

20. Facility according to any of the preceding claims, wherein the region of origin of the emerging Bremsstrahlung photons (15), apart from some optional wobbling or some movement of the common shaft (13) with an amplitude in the range of millimeters, is fixed in space.

21. Converter target assembly (21) for a facility according to any of the preceding claims, comprising a sealed housing (9), the housing (9)

- enclosing a cavity (19) which holds the converter target (20),
- comprising an entry window holder (8) with a mounted entry window disk (23) for an electron beam (2) and an exit window (22) for Bremsstrahlung photons,
- comprising cooling medium ports (10), these ports being designated to be connected to a cooling circuit (11) for establishing a cooling flow through the cavity (19), thereby cooling the converter target (20) and the entry window holder (8) with its mounted entry window disk (23),

wherein the converter target (20) comprises a number of rotatable converter disks (12), and wherein the respective converter disk (12) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of an incoming electron beam (2) over a series of near circular beam spots, which, over multiple irradiation cycles and rotations of the converter disk, form a homogeneously irradiated annular area of the converter disk (12).

22. Converter target assembly (21) according claim 21, wherein the entry window holder (8) comprises a rotatable window disk (23), wherein the window disk (23) is designed to rotate during operation of the facility, thereby, in the course of time, spreading the focal spot of an incoming electron beam (2) over a series of near circular beam spots, which, over multiple irradiation cycles and rotations of the window disk, form a homogeneously irradiated annular area of the window disk (23).

23. Method of producing radionuclides, wherein an electron beam (2) is directed onto a converter target (20) with a number of rotating converter disks (12), such that, in the course of time, the focal spot of the electron beam (2) is spread over an annular area of the respective converter disk (12), thereby producing a beam of Bremsstrahlung photons (15) for irradiation of a production target (17), wherein the converter target (20) is cooled by a flow of cooling medium, in particular gaseous Helium or liquid water.

24. Method according to claim 23, wherein the converter target (20) is arranged inside a housing (9), and wherein the electron beam (2) is lead through a rotating entry window holder (8) with a mounted entry window disk (23) of the housing (9), such that, in the course of time, the focal spot of the electron beam (2) is spread over a series of near circular beam spots, which, over multiple irradiation cycles, form a homogeneously irradiated annular area of the entry window disk (23).

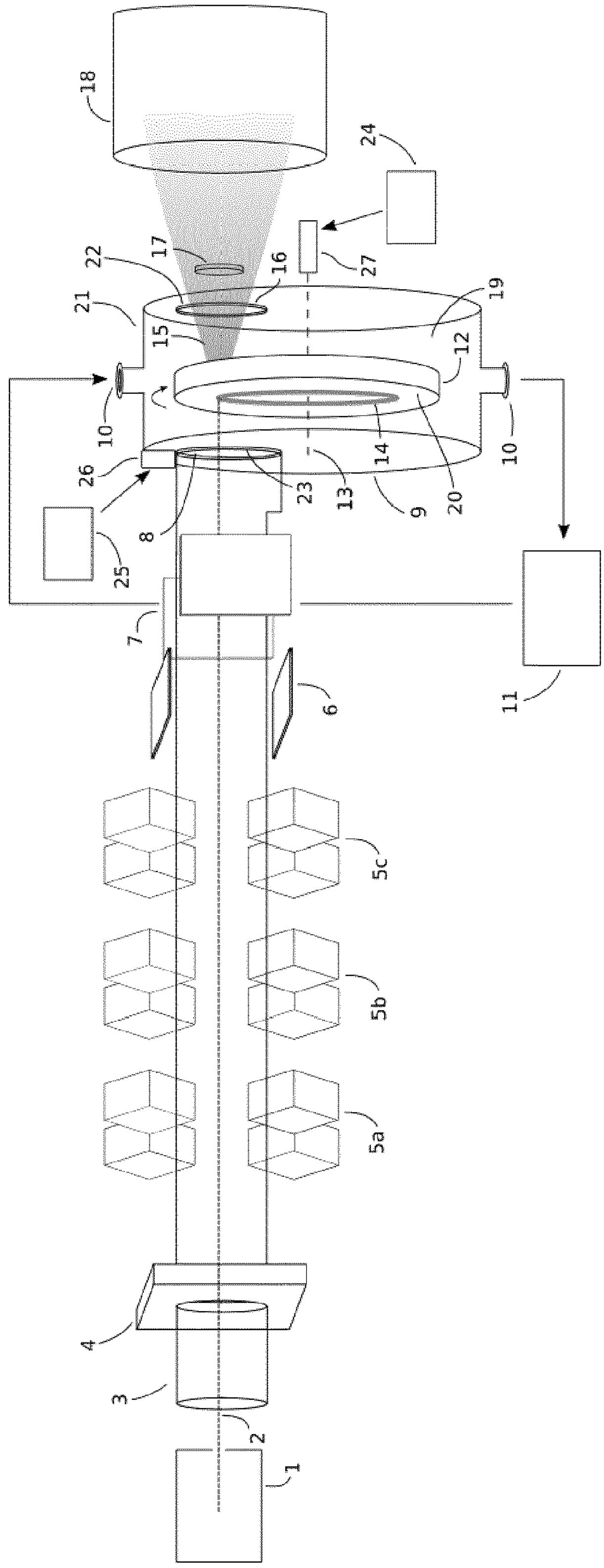
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FIG. 1

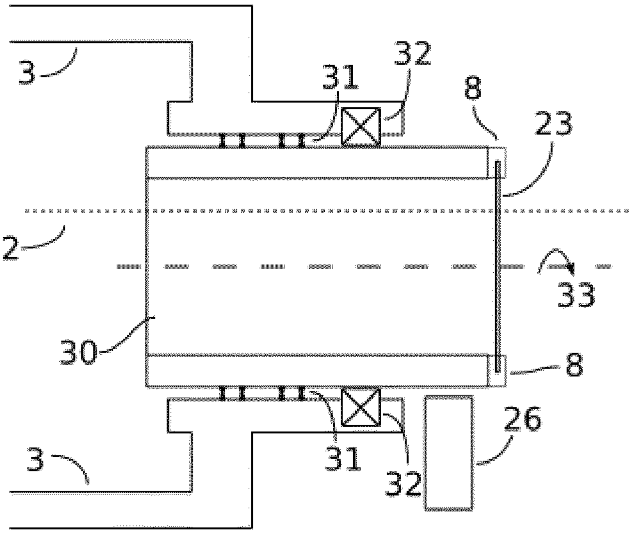
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FIG. 2

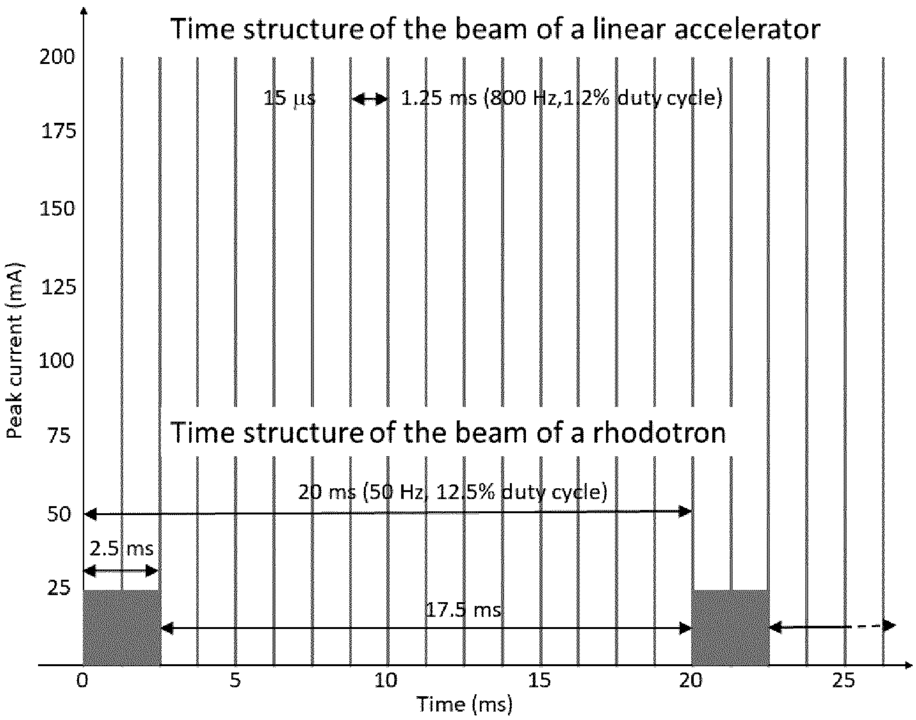
Time structure of the beam of a linear accelerator
15 µs
1.25 ms (800 Hz, 1.2% duty cycle)
Time structure of the beam of a rhodotron
20 ms (50 Hz, 12.5% duty cycle)
2.5 ms
17.5 ms
Peak current (mA)
200
175
150
125
100
75
50
25
0
5
10
15
20
25
Time (ms)

FIG. 3

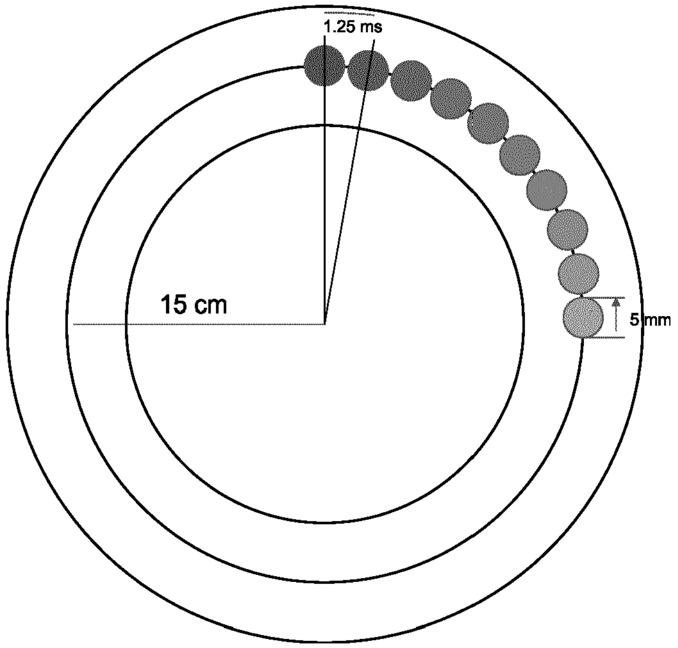

FIG. 4

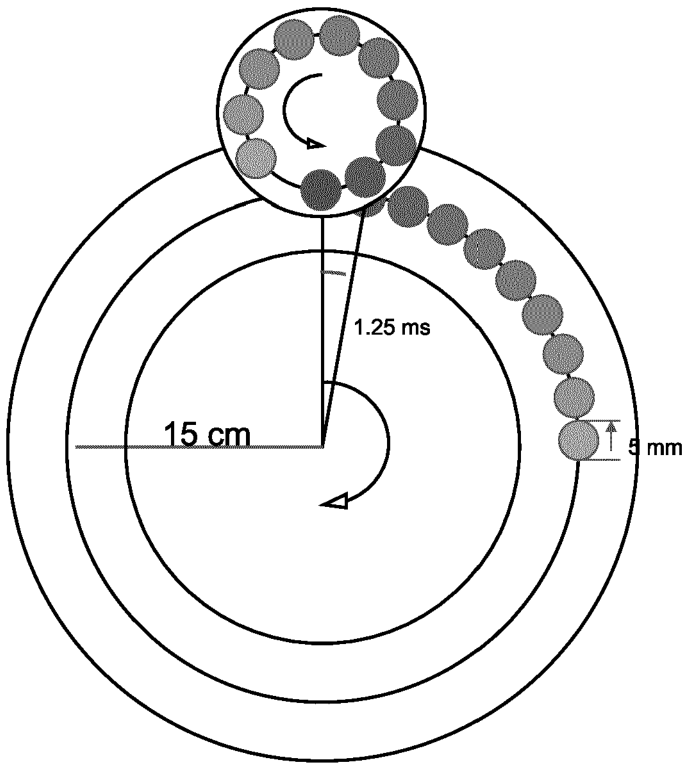

FIG. 5

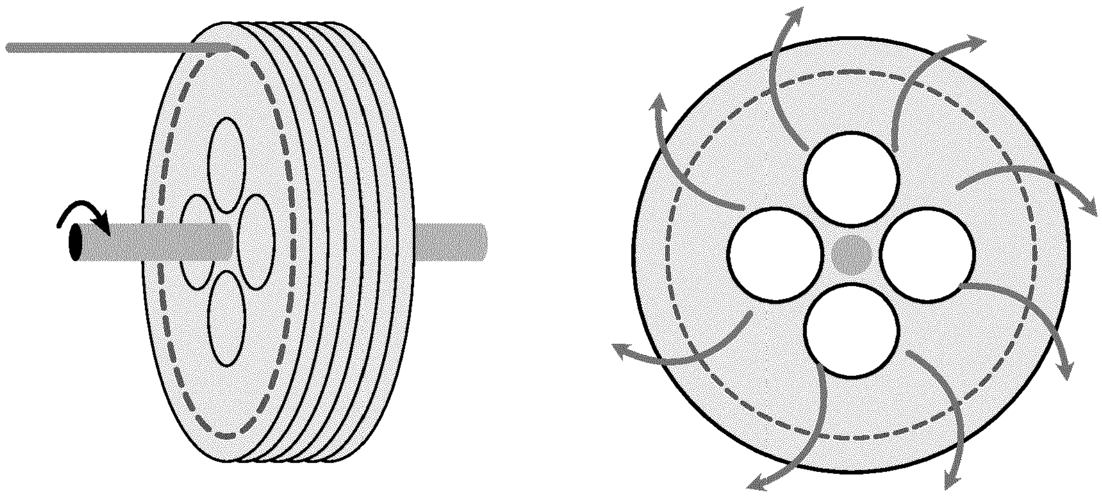

FIG. 6

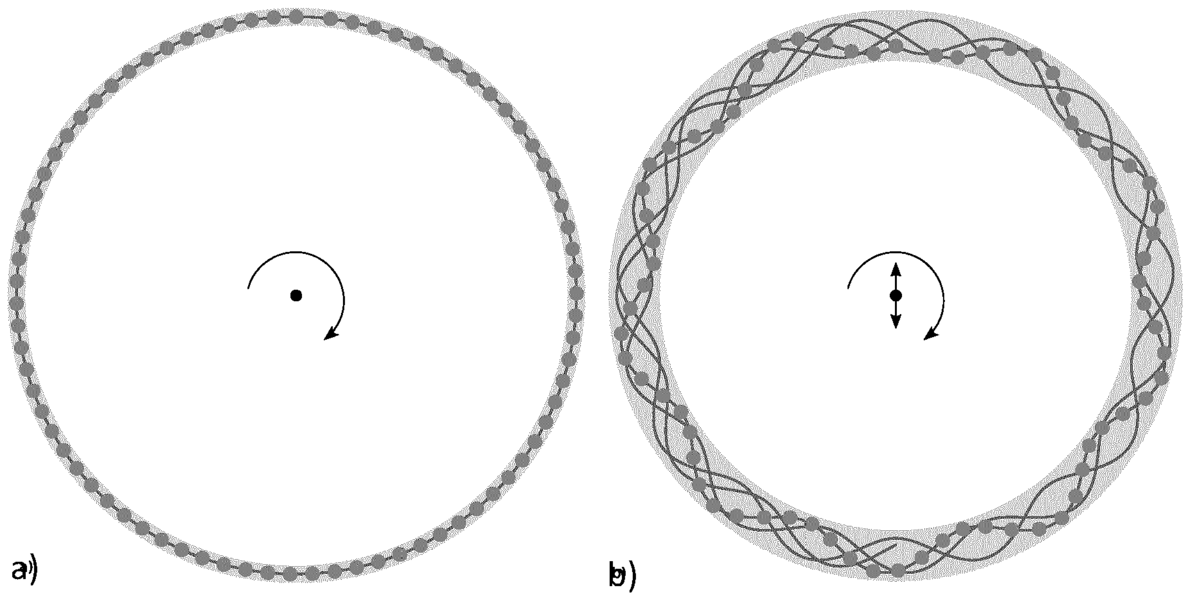

FIG. 7

Component	Material	Thickness	Absorbed power (kW)
Vacuum window	Beryllium	100 μm	0.08
Converter disk 1	Tantalum	1.125 mm	8.56
Converter disk 2	Tantalum	1.125 mm	11.7
Converter disk 3	Tantalum	1.125 mm	13.3
Converter disk 4	Tantalum	1.125 mm	11.5
Flattening filter	Aluminum	2 mm	2.03
Water cooling	Water	3 mm	1.25
Massive beam stop	Lead	50 cm	67.6

Table 1

Europäisches Patentamt
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EUROPEAN SEARCH REPORT

Application Number
EP 23 15 9029

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
E	EP 4 191 613 A1 (UNIV BERN [CH]; EIDGENOESSISCHES INST FUER METROLOGIE METAS [CH]) 7 June 2023 (2023-06-07) * the whole document * -----	1-11, 14-24	INV. G21G1/10 H05H6/00
A	US 2012/281799 A1 (WELLS DOUGLAS P [US] ET AL) 8 November 2012 (2012-11-08) * claims; figures * -----	1-24	
A	US 6 907 106 B1 (MCINTYRE RAYMOND D [US] ET AL) 14 June 2005 (2005-06-14) * claims; figures * -----	1-24	
A	JP 2021 004768 A (HITACHI LTD) 14 January 2021 (2021-01-14) * figures * -----	1-24	
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	12 July 2023	Smith, Christopher

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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T : theory or principle underlying the invention
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D : document cited in the application
L : document cited for other reasons
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EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 23 15 9029

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The members are as contained in the European Patent Office EDP file on
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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- A Point Source High Power Converter Target to Produce Bremsstrahlung for Photonuclear Reaction. **M. VAGHEIAN.** PhD thesis. University of Bern, 25 February 2022 **[0068]**