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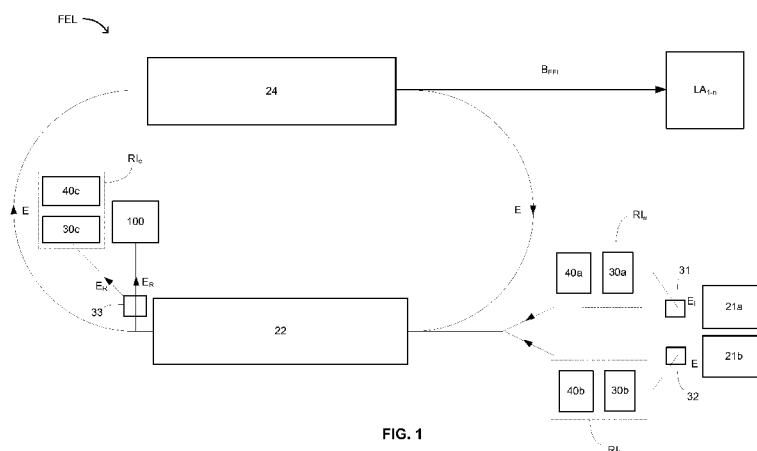
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(57) **Abstract:** A system comprising a free electron laser and a radioisotope production apparatus, wherein the free electron laser comprises an electron injector, an energy recovery linear accelerator and an undulator, and the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target, wherein the further linear accelerator is positioned to receive an electron beam after it has been accelerated then decelerated by the energy recovery linear accelerator, the further linear accelerator being configured to accelerate electrons of the electron beam to an energy of around 14 MeV or more for subsequent delivery to the electron target.

Radioisotope Production

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 15157433.2 which was filed on
5 March 3, 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to radioisotope production apparatus and associated
methods. The present invention also relates to a system comprising a free electron laser and a
10 radioisotope production apparatus

BACKGROUND

[0003] Radioisotopes are isotopes which are not stable. A radioisotope will decay after a
period of time by emitting a proton and/or neutron. Radioisotopes are used for medical
15 diagnostics and for medical treatments, and are also used in industrial applications

[0004] The most commonly used medical radioisotope is Tc-99m (Technetium), which is
used in diagnostic applications. Production of Tc-99m uses a high flux nuclear reactor. Highly
enriched uranium, comprising a mixture of U-238 and U-235 is bombarded with neutrons in the
nuclear reactor. This causes some of the U-235 to undergo fission and to separate into Mo-99 +
20 $\text{Sn}(x13) + \text{neutrons}$. The Mo-99 is separated out from the other fission products and shipped to a
radiopharmacy. Mo-99 has a half-life of 66 hours and decays to Tc-99m. The Tc-99m has a
half-life of only 6 hours (which is useful for medical diagnostic techniques). At the
radiopharmacy Tc-99m is separated from the Mo-99 and is then used for medical diagnostic
techniques.

25 [0005] Mo-99 is widely used around the world to generate Tc-99m for medical diagnostic
techniques. However, there are only a handful of high flux nuclear reactors which can be used to
generate Mo-99. Other radioisotopes are also made using these high flux nuclear reactors. All
of the high flux nuclear reactors are over 40 years old and cannot be expected to continue to
operate indefinitely.

30 [0006] It may be considered desirable to provide an alternative radioisotope production
apparatus and associated methods and/or associated systems.

SUMMARY

[0007] According to an aspect of the invention there is provided a system comprising a free electron laser and a radioisotope production apparatus, wherein the free electron laser comprises an electron injector, an energy recovery linear accelerator and an undulator, and the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target, wherein the further linear accelerator is positioned to receive an electron beam after it has been accelerated then decelerated by the energy recovery linear accelerator, the further linear accelerator being configured to accelerate electrons of the electron beam to an energy of around 14 MeV or more for subsequent delivery to the electron target.

[0008] The system is advantageous because components used for radioisotope production are also used by the free electron laser (which may be used to generate EUV radiation for use by lithography apparatuses). This provides a cost saving compared with the cost that would be incurred if a radioisotope production apparatus and a free electron laser were provided entirely separately from each other (e.g. at different locations). The radioisotope production may take place in parallel with operation of the free electron laser (e.g. in parallel with generation of an EUV radiation beam). The electron beam may be used to generate EUV radiation and then be used to produce radioisotopes.

[0009] A kicker may be configured to switch the electron beam between the further linear accelerator and a beam dump.

[0010] According to a second aspect of the invention there is provided a system comprising a free electron laser and a radioisotope production apparatus, wherein the free electron laser comprises a plurality of electron injectors, a linear accelerator and an undulator, and the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target, wherein the further linear accelerator is positioned to receive an electron beam from one of the electron injectors when it is not being used to provide an electron beam to the linear accelerator, the further linear accelerator being configured to accelerate electrons of the electron beam to an energy of 14 MeV or more for subsequent delivery to the electron target and the photon target.

[0011] The system is also advantageous because components used for radioisotope production are also used by the free electron laser (which may be used to generate EUV radiation for use by lithography apparatuses). This provides a cost saving compared with the cost that would be incurred if a radioisotope production apparatus and a free electron laser were provided
5 entirely separately from each other (e.g. at different locations). The radioisotope production may take place in parallel with operation of the free electron laser (e.g. in parallel with generation of an EUV radiation beam). That is, one linear injector may be used to produce radioisotopes whilst the other is being used to provide an electron beam for the free electron laser.

[0012] A plurality of radioisotope production apparatuses may be provided.

10 [0013] A kicker may be located after each electron injector, the kicker being configured to switch the electron beam generated by that electron injector between the linear accelerator of the free electron laser and one of the radioisotope production apparatuses.

[0014] The number of electron injectors may be one more than the number of radioisotope production apparatuses.

15 [0015] The linear accelerator of the free electron laser may be an energy recovery linear accelerator.

[0016] The further linear accelerator may be configured to accelerate electrons of the electron beam to an energy of around 30 MeV or more.

[0017] The system may further comprise an electron target held by the electron target
20 support structure, the electron target comprising material which will decelerate the electrons and generate photons, and may further comprise a photon target held by the photon target support structure, the photon target comprising material which will eject neutrons when the photons are incident upon it and which will thereby form a radioisotope.

[0018] The photon target may comprise Mo-100.

25 [0019] According to a third aspect of the invention there is provided a system comprising a free electron laser and a radioisotope production apparatus, wherein the free electron laser comprises an electron injector, a linear accelerator and an undulator, and the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a
30 photon target, wherein the electron injector is configured to generate an electron beam with a current of 10 mA or more and the further linear accelerator is configured to accelerate electrons

of the electron beam to 14 MeV or more for subsequent delivery to the electron target and the photon target.

[0020] Providing the electron beam with a current of 10 mA or more is advantageous compared with providing a lower electron beam current because it increases the specific activity of the radioisotope that can be produced using the electron beam.

[0021] The electron injector may be configured to generate an electron beam with a current of 30 mA or more. The electron injector may be configured to generate an electron beam with a current of 100 mA or more.

[0022] The further linear accelerator may be configured to accelerate electrons of the electron beam to an energy of around 30 MeV or more.

[0023] According to a fourth aspect of the invention there is provided a radioisotope production apparatus comprising a linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target, wherein an electron beam distribution apparatus is arranged to receive an electron beam following acceleration by the linear accelerator and before the electron beam is incident upon the electron target, the electron beam distribution apparatus being configured to control the surface area of the electron target upon which the electron beam is incident.

[0024] Distributing the electron beam is advantageous because it distributes heat delivered by the electron beam, thereby reducing localised heating of the electron target.

[0025] The electron beam distribution apparatus may comprise a lens configured to increase the cross-sectional area of the electron beam.

[0026] The lens may comprise a defocussing quadrupole magnet.

[0027] The electron beam distribution apparatus may comprise a beam kicker which is configured to scan the electron beam over the surface of the electron target.

[0028] According to a fifth aspect of the invention there is provided a radioisotope production apparatus comprising a linear accelerator, a beam kicker, a plurality of electron target support structures configured to hold electron targets and a plurality of associated photon target support structures configured to hold photon targets, wherein the beam kicker is configured to receive an electron beam following acceleration by the linear accelerator and is configured to direct the electron beam to each of the electron target support structures sequentially.

[0029] Distributing the electron beam to different electron target support structures such that the electron beam is incident on different electron targets is advantageous because it distributes heat delivered by the electron beam, thereby reducing localised heating of the electron targets.

5 [0030] According to a sixth aspect of the invention there is provided a radioisotope production apparatus comprising a linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target, wherein the radioisotope production apparatus further comprises one or more coolant fluid conduits configured to transport a coolant fluid past a photon target and/or an electron target held by the support structures and thereby remove heat from the photon target
10 and/or the electron target, and wherein the radioisotope production apparatus further comprises a waste heat recovery system configured to recover some of the heat removed from the photon target and/or the electron target.

[0031] The waste heat recovery system advantageously allows some of the power used to generate the radioisotope to be recovered.

15 [0032] The waste heat recovery system may be configured to generate electricity using the recovered heat.

[0033] The waste heat recovery system may comprise a closed loop which uses a working fluid.

20 [0034] The working fluid of the closed loop may be different from the coolant fluid used to cool the photon target and/or an electron target, and wherein the system further comprises a heat exchanger configured to transfer heat from the coolant fluid to the working fluid.

[0035] The closed loop may include an expansion turbine configured to drive an electricity generator.

25 [0036] According to a seventh aspect of the invention there is provided a system comprising the radioisotope production apparatus of any of the fourth to sixth aspects of the invention, and further comprising a free electron laser.

[0037] The system of any of the aspects of the invention may further comprise a plurality of lithographic apparatuses.

30 [0038] According to an eighth aspect of the invention there is provided a method of radioisotope production comprising injecting an electron beam into an energy recovery linear accelerator of a free electron laser, accelerating then decelerating the electron beam using the

energy recovery linear accelerator, using a further linear accelerator to accelerate the electron beam following deceleration, the electron beam being accelerated to an energy of around 14 MeV or more, and directing the electron beam onto an electron target to generate photons which are then incident upon a photon target to generate the radioisotope.

5 [0039] According to a ninth aspect of the invention there is provided a method of radioisotope production using an injector of a free electron laser when that injector is not being used to provide electrons to the free electron laser, the method comprising generating an electron beam using the injector, using a linear accelerator to accelerate the electron beam to an energy of around 14 MeV or more, and directing the electron beam onto an electron target to generate
10 photons which are then incident upon a photon target to generate the radioisotope.

[0040] The injector may be one of a plurality of injectors, and one of the other injectors may simultaneously provide electrons to the free electron laser.

[0041] The electron beam directed to the electron target may have a current of 10 mA or more.

15 [0042] According to a tenth aspect of the invention there is provided a method of radioisotope production comprising injecting an electron beam into linear accelerator, accelerating the electron beam using the linear accelerator, passing the electron beam through an electron beam distribution apparatus, and directing the electron beam onto an electron target to generate photons which are then incident upon a photon target to generate the radioisotope,
20 wherein the electron beam distribution apparatus controls the surface area of the electron target upon which the electron beam is incident.

[0043] According to an eleventh aspect of the invention there is provided a method of radioisotope production comprising injecting an electron beam into linear accelerator, accelerating the electron beam using the linear accelerator, and using a beam kicker to
25 sequentially direct the electron beam onto each a plurality of electron targets to generate photons which are then incident upon associated photon targets to generate the radioisotope.

[0044] According to a twelfth aspect of the invention there is provided a method of radioisotope production comprising injecting an electron beam into linear accelerator, accelerating the electron beam using the linear accelerator, and directing the electron beam onto
30 an electron target to generate photons which are then incident upon a photon target to generate the radioisotope, wherein the method further comprises transporting a coolant fluid past the

electron target and/or the photon target to remove heat from the electron target and/or the photon target, and using a waste heat recovery system to recover some of the heat removed from the electron target and/or the photon target.

[0045] Features of any given aspect of the invention may be combined with features of other aspects of the invention.

[0046] Various aspects and features of the invention set out above or below may be combined with various other aspects and features of the invention as will be readily apparent to the skilled person.

BRIEF DESCRIPTION OF THE DRAWINGS

[0047] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 is a schematic illustration of a system comprising a free electron laser and a radioisotope production apparatuses;

- Figure 2 is a schematic illustration of a radioisotope production apparatus according to an embodiment of the invention;

- Figure 3 is a schematic illustration of part of a system comprising a free electron laser and a radioisotope production apparatuses according to an embodiment of the invention;

- Figure 4 is a schematic illustration of an electron target and a photon target of a radioisotope production apparatus according to an embodiment of the invention;

- Figure 5 is a schematic illustration of a waste heat recovery system which may form part of a system according to an embodiment of the invention;

- Figure 6 is a schematic illustration of an electron beam distribution apparatus which may form part of a radioisotope production apparatus according to an embodiment of the invention;

- Figure 7 is a schematic illustration of an alternative electron beam distribution apparatus which may form part of a radioisotope production apparatus according to an embodiment of the invention; and

- Figure 8 is a schematic illustration of a further alternative electron beam distribution apparatus which may form part of a radioisotope production apparatus according to an embodiment of the invention.

DETAILED DESCRIPTION

[0048] Figure 1 schematically shows a system which comprises a free electron laser FEL and radioisotope production apparatus RI_{a-c} . The free electron laser FEL is capable of generating an EUV radiation beam B_{FEL} which is sufficiently powerful to supply a plurality of lithographic apparatus LA_{1-n} with EUV radiation beams that may be used to project patterns onto substrates.

[0049] The free electron laser FEL comprises two electron injectors 21a,b, a linear accelerator 22, an undulator 24 and a beam dump 100. The free electron laser may also comprise a bunch compressor (not illustrated). The system in Figure 1 can be switched between different modes of operation in which an electron beam E follows different paths. In the illustrated mode the electron beam E is depicted by a solid line, with alternative electron beam paths being depicted by a dashed line.

[0050] Each electron injector 21a,b is arranged to produce a bunched electron beam and comprises an electron source (for example a photo-cathode which is illuminated by a pulsed laser beam) and a booster which provides an accelerating electric field. The accelerating electric field provided by the booster may for example accelerate the electrons of the electron beam to an energy of around 10 MeV. Radioisotope production apparatus RI_{a-b} comprises components 30a,b, 40a,b downstream of the electron injectors 21a,b, which are described further below. In the depicted mode of operation the second electron injector 21b provides an electron beam E which is used by the free electron laser to generate an EUV radiation beam B_{FEL} . The first electron injector 21a provides an electric beam E_I which is used to generate radioisotopes (as described further below).

[0051] Electrons in the electron beam E are steered to the linear accelerator 22 by magnets (not shown). The linear accelerator accelerates the electron beam E. In an example, the linear accelerator 22 may comprise a plurality of radio frequency cavities which are axially spaced, and one or more radio frequency power sources which are operable to control the electromagnetic fields along the common axis as bunches of electrons pass between them so as to accelerate each bunch of electrons. The cavities may be superconducting radio frequency cavities. Advantageously, this allows: relatively large electromagnetic fields to be applied at high duty cycles; larger beam apertures, resulting in fewer losses due to wakefields; and for the fraction of radio frequency energy that is transmitted to the beam (as opposed to dissipated through the cavity walls) to be increased. Alternatively, the cavities may be conventionally conducting (i.e.

not superconducting), and may be formed from, for example, copper. Other types of linear accelerators may be used such as, for example, laser wake-field accelerators or inverse free electron laser accelerators.

[0052] Although the linear accelerator 22 is depicted as lying along a single axis in Figure 1, the linear accelerator may comprise modules which do not lie on a single axis. For example, a bend may be present between some linear accelerator modules and other linear accelerator modules.

[0053] Following acceleration by the linear accelerator 22 the electron beam E is steered to the undulator 24 by magnets (not shown). Optionally, the electron beam E may pass through a bunch compressor (not shown), disposed between the linear accelerator 22 and the undulator 24. The bunch compressor may be configured to spatially compress existing bunches of electrons in the electron beam E.

[0054] The electron beam E then passes through the undulator 24. Generally, the undulator 24 comprises a plurality of modules. Each module comprises a periodic magnet structure, which is operable to produce a periodic magnetic field and is arranged so as to guide the electron beam E produced by the electron injector 21a,b and linear accelerator 22 along a periodic path within that module. The periodic magnetic field produced by each undulator module causes the electrons to follow an oscillating path about a central axis. As a result, within each undulator module, the electrons radiate electromagnetic radiation generally in the direction of the central axis of that undulator module. The radiated electromagnetic radiation forms a beam B_{FEL} of EUV radiation which is passed to lithographic apparatus LA_{1-n} and is used by those lithographic apparatus to project patterns onto substrates.

[0055] The path followed by the electrons may be sinusoidal and planar, with the electrons periodically traversing the central axis. Alternatively, the path may be helical, with the electrons rotating about the central axis. The type of oscillating path may affect the polarization of radiation emitted by the free electron laser. For example, a free electron laser which causes the electrons to propagate along a helical path may emit elliptically polarized radiation, which may be desirable for exposure of a substrate W by some lithographic apparatus.

[0056] As electrons move through each undulator module, they interact with the electric field of the radiation, exchanging energy with the radiation. In general the amount of energy exchanged between the electrons and the radiation will oscillate rapidly unless conditions are

close to a resonance condition. Under resonance conditions, the interaction between the electrons and the radiation causes the electrons to bunch together into microbunches, modulated at the wavelength of radiation within the undulator, and coherent emission of radiation along the central axis is stimulated. The resonance condition may be given by:

$$\lambda_{em} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{A} \right), \quad (1)$$

5 where λ_{em} is the wavelength of the radiation, λ_u is the undulator period for the undulator module that the electrons are propagating through, γ is the Lorentz factor of the electrons and K is the undulator parameter. A is dependent upon the geometry of the undulator 24: for a helical undulator that produces circularly polarized radiation $A=1$, for a planar undulator $A=2$, and for a helical undulator which produces elliptically polarized radiation (that is neither circularly
10 polarized nor linearly polarized) $1 < A < 2$. In practice, each bunch of electrons will have a spread of energies although this spread may be minimized as far as possible (by producing an electron beam E with low emittance). The undulator parameter K is typically approximately 1 and is given by:

$$K = \frac{q\lambda_u B_0}{2\pi mc}, \quad (2)$$

15 where q and m are, respectively, the electric charge and mass of the electrons, B_0 is the amplitude of the periodic magnetic field, and c is the speed of light.

[0057] The resonant wavelength λ_{em} is equal to the first harmonic wavelength spontaneously radiated by electrons moving through each undulator module. The free electron laser FEL may operate in self-amplified spontaneous emission (SASE) mode. Operation in SASE mode may require a low energy spread of the electron bunches in the electron beam E before it enters each
20 undulator module. Alternatively, the free electron laser FEL may comprise a seed radiation source, which may be amplified by stimulated emission within the undulator 24. The free electron laser FEL may operate as a recirculating amplifier free electron laser (RAFEL), wherein a portion of the radiation generated by the free electron laser FEL is used to seed further generation of radiation.

25 [0058] The electron beam E which exits the undulator 24 is steered by magnets (not shown) back into the linear accelerator 22. The electron beam E enters the linear accelerator 22 with a phase difference of 180 degrees relative to the electron beam produced by the electron injector

21a,b. The RF fields in the linear accelerator therefore serve to decelerate the electrons which are output from the undulator 24 and to accelerate electrons output from the electron injector 21a,b. As the electrons decelerate in the linear accelerator 22 some of their energy is transferred to the RF fields in the linear accelerator 22. Energy from the decelerating electrons is therefore recovered by the linear accelerator 22 and is used to accelerate the electron beam E output from the electron injector 21. Such an arrangement is known as an energy recovery linear accelerator (ERL).

[0059] After deceleration by the linear accelerator 22, the electron beam E_R is absorbed by a beam dump 100. Radioisotope production apparatus RI_c , which comprises components 30c, 40c, is described further below. The beam dump 100 may comprise a sufficient quantity of material to absorb the electron beam E_R . The material may have a threshold energy for induction of radioactivity. Electrons entering the beam dump 100 with an energy below the threshold energy may produce only gamma ray showers but will not induce any significant level of radioactivity. The material may have a high threshold energy for induction of radioactivity by electron impact. For example, the beam dump 100 may comprise aluminium (Al), which has a threshold energy of around 17 MeV. The energy of electrons of the electron beam E after leaving the linear accelerator 22 may be less than 17 MeV (it may for example be around 10 MeV), and thus may be below the threshold energy of the beam dump 100. This removes, or at least reduces, the need to remove and dispose of radioactive waste from the beam dump 100.

[0060] In addition to comprising a free electron laser FEL and lithographic apparatus LA_{1-n} , the system depicted in Figure 1 further comprises radioisotope production apparatus RI_{a-c} . Three radioisotope production apparatus RI_{a-c} are depicted, each of which has the same general configuration. The first radioisotope production apparatus RI_a comprises a linear accelerator 30a which is configured to accelerate electrons provided by the electron injector 21a. The linear accelerator 30a may, for example, accelerate electrons to an energy of around 14 MeV or more. The linear accelerator may accelerate electrons to an energy of around 30 MeV or more (e.g. up to around 45 MeV). It may be beneficial not to accelerate the electrons to an energy greater than around 45 MeV because at such energies large quantities of unwanted products other than the desired radioisotope may be generated. In an embodiment, the linear accelerator 30a may accelerate electrons to an energy of around 35 MeV.

[0061] The radioisotope production apparatus RI_a further comprises a target 40a which is configured to receive the electrons and to use the electrons to convert a source material into a radioisotope. An example of a target 40a-c is depicted schematically in Figure 2 (the target has the same construction for each of the radioisotope production apparatus RI_{a-c}). In Figure 2 the
5 electron beam E is incident upon an electron target 42a-c. The electron target 42a-c may, for example, be formed from tungsten, tantalum or some other material which will decelerate the electrons and generate photons. The electron target is held by a support structure 43a-c. The electron target may be formed from the same material as a photon target (e.g. Mo-100). The mechanism via which the photons are generated is Bremsstrahlung radiation (in English: braking
10 radiation). The energy of the photons generated in this manner may, for example, be greater than 100 keV, may be greater than 1 MeV, and may be greater than 10 MeV. The photons may be described as very hard X-rays.

[0062] In an embodiment, the photon target is Mo-100 which is to be converted into Mo-99 via photon induced neutron emission. This reaction has a threshold energy of 8.29 MeV, and
15 thus will not occur if photons incident upon the photon target have an energy less than 8.29 MeV. The reaction has a cross-section which peaks at around 14 MeV (the reaction cross-section is indicative of the chances of the reaction being induced by a photon with a given energy). In other words, the reaction has a resonance peak at around 14 MeV. Therefore, in an embodiment photons with an energy of around 14 MeV or more may be used to convert a Mo-
20 100 photon target into Mo-99.

[0063] The energy of the photons generated by the photon target has an upper limit which is set by the energy of the electrons in the electron beam. The photons will have a distribution of energies, but the upper limit of that distribution will not extend beyond the energy of the electrons in the electron beam. Thus, in an embodiment used to convert a Mo-100 photon target
25 into Mo-99 the electron beam will have an energy of at least 8.29 MeV. In an embodiment the electron beam may have an energy of around 14 MeV or more.

[0064] As the energy of the electron beam is increased more photons with energies sufficient to cause the desired reaction will be generated (for the same current of electrons). For example, as noted above Mo-99 generation has a cross-section which peaks at around 14 MeV. If the
30 electron beam has an energy of around 28 MeV then each electron may generate two photons with an energy of around 14 MeV, thereby increasing conversion of the photon target to Mo-99.

However, as the energy of the electron beam is increased photons with higher energies will induce other unwanted reactions. For example, photon induced emission of a neutron and a proton has a threshold energy of 18 MeV. This reaction is not desired because it does not generate Mo-99 but instead generates an unwanted reaction product.

5 [0065] In general, the selection of the energy of the electron beam (and hence the maximum energy of the photons) may be based on a comparison between the yield of wanted products (e.g. Mo-99) and the yield of unwanted products. In an embodiment, the electron beam may have an energy of around 14 MeV or more. The electron beam may for example have an energy of around 30 MeV or more (e.g. up to around 45 MeV). This range of electron beam energies may
10 provide good productivity of photons with energies around the reaction resonance peak of 14 MeV. The electron beam may for example have an energy of around 35 MeV.

[0066] The photons are emitted from the electron target 42a-c and are incident upon a photon target 44a-c which is held by a support structure 45a-c. The photons are schematically depicted by wavy lines γ in Figure 2. The photon target 44a-c comprises a plurality of plates which
15 comprise Mo-100 (Mo-100 is a stable and naturally occurring isotope of Mo). When a photon γ is incident upon an Mo-100 nucleus it causes a photonuclear reaction via which a neutron is ejected from the nucleus. The Mo-100 atom is thereby converted to an Mo-99 atom.

[0067] The photon target 44a-c receives photons γ for a period of time, during which the proportion of Mo-99 in the photon target increases and the proportion of Mo-100 in the photon
20 target decreases. The photon target 44a-c is then removed from the radioisotope production apparatus RI_a for processing and transportation to a radiopharmacy. Tc-99, which is the decay product of Mo-99, is extracted and used in medical diagnostic applications.

[0068] Although the photon target 44a-c shown in Figure 2 comprises three plates, the photon target may comprise any suitable number of plates. Although the described photon target
25 comprises Mo-100, the photon target may comprise any suitable material. Similarly, the material of the photon target may be provided in any suitable shape and/or configuration. Shielding may be provided around electron target 42a-c and the photon target 44a-c (e.g. lead shielding).

[0069] Although the electron target 42a-c is depicted as a single block of material, it may be provided as a plurality of plates. The plates may for example have a construction which
30 corresponds with the photon target plates 44a-c described above. Similarly, the support structure 43a-c may be configured to hold a plurality of electron target plates.

[0070] The electron target 42a-c and the photon target 44a-c may be provided in conduits through which coolant liquid is flowed, as described further below.

[0071] Referring again to Figure 1, production of a radioisotope using the first radioisotope production apparatus RI_a is performed when the electron beam E_I generated by the first electron injector 21a is not being used by the free electron laser FEL to generate an EUV radiation beam B_{FEL} . A kicker 31 directs the electron beam E_I towards the first radioisotope production apparatus RI_a . The second electron injector 21b is operable to provide an electron beam E to the free electron laser FEL during this time. A kicker 32 provided after the second electron injector 21b does not direct the electron beam E towards the second radioisotope production apparatus, but instead allows the electron beam to travel to the linear accelerator 22. The two electron injectors 21a,b are operating simultaneously, the first electron injector 21a providing an electron beam which is used to generate radioisotopes and the second electron injector 21b providing an electron beam which is used by the free electron laser FEL to generate an EUV radiation beam B_{FEL} .

[0072] The second radioisotope production apparatus RI_b has the same configuration as the first radioisotope production apparatus RI_a and thus comprises a linear accelerator 30b and a target 40b. When the second electron injector 21b is providing an electron beam used by the radioisotope production apparatus RI_b to generate radioisotopes, the first electron injector 21a provides an electron beam used by the free electron laser FEL to generate an EUV radiation beam B_{FEL} . The paths travelled by electron beams E are thus opposite to those depicted in Figure 1. Switching of the electron beam paths is achieved by switching the configurations of the kickers 31, 32. The first kicker 31 no longer directs the electron beam generated by the first electron injector 21a to the first radioisotope production apparatus RI_a but instead allows the electron beam to travel to the linear accelerator 22 of the free electron laser. The second kicker 32 directs the electron beam generated by the second electron injector 21b to the second radioisotope production apparatus RI_b .

[0073] The third radioisotope production apparatus RI_c is located after the linear accelerator 22. The linear accelerator 22 is an energy recovery linear accelerator, and provides an electron beam E_R from which energy has been recovered. This electron beam E_R has an energy which substantially corresponds to the energy of the electron beam E provided from an electron injector 21a,b before it is accelerated by the linear accelerator 22. The energy of the electron beam as

output from the electron injector 21a,b and following energy recovery in the linear accelerator 22 may, for example, be around 10 MeV.

[0074] In common with the previously described radioisotope production apparatus, the third radioisotope production apparatus RI_c comprises a linear accelerator 30c which is configured to increase the energy of the electrons in the electron beam. The linear accelerator 30c may, for example, accelerate electrons to an energy of 15 MeV or more. The linear accelerator 30c may accelerate electrons to an energy of 30 MeV or more (e.g. up to around 45 MeV). In an embodiment, the linear accelerator 30c may accelerate electrons to an energy of around 35 MeV. The radioisotope production apparatus further comprises a target 40c. The target 40c corresponds with that described above in connection with Figure 2, and comprises an electron target 42a-c and a photon target 44a-c (see Figure 2).

[0075] When radioisotope production is not required using the third radioisotope production apparatus RI_c, the electron beam E_R is directed to the beam dump 100 instead of being directed to the third radioisotope production apparatus. In Figure 1 the electron beam is directed to the beam dump 100 (as indicated by a solid line), and is not directed to the third radioisotope production apparatus RI_c (as indicated by a dashed line). However, the electron beam E_R may be directed by a kicker 33 towards the third radioisotope production apparatus RI_c. In an embodiment, the third radioisotope production apparatus RI_c may be operative to produce radio isotopes at the same time as the first (or second) radioisotope production apparatus RI_a, RI_b.

[0076] A merger (not shown) may be used to combine the electron beam provided by the electron injector 21a,b with the recirculating electron beam E. A demerger (not shown) may be used to separate the electron beam E_R from which energy has been recovered and the electron beam E which has been accelerated by the linear accelerator 22.

[0077] Although Figure 1 shows radioisotope production apparatus RI_{a-c} located both before and after the linear accelerator 22 of the free electron laser FEL, in other embodiments the radioisotope production apparatus may be provided in only one of those locations (i.e. provided only before the linear accelerator or provided only after the linear accelerator).

[0078] Although the embodiment illustrated in Figure 1 is an energy recovery linear accelerator, the radioisotope production apparatus may be provided as part of a system which comprises a free electron laser FEL with an accelerator which is not an energy recovery linear accelerator. For example, radioisotope production apparatus may be provided after one or more

electron injectors of a free electron laser which comprises a linear accelerator that is not an energy recovery linear accelerator.

[0079] Although only a single linear accelerator 22 is depicted in Figure 1, the free electron laser FEL may comprise two or more linear accelerators. For example, a linear accelerator may be provided at the position at which the undulator 24 is depicted in Figure 1. Where this is the case, the electron beam may pass through the linear accelerators a plurality of times such that the electron beam is accelerated by each linear accelerator two or more times. In such an arrangement, a beam de-merger may be used to separate the accelerated electron beam such that it passes through an undulator to generate an EUV radiation beam. A beam merger may then be used to direct the electron beam from the undulator back into the linear accelerators for subsequent deceleration.

[0080] Figure 3 schematically depicts an arrangement of electron injectors and radioisotope production apparatuses according to an embodiment of the invention. In Figure 3 four electron injectors 121a-d are shown and three radioisotope production apparatus RI_{d-f} are shown. Each electron injector 121a-d comprises an electron source 122a-d and a booster 123a-d which provides an accelerating electric field. Each electron source may, for example, comprise a photo-cathode which is illuminated by a pulsed laser beam generated by a laser (not shown). The accelerating electric field provided by each booster 123a-d may, for example, accelerate electrons provided by an electron source 122a-d to an energy of around 10 MeV (or some other relativistic energy).

[0081] Each radioisotope production apparatus RI_{d-f} comprises a linear accelerator 130a-c. Each linear accelerator is depicted as three modules, but may comprise any suitable number of modules (including, for example, a single module). Each linear accelerator 130a-c may accelerate electrons in the electron beam to an energy of 15 MeV or more. Each linear accelerator 130a-c may accelerate electrons to energy of 30 MeV or more (e.g. up to around 45 MeV). In an embodiment, each linear accelerator 130a-c may accelerate electrons to an energy of around 35 MeV.

[0082] Each radioisotope production apparatus RI_{d-f} further comprises a target 140a-c. The targets may correspond with the targets shown in Figure 2. The targets 140a-c receive electrons which have been accelerated by the linear accelerators 130a-c and convert a source material into a radioisotope.

[0083] A linear accelerator 122 which forms part of a free electron laser FEL is also depicted in Figure 3. The linear accelerator 122 receives an electron beam generated by one of the electron injectors 121a-d and accelerates it for EUV generation using an undulator (not shown) in the manner described further above in connection with Figure 1.

5 [0084] As will be appreciated from Figure 3, since there are four electron injectors 121a-d and only three radioisotope production apparatus RI_{d-f} , all of the radioisotope production apparatus may be operative to produce radioisotopes at the same time as an EUV radiation beam is being generated by the free electron laser. Kickers (not depicted) may be used to switch
10 electron beams between radioisotope production apparatus RI_{d-f} and the linear accelerator 122 of the free electron laser. The electron beam paths are arranged such that each radioisotope production apparatus RI_{d-f} can receive an electron beam from two different electron injectors 121a-d. For example, a first radioisotope production apparatus RI_d may receive an electron beam from a first electron injector 121a or from a second electron injector 121b. Thus, for example, the first electron injector 121a may be used to provide an electron beam to the linear accelerator
15 122 whilst the second electron injector 121b is used to provide an electron beam to the first radioisotope production apparatus RI_d . Alternatively, the first electron injector 121a may be used to provide an electron beam to the first radioisotope production apparatus RI_d whilst the second electron injector 121b is used to provide an electron beam to linear accelerator 122. Various combinations of electron beam paths are possible, as will be understood from
20 consideration of Figure 3.

[0085] In an embodiment, a system comprising a free electron laser and a radioisotope production apparatus may be configured to provide an electron beam with a current of 10 mA or more. The current provided by the system may, for example, be 20 mA or more or may be 30 mA or more. The current may, for example, be up to 100 mA or more. An electron beam with a
25 high current (e.g. 10 mA or more) is advantageous because it increases the specific activity of the radioisotope produced by the radioisotope production apparatus.

[0086] As explained further above, Mo-100 may be converted to Mo-99 (a desired radioisotope) using very hard X-ray photons generated by an electron beam hitting an electron target. The half life of Mo-99 is 66 hours. As a consequence of this half-life there is a limit to
30 the specific activity of Mo-99 which can be provided when starting with Mo-100, the limit being determined by the rate at which Mo-99 is generated. If the Mo-99 is generated at a relatively

low rate, for example using an electron beam current of around 1-3mA, then it may not be possible to provide a specific activity of more than around 40 Ci/g of Mo-99 in the target. This is because although the irradiation time may be increased in order to allow generation of more Mo-99 atoms, a significant proportion of those atoms will decay during the irradiation time. The threshold of specific activity of Mo-99 used in medical applications in Europe should be 100 Ci/g, and thus Mo-99 with a specific activity of 40 Ci/g or less is not useful.

[0087] When a higher electron beam current is used the rate at which Mo-99 atoms are generated is increased accordingly (assuming that the volume of Mo-99 which receives photons remains the same). Thus, for example, for a given volume of Mo-99, an electron beam current of 10 mA will generate Mo-99 at 10 times the rate of generation provided by an electron beam current of 1mA. The electron beam current used by embodiments of the invention may be sufficiently high that a specific activity of Mo-99 in excess of 100 Ci/g is achieved. For example, an embodiment of the invention may provide an electron beam with a beam current of around 30 mA. Simulations indicate that, for a beam current of around 30 mA, if the electron beam has an energy of around 35 MeV and the volume of the Mo-100 target is around 5000mm³ then a specific activity of Mo-99 in excess of 100 Ci/g can be obtained. The Mo-100 target may for example comprise 20 plates with a diameter of around 25mm and a thickness of around 0.5mm. Other numbers of plates, which may have non-circular shapes and may have other thicknesses, may be used.

[0088] As noted further above, an electron injector of an embodiment of the invention may be a photo-cathode which is illuminated by a pulsed laser beam. The laser may, for example, comprise a Nd:YAG laser together with associated optical amplifiers. The laser may be configured to generate picosecond laser pulses. The current of the electron beam may be adjusted by adjusting the power of the pulsed laser beam. For example, increasing the power of the pulsed laser beam will increase the number of electrons emitted from the photo-cathode and thereby increase the electron beam current.

[0089] The electron beam received by a radioisotope production apparatus according to an embodiment of the invention may, for example, have a diameter of 1mm and a divergence of 1mrad. Increasing the current in the electron beam will tend to cause the electrons to spread out due to space charge effects, and thus may increase the diameter of the electron beam. Increasing the current of the electron beam may therefore reduce the brightness of the electron beam.

However, the radioisotope production apparatus does not require an electron beam with, for example, a diameter of 1mm and may utilize an electron beam with a greater diameter. Thus, increasing the current of the electron beam may not reduce the brightness of the beam to such an extent that radioisotope production is significantly negatively affected. Indeed, as is explained
5 further below, providing the electron beam with a diameter greater than 1mm may be advantageous because it spreads the thermal load delivered by the electron beam.

[0090] Figure 4 shows schematically a target 240 of a radioisotope production apparatus according to an embodiment of the invention. The target 240 comprises a photon target 242 and an electron target 244. The photon target comprises four plates 251 held by a support structure
10 (not shown). Although four plates are shown any number of plates may be provided. The plates 251 may for example be disks. The plates may have any suitable shape. The plates 251 may be formed from tungsten, tantalum or some other material which will decelerate electrons and generate photons. The plates 251 are located in a conduit 252 which is connected to a source of coolant fluid (not shown). During operation of the radioisotope production apparatus the
15 electron beam will deliver a substantial amount of heat to the plates 251. Coolant fluid flowing through the conduit 252 removes some of this heat from the plates 251 and carries it away. The coolant fluid may be water or some other suitable liquid, or may be a gas such as helium.

[0091] In an alternative arrangement Lead-Bismuth Eutectic (LBE) may be used as both the electron target and a coolant liquid. LBE provides an advantage in that it has a higher boiling
20 point than other coolant liquids (e.g. water). Other suitable liquids may be used as both the electron target and a coolant liquid.

[0092] The photon target shown in Figure 4 comprises twenty plates 253 formed from a material which will be converted into a radioisotope when very hard X-rays are incident upon it. The material may, for example, be Mo-100. Although twenty plates are shown any number of
25 plates may be provided. The plates 253 may for example be disks. The plates may have any suitable shape. The plates 253 are held by a support structure which comprises a pair of supports 257. The plates 253 are located in a conduit 254 which is configured to transport coolant liquid. The conduit 254 extends in a direction which is transverse to the plane of the Figure. Photons which are incident upon the plates 253 will deliver a substantial amount of heat to the plates.
30 Some of this heat is transferred to the coolant liquid flowing through the conduit 254, and the

coolant liquid carries the heat away from the plates 253. The coolant liquid may be water or may be some other suitable fluid.

[0093] The photon target plates 253 are held by a support structure which comprises a pair of supports 257 provided with recesses. The plates 253 are inserted into the recesses and are thereby held in place by the supports 257. The supports 257 are configured such that they do not prevent flow of cooling liquid through the conduit 254 (the supports mainly extend in the direction of coolant fluid flow rather than across the direction of coolant fluid flow). Any suitable support structure may be used to support the photon target plates 253. Although not illustrated, a support structure is also used to support the electron target plates 251. The support structure may have a configuration which corresponds with the photon plate support structure, or may have any other suitable form.

[0094] Figure 5 schematically depicts a Rankine cycle waste heat recovery system which may form part of a radioisotope production apparatus according to an embodiment of the invention. The waste heat recovery system comprises a closed loop around which a fluid circulates (the direction of fluid circulation is indicated by arrows). The closed loop is provided with a heater 260, an expansion turbine 261, a condenser 262 and a pump 263. The expansion turbine 261 is connected to an electricity generator 264, and drives the electricity generator when it rotates.

[0095] The heater 260 receives heat from the electron target 242 and/or the photon target 244. In an embodiment the coolant liquid of the closed loop is heated by flowing through either or both of the conduits 252, 254 depicted in Figure 4. The resultant heated fluid passes to the expansion turbine 261 and flows through the expansion turbine thereby causing it to rotate. The expansion turbine 261 drives the electricity generator 264 to rotate, thereby generating electricity. Since the heated fluid performs work by driving the expansion turbine 261 and electricity generator 264, energy is thereby removed from the fluid. The fluid is then condensed by the condenser 262. The resulting liquid is pumped by the pump 263 into the heater 260. The waste heat recovery cycle is then repeated.

[0096] In the above described embodiment the liquid which cools the electron target and photon target is the working fluid of the waste heat recovery system. In any alternative arrangement the liquid which is used to cool the electron target and the photon target may be kept separate from working fluid of the waste heat recovery system. Where this is the case a

heat exchanger may be used to transfer heat from the liquid used to cool the electron target and the working fluid of the waste heat recovery system. An advantage of having two separated fluids is that this avoids the possibility of material from the electron target or photon target entering the expansion turbine 261 or other parts of the waste heat recovery system. A further
5 advantage is that a fluid may be used in the waste heat recovery system which has different properties from the fluid used to cool the electron target and photon target. For example, the waste heat recovery system may use an organic working fluid such as HFCs (e.g. R134a or R245fa), which might not be suitable as cooling liquids for the electron target 242 or photon target 244.

10 [0097] Although the waste heat recovery system shown in Figure 5 is a Rankine cycle system, any suitable waste heat recovery system may be used. For example, a Stirling engine or a Brayton cycle system may be used.

[0098] In an embodiment the electron beam E incident upon the electron target comprises electrons with an energy of around 35 MeV and the electron beam current is between 30 and 100
15 mA. Thus, a power of between around 1 MW and around 3.5 MW may be delivered to the electron target and photon target. A significant proportion of this power may be converted into electricity using an embodiment of the invention. The electricity may be used as a component of the power which is used to generate and accelerate the electron beam.

[0099] As noted above, the electron beam may deliver a substantial amount of power to the
20 electron target (e.g. up to around 3.5 MW). The electron beam may, for example, have a diameter of around 1 mm. In order to avoid possible damage to the electron target, the radioisotope production apparatus may comprise an electron beam distribution apparatus configured to control the surface area of the electron target upon which the electron beam is incident.

25 [00100] An embodiment of an electron beam distribution apparatus is depicted schematically in Figure 6. In this embodiment a lens 300 is used to defocus the electron beam E and thereby increase its diameter. The diameter of the electron beam E may, for example, be increased by a factor of 10 or more. The diameter of the electron beam may, for example, be increased to a few centimeters (e.g. up to around 10 cm). The diameter of the electron beam may be increased to a
30 size which generally corresponds with the size of the electron target plates. Increasing the

diameter of the electron beam E is advantageous because it increases the area of the electron target plates to which the thermal load is applied.

[00101] In Figure 6 a second lens 301 is used to collimate the electron beam E following the defocusing caused by the first lens 300. Collimation of the electron beam E is useful because a diverging electron beam would increase the divergence of photons generated by the electron target. This would in turn require larger photon targets in order to collect the photons, which would reduce the specific activity of Mo-99 (or other radioisotope) generated at the photon targets.

[00102] The lenses 300, 301 may, for example, be formed from magnets. The lenses may, for example, be quadrupole lenses.

[00103] Figure 7 shows another embodiment of an electron beam distribution apparatus. This embodiment comprises a kicker 305 which is configured to move the electron beam E across the surface of the electron beam target (not shown). The kicker may, for example, be configured to move the electron beam over the surface of the electron beam target in a scanning motion. This may be achieved by applying a continuously varying voltage to plates of the kicker.

[00104] Figure 8 depicts another embodiment of an electron beam distribution apparatus. In this embodiment a kicker 306 moves the electron beam E such that it is directed towards one of three targets 340a-c. Each target comprises an electron target and a photon target (e.g. as described further above). The kicker 306 is configured to periodically switch the direction of the electron beam E between the three targets 340a-c. This may be achieved by periodically switching between three different voltages applied to the kicker 306. Switching the electron beam E between three different targets 340a-c is advantageous because it distributes the thermal load of the electron beam between those three targets.

[00105] The embodiment depicted in Figure 6 may be used in combination with the embodiments depicted in Figures 7 and 8. That is, the cross-sectional area of the electron beam E may be increased before distribution using a kicker.

[00106] Although embodiments of the invention have been described in connection with generation of the radioisotope Mo-99, embodiments of the invention may be used to generate other radioisotopes. In general, embodiments of the invention may be used to generate any radioisotope which may be formed via direction of very hard X-rays onto a source material.

[00107] An advantage of the invention is that it provides production of radioisotopes without requiring the use of a high flux nuclear reactor. A further advantage is that it does not require the use of highly enriched uranium (a dangerous material which is subject to non-proliferation rules).

[00108] Providing the radioisotope production apparatus as part of a system which also
5 comprises a free electron laser is advantageous because it utilizes apparatus already required by the free electron laser. That is, the radioisotope production uses apparatus which is, in part, already provided. Similarly, the radioisotope production apparatus may be located in an underground space (which may be referred to as a bunker) which includes shielding that contains radiation and prevents it from spreading to the environment. The underground space and at least
10 some of the shielding may already be provided as part of the free electron laser, and thus the expense of providing an entirely separate underground space and associated shielding for the radioisotope production apparatus is avoided.

[00109] In an embodiment, a system may comprise a free electron laser and a radioisotope production apparatus which are capable of operating independently of each other. For example,
15 the free electron laser may be capable of operating without the radioisotope production apparatus operating, and the radioisotope production apparatus may be capable of operating without the free electron laser operating. The free electron laser and radioisotope production apparatus may be provided in a common bunker.

[00110] Whilst embodiments of a radiation source SO have been described and depicted as
20 comprising a free electron laser FEL, it should be appreciated that a radiation source may comprise any number of free electron lasers FEL. For example, a radiation source may comprise more than one free electron laser FEL. For example, two free electron lasers may be arranged to provide EUV radiation to a plurality of lithographic apparatus. This is to allow for some redundancy. This may allow one free electron laser to be used when the other free electron laser
25 is being repaired or undergoing maintenance.

[00111] Although embodiments of the invention have been described as using Mo-100 to generate Mo-99 radioisotope which decays to Tc-99, other medically useful radioisotopes may be generated using embodiments of the invention. For example, embodiments of the invention may be used to generate Ge-68, which decays to Ga-68. Embodiments of the invention may be
30 used to generate W-188, which decays to Re-188. Embodiments of the invention may be used to generate Ac-225, which decays to Bi-213.

[00112] Although the described embodiment of a lithographic system LS comprises eight lithographic apparatuses LA₁-LA_n, a lithographic system LS may comprise any number of lithographic apparatus. The number of lithographic apparatus which form a lithographic system LS may, for example, depend on the amount of radiation which is output from a radiation source
5 SO and on the amount of radiation which is lost in a beam delivery system BDS. The number of lithographic apparatus which form a lithographic system LS may additionally or alternatively depend on the layout of a lithographic system LS and/or the layout of a plurality of lithographic systems LS.

[00113] Embodiments of a lithographic system LS may also include one or more mask inspection apparatus MIA and/or one or more Aerial Inspection Measurement Systems (AIMS). In some embodiments, the lithographic system LS may comprise a plurality of mask inspection apparatuses to allow for some redundancy. This may allow one mask inspection apparatus to be used when another mask inspection apparatus is being repaired or undergoing maintenance. Thus, one mask inspection apparatus is always available for use. A mask inspection apparatus
10 may use a lower power radiation beam than a lithographic apparatus. Further, it will be appreciated that radiation generated using a free electron laser FEL of the type described herein may be used for applications other than lithography or lithography related applications.

[00114] It will be further appreciated that a free electron laser comprising an undulator as described above may be used as a radiation source for a number of uses, including, but not
20 limited to, lithography.

[00115] The term “relativistic electrons” should be interpreted to mean electrons which have relativistic energies. An electron may be considered to have a relativistic energy when its kinetic energy is comparable to or greater than its rest mass energy (511 keV in natural units). In practice a particle accelerator which forms part of a free electron laser may accelerate electrons
25 to energies which are much greater than its rest mass energy. For example a particle accelerator may accelerate electrons to energies of >10 MeV, >100 MeV, >1GeV or more.

[00116] Embodiments of the invention have been described in the context of a free electron laser FEL which outputs an EUV radiation beam. However a free electron laser FEL may be configured to output radiation having any wavelength. Some embodiments of the invention may
30 therefore comprise a free electron which outputs a radiation beam which is not an EUV radiation beam.

[00117] The term “EUV radiation” may be considered to encompass electromagnetic radiation having a wavelength within the range of 4-20 nm, for example within the range of 13-14 nm. EUV radiation may have a wavelength of less than 10 nm, for example within the range of 4-10 nm such as 6.7 nm or 6.8 nm.

5 [00118] The lithographic apparatuses LA_a to LA_n may be used in the manufacture of ICs. Alternatively, the lithographic apparatuses LA_a to LA_n described herein may have other applications. Possible other applications include the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc.

10 [00119] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

[00120] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below.

15

CLAIMS:

1. A system comprising a free electron laser and a radioisotope production apparatus, wherein:

5 the free electron laser comprises an electron injector, an energy recovery linear accelerator and an undulator; and

the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target; wherein

10 the further linear accelerator is positioned to receive an electron beam after it has been accelerated then decelerated by the energy recovery linear accelerator, the further linear accelerator being configured to accelerate electrons of the electron beam to an energy of around 14 MeV or more for subsequent delivery to the electron target.

15 2. The system of claim 1, wherein a kicker is configured to switch the electron beam between the further linear accelerator and a beam dump.

3. A system comprising a free electron laser and a radioisotope production apparatus, wherein:

20 the free electron laser comprises a plurality of electron injectors, a linear accelerator and an undulator; and

the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target; wherein

25 the further linear accelerator is positioned to receive an electron beam from one of the electron injectors when it is not being used to provide an electron beam to the linear accelerator, the further linear accelerator being configured to accelerate electrons of the electron beam to an energy of 14 MeV or more for subsequent delivery to the electron target and the photon target.

30 4. The system of claim 3, wherein a plurality of radioisotope production apparatuses are provided.

5. The system of claim 4, wherein a kicker is located after each electron injector, the kicker being configured to switch the electron beam generated by that electron injector between the linear accelerator of the free electron laser and one of the radioisotope production apparatuses.

5

6. The system of claim 4 or 5, wherein the number of electron injectors is one more than the number of radioisotope production apparatuses.

7. The system of any of claims 3 to 6, wherein the linear accelerator of the free electron
10 laser is an energy recovery linear accelerator.

8. The system of any preceding claim, wherein the further linear accelerator is configured to accelerate electrons of the electron beam to an energy of around 30 MeV or more.

15 9. The system of any preceding claim, further comprising an electron target held by the electron target support structure, the electron target comprising material which will decelerate the electrons and generate photons, and further comprising a photon target held by the photon target support structure, the photon target comprising material which will eject neutrons when the photons are incident upon it and which will thereby form a radioisotope.

20

10. The system of claim 9, wherein the photon target comprises Mo-100.

11. A system comprising a free electron laser and a radioisotope production apparatus, wherein:

25 the free electron laser comprises an electron injector, a linear accelerator and an undulator; and

the radioisotope production apparatus comprises a further linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target; wherein

the electron injector is configured to generate an electron beam with a current of 10 mA or more and the further linear accelerator is configured to accelerate electrons of the electron beam to 14 MeV or more for subsequent delivery to the electron target and the photon target.

5 12. The system of claim 11, wherein the electron injector is configured to generate an electron beam with a current of 30 mA or more.

13. The system of claim 10 or claim 11, wherein the further linear accelerator is configured to accelerate electrons of the electron beam to an energy of around 30 MeV or more.

10

14. A radioisotope production apparatus comprising a linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target; wherein

15 an electron beam distribution apparatus is arranged to receive an electron beam following acceleration by the linear accelerator and before the electron beam is incident upon the electron target, the electron beam distribution apparatus being configured to control the surface area of the electron target upon which the electron beam is incident.

20 15. The electron beam distribution apparatus of claim 14, wherein the electron beam distribution apparatus comprises a lens configured to increase the cross-sectional area of the electron beam.

16. The electron beam distribution apparatus of claim 15, wherein the lens comprises a defocussing quadruple magnet.

25

17. The electron beam distribution apparatus of any of claims 14 to 16, wherein the electron beam distribution apparatus comprises a beam kicker which is configured to scan the electron beam over the surface of the electron target.

18. A radioisotope production apparatus comprising a linear accelerator, a beam kicker, a plurality of electron target support structures configured to hold electron targets and a plurality of associated photon target support structures configured to hold photon targets; wherein

the beam kicker is configured to receive an electron beam following acceleration by the linear accelerator and is configured to direct the electron beam to each of the electron target support structures sequentially.

19. A radioisotope production apparatus comprising a linear accelerator, an electron target support structure configured to hold an electron target and a photon target support structure configured to hold a photon target; wherein

the radioisotope production apparatus further comprises one or more coolant fluid conduits configured to transport a coolant fluid past a photon target and/or an electron target held by the support structures and thereby remove heat from the photon target and/or the electron target, and wherein the radioisotope production apparatus further comprises a waste heat recovery system configured to recover some of the heat removed from the photon target and/or the electron target.

20. The system of claim 19, wherein the waste heat recovery system is configured to generate electricity using the recovered heat.

20

21. The system of claim 19 or claim 20, wherein the waste heat recovery system comprises a closed loop which uses a working fluid.

22. The system of claim 21, wherein the working fluid of the closed loop is different from the coolant fluid used to cool the photon target and/or an electron target, and wherein the system further comprises a heat exchanger configured to transfer heat from the coolant fluid to the working fluid.

25

23. The system of claim 21 or claim 22, wherein the closed loop includes an expansion turbine configured to drive an electricity generator.

30

24. A system comprising the radioisotope production apparatus of any of claims 14 to 24 and further comprising a free electron laser.

25. The system of any preceding claim, wherein the system further comprises a plurality of lithographic apparatuses.

26. A method of radioisotope production comprising:
injecting an electron beam into an energy recovery linear accelerator of a free electron laser;

accelerating then decelerating the electron beam using the energy recovery linear accelerator;

using a further linear accelerator to accelerate the electron beam following deceleration, the electron beam being accelerated to an energy of around 14 MeV or more; and

directing the electron beam onto an electron target to generate photons which are then incident upon a photon target to generate the radioisotope.

27. A method of radioisotope production using an injector of a free electron laser when that injector is not being used to provide electrons to the free electron laser, the method comprising:

generating an electron beam using the injector;

using a linear accelerator to accelerate the electron beam to an energy of around 14 MeV or more; and

directing the electron beam onto an electron target to generate photons which are then incident upon a photon target to generate the radioisotope.

28. The method of claim 27, wherein the injector is one of a plurality of injectors and wherein one of the other injectors simultaneously provides electrons to the free electron laser.

29. The method of claim 27 or claim 28, wherein the electron beam directed to the electron target has a current of 10 mA or more.

30. A method of radioisotope production comprising:

injecting an electron beam into linear accelerator;
accelerating the electron beam using the linear accelerator;
passing the electron beam through an electron beam distribution apparatus; and
directing the electron beam onto an electron target to generate photons which are then

5 incident upon a photon target to generate the radioisotope; wherein

the electron beam distribution apparatus controls the surface area of the electron target upon which the electron beam is incident.

31. A method of radioisotope production comprising:

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injecting an electron beam into linear accelerator;
accelerating the electron beam using the linear accelerator; and

using a beam kicker to sequentially direct the electron beam onto each a plurality of electron targets to generate photons which are then incident upon associated photon targets to generate the radioisotope.

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32. A method of radioisotope production comprising:

injecting an electron beam into linear accelerator;
accelerating the electron beam using the linear accelerator; and

directing the electron beam onto an electron target to generate photons which are then

20 incident upon a photon target to generate the radioisotope; wherein

the method further comprises transporting a coolant fluid past the electron target and/or the photon target to remove heat from the electron target and/or the photon target, and using a waste heat recovery system to recover some of the heat removed from the electron target and/or the photon target.

25

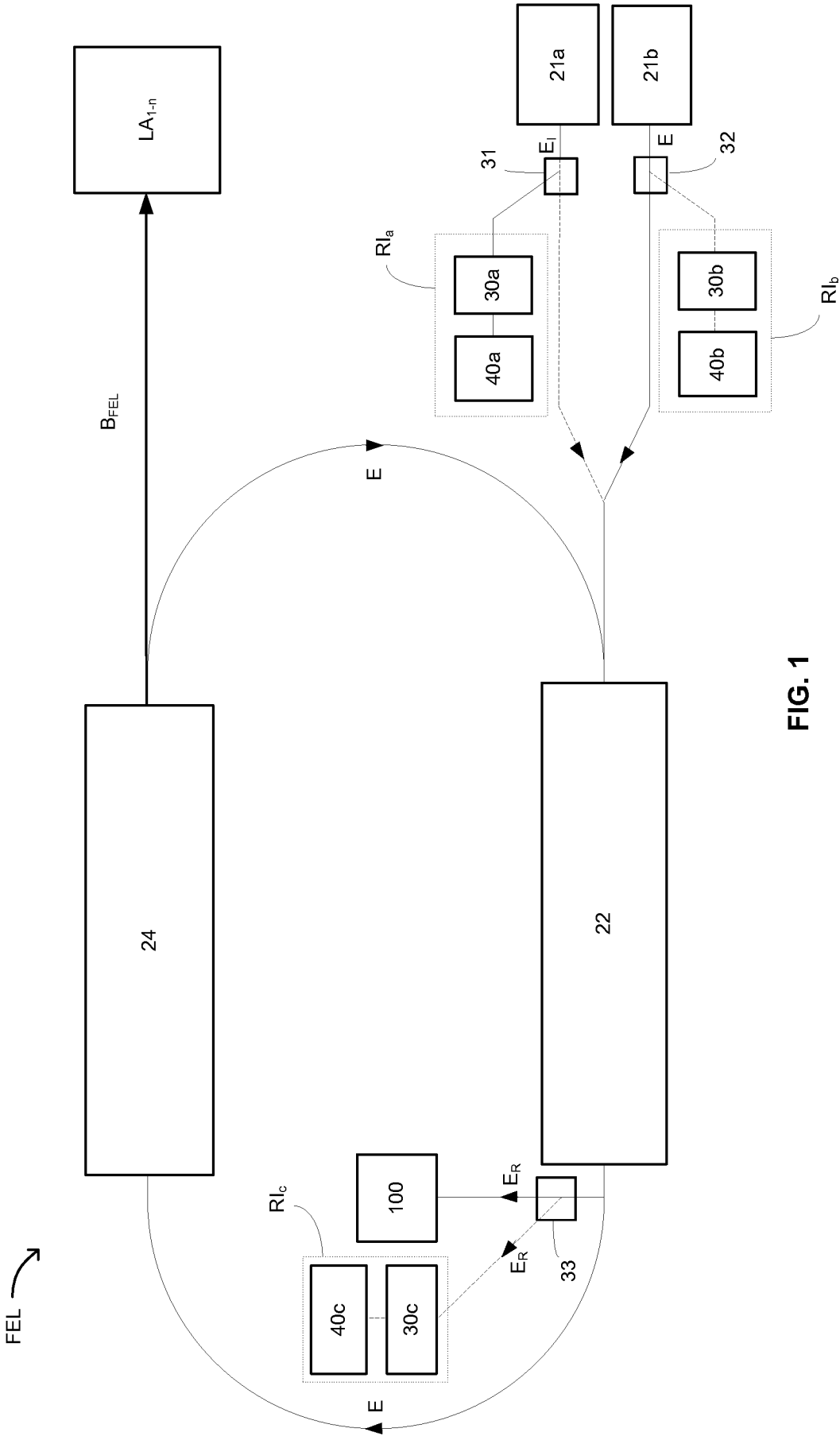


FIG. 1

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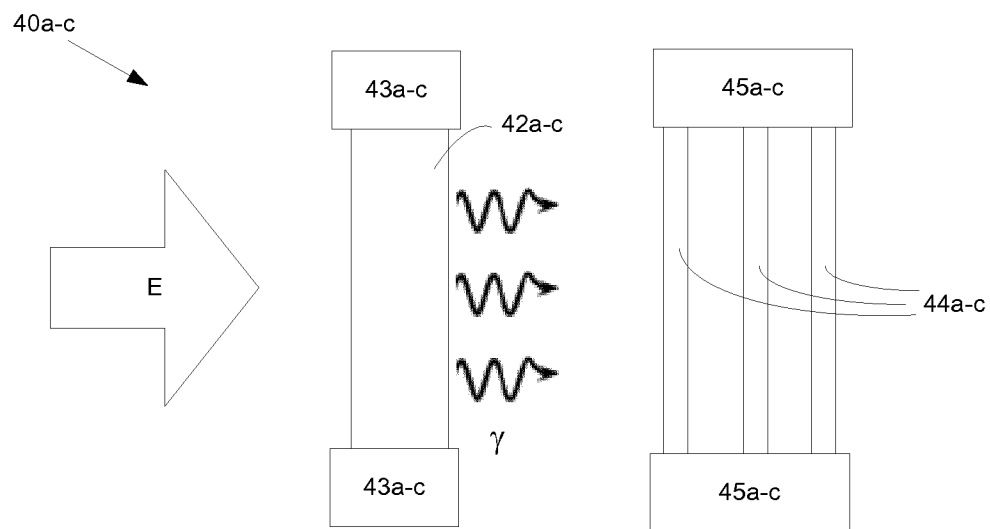


FIG. 2

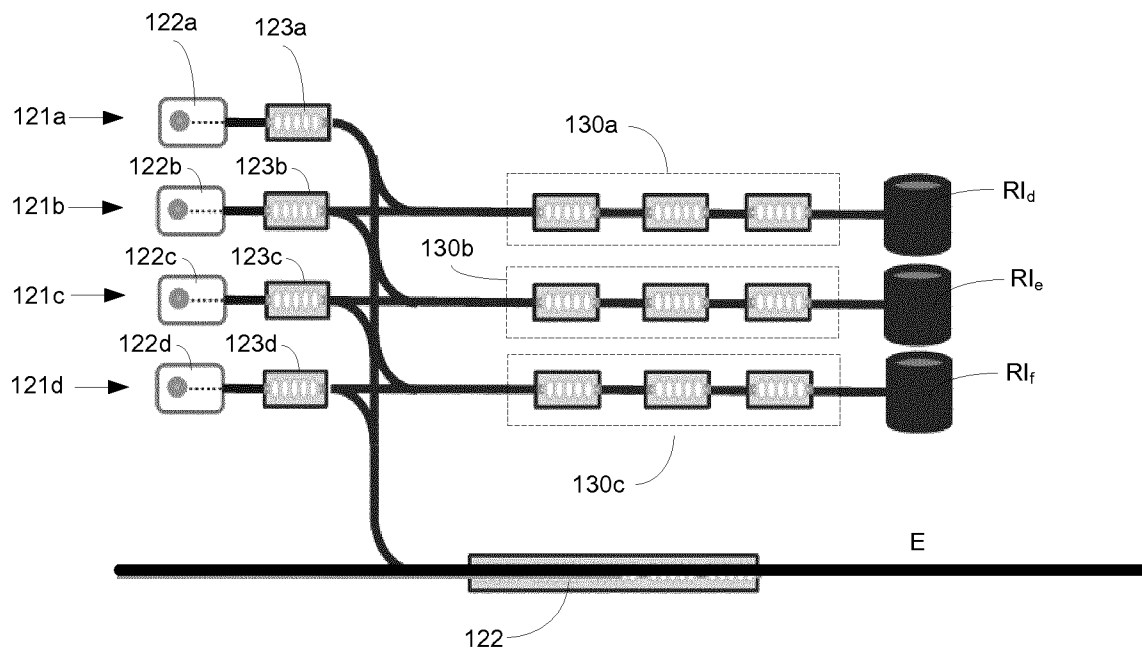


FIG. 3

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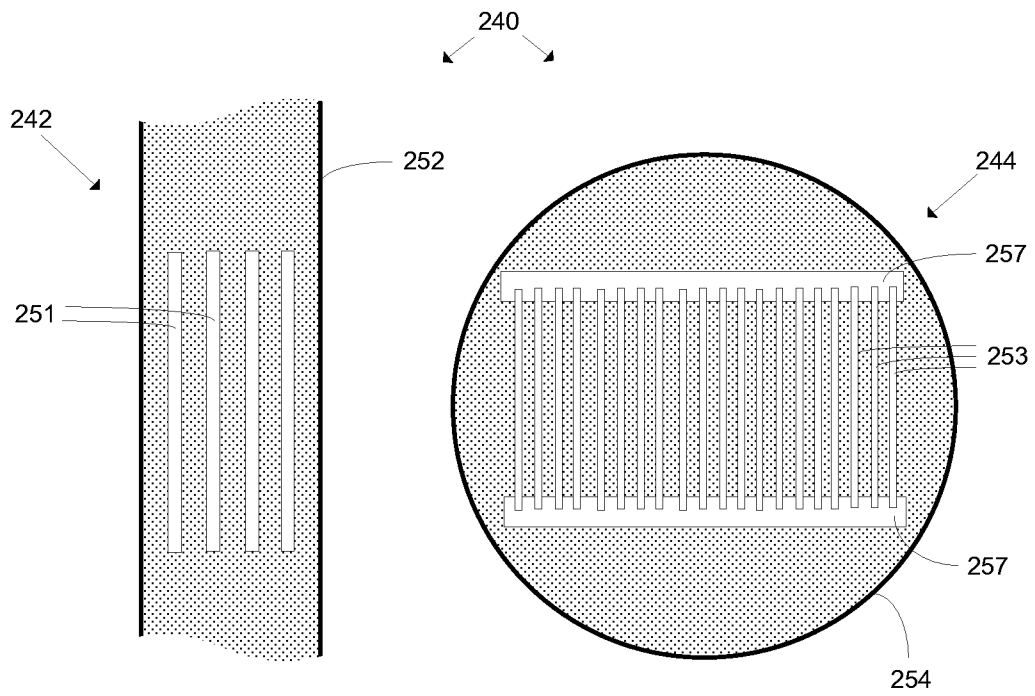


FIG. 4

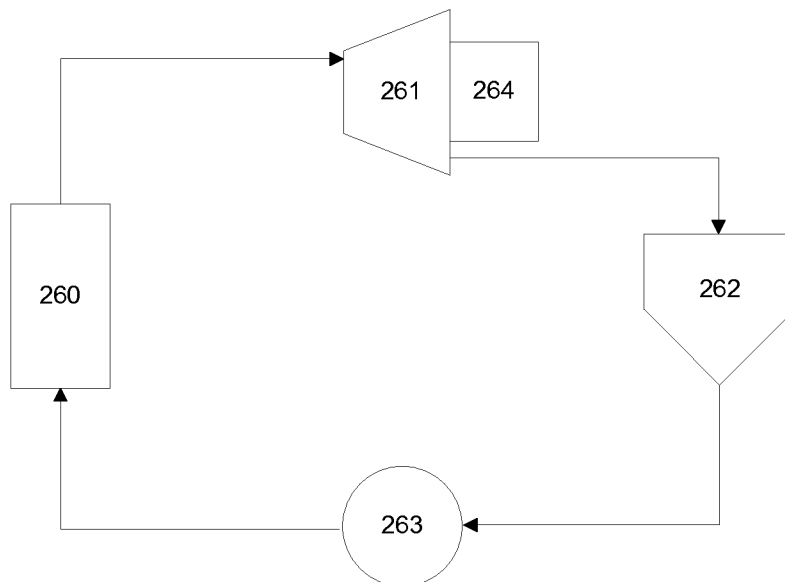


FIG. 5

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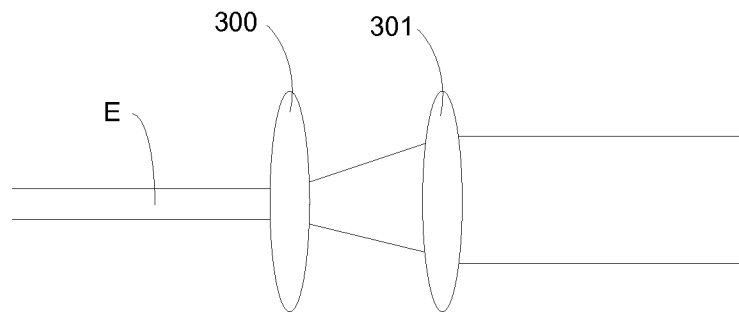


FIG. 6

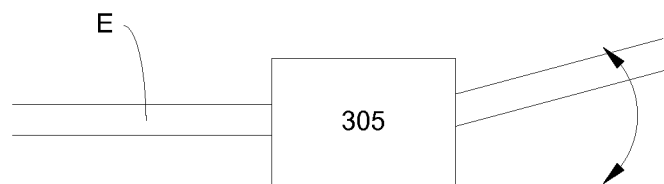


FIG. 7

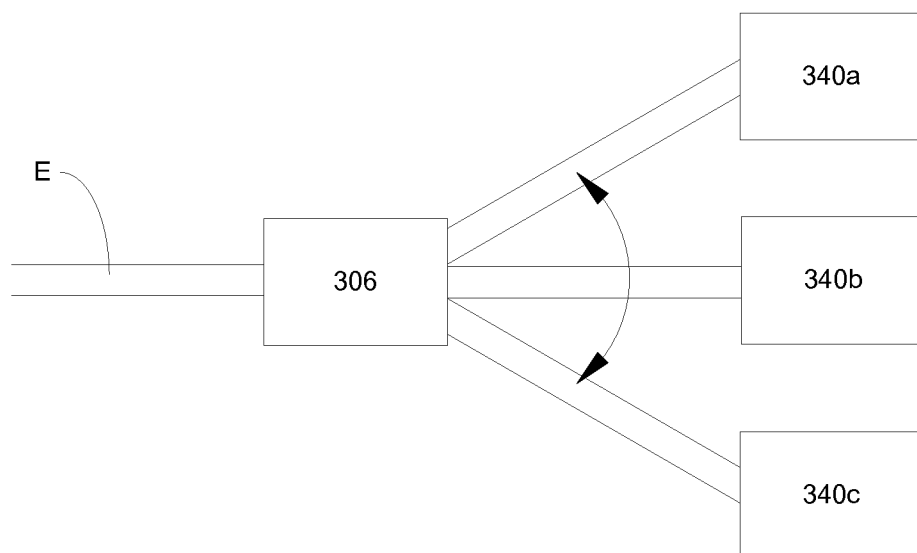


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2016/050885

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of Item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☒ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/050885

A. CLASSIFICATION OF SUBJECT MATTER
INV. G21G1/10
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G21G H01S H05G H05H

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

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

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96/36391 A2 (SHAPIRO STEPHEN [US]; SPENCER JAMES E [US]) 21 November 1996 (1996-11-21) page 4, line 15 - line 25; figures -----	1-13, 25-29
A	US 2013/083880 A1 (NOONAN JOHN [US] ET AL) 4 April 2013 (2013-04-04) abstract; paragraph [0010]; figures -----	1
X	US 2012/025105 A1 (BROWN DAVID A [CA] ET AL) 2 February 2012 (2012-02-02)	14-17
A	claims; figures -----	24,25
Y	US 6 444 990 B1 (MORGAN IRA LON [US] ET AL) 3 September 2002 (2002-09-03) abstract; claims; figures -----	18,31
	-/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

23 June 2016

Date of mailing of the international search report

30/06/2016

Name and mailing address of the ISA/

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Authorized officer

Smith, Christopher

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/050885

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012/281799 A1 (WELLS DOUGLAS P [US] ET AL) 8 November 2012 (2012-11-08) paragraphs [0016], [0023]; figure 1 -----	18,31
A	US 2014/192942 A1 (TSECHANSKI ALEXANDER [IL]) 10 July 2014 (2014-07-10) abstract; figure -----	14-17, 19-24, 30,32
A	WO 2014/186898 A1 (CANADIAN LIGHT SOURCE INC [CA]) 27 November 2014 (2014-11-27) abstract -----	19-25,32
A	US 2013/163707 A1 (HABS DIETRICH [DE] ET AL) 27 June 2013 (2013-06-27) abstract; claims; figures 4a,4b -----	1-32

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/050885

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
WO 9636391	A2	21-11-1996	AU 5717896 A WO 9636391 A2	29-11-1996 21-11-1996
US 2013083880	A1	04-04-2013	NONE	
US 2012025105	A1	02-02-2012	CA 2713972 A1 US 2012025105 A1	27-01-2012 02-02-2012
US 6444990	B1	03-09-2002	AU 2142900 A EP 1131986 A2 TW 449756 B US 6444990 B1 US 2003015666 A1 WO 0028796 A2	29-05-2000 12-09-2001 11-08-2001 03-09-2002 23-01-2003 18-05-2000
US 2012281799	A1	08-11-2012	NONE	
US 2014192942	A1	10-07-2014	EP 2748825 A1 US 2014192942 A1 WO 2013027207 A1	02-07-2014 10-07-2014 28-02-2013
WO 2014186898	A1	27-11-2014	AU 2014271174 A1 CA 2816453 A1 CN 105453187 A EP 3000114 A1 WO 2014186898 A1	10-12-2015 23-11-2014 30-03-2016 30-03-2016 27-11-2014
US 2013163707	A1	27-06-2013	EP 2421006 A1 EP 2606489 A1 US 2013163707 A1 WO 2012022491 A1	22-02-2012 26-06-2013 27-06-2013 23-02-2012

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-13, 25-29

Systems and method for producing isotopes with an accelerator as part of a free electron laser system having a further accelerator for the isotope production apparatus.

2. claims: 14-17, 24, 25, 30

System and methods for producing isotopes with an accelerator making use of an electron beam distribution apparatus for controlling the area to be irradiated.

3. claims: 18, 24, 25, 31

System and methods for producing isotopes with an accelerator making use of a beam kicker to control where the electron targets.

4. claims: 19-25, 32

System and methods for producing isotopes with an accelerator having a cooling system and waste heat recovery.
