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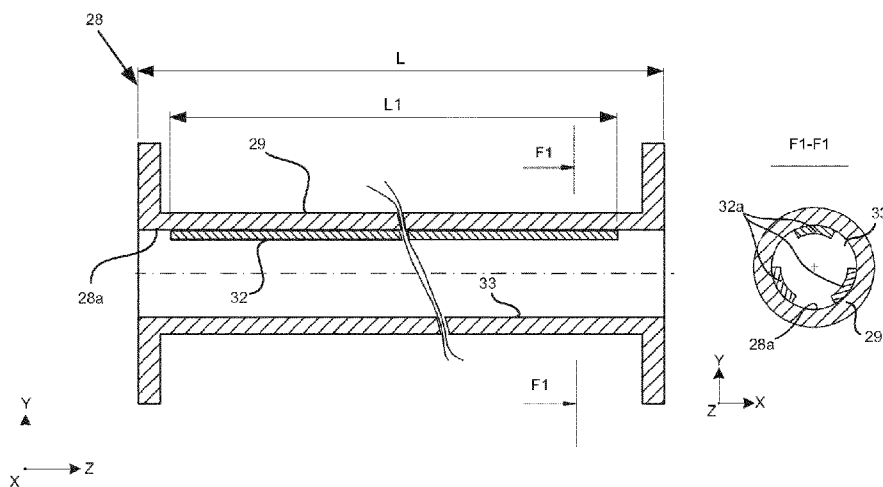


FIG. 5

(57) Abstract: A beam pipe (29) for an electron beam comprising a first section having an inner surface (28a), a vacuum layer (35) provided on a portion of the inner surface, and a conductive layer (36,37a). The vacuum layer is arranged such that at least a portion of the conductive layer is exposed to an electron beam during use and the conductive layer has a lower electrical resistance than the vacuum layer.

Improved Beam Pipe

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 15155376.5 which was filed on February 17, 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to beam pipes for electron beams. Particularly, but not exclusive, the present invention has application within lithographic systems that incorporate one or more free electron lasers.

BACKGROUND

[0003] A lithographic system comprises a radiation source and at least one lithographic apparatus. A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may for example project a pattern from a patterning device (e.g. a mask) onto a layer of radiation-sensitive material (resist) provided on a substrate.

[0004] The wavelength of radiation used by a lithographic apparatus to project a pattern onto a substrate determines the minimum size of features which can be formed on that substrate. A lithographic apparatus which uses EUV radiation, being electromagnetic radiation having a wavelength within the range 4-20 nm, may be used to form smaller features on a substrate than a conventional lithographic apparatus (which may for example use electromagnetic radiation with a wavelength of 193 nm).

[0005] A lithographic apparatus may be provided with radiation from a radiation source which forms part of a lithographic system. A plurality of lithographic apparatus may be supplied by a single radiation source. The radiation source may comprise at least one free electron laser which emits EUV radiation.

[0006] It is desirable to provide a beam delivery apparatus or method that is suitable for a radiation source for providing one or more tools with radiation and which obviates or mitigates one or more of the problems associated with known beam delivery apparatuses or methods.

SUMMARY

[0007] According to a first aspect there is provided a beam pipe for an electron beam, comprising a first section having an inner surface, a vacuum layer provided on a portion of the inner surface, and a conductive layer. The vacuum layer is arranged such that at least a

portion of the conductive layer is exposed to an electron beam during use. The conductive layer has a lower electrical resistance than the vacuum layer.

[0008] In this way, the benefits of a vacuum layer may be obtained while avoiding severe detrimental impacts on conductivity within the beam pipe that result from use of existing vacuum layer arrangements.

[0009] The conductive layer may be provided by the inner surface. In this way, the conductive layer can be provided by the beam pipe itself, such that an additional conductive layer need not be applied.

[0010] Alternatively, the conductive layer may be disposed between the inner surface and the vacuum layer. In this way, the conductive layer can be applied atop the vacuum layer, which may provide for easier application and more flexibility in the choice of the conductive layer.

[0011] The vacuum layer may comprise one or more discrete portions provided on the conductive layer and arranged such that one or more portions of the conductive layer are not covered by the vacuum layer. In this way, a surface area of the vacuum layer can be tailored to the requirements of the particular application. For example, where the vacuum layer provides surface pumping within the beam pipe, the surface area of the vacuum layer may be selected so as to provide a desired amount of surface pumping.

[0012] The vacuum layer may comprise a plurality of stripes disposed radially around the inner surface. Such an arrangement may be particularly easy to manufacture by the use of masks during a deposition process.

[0013] At least one of the discrete portions may extend for a majority of a length of the first section. In this way, the surface pumping and/or anti-diffusion properties of the vacuum layer can be provided along a majority of the path of the electron beam within the first section of the beam pipe.

[0014] The conductive layer may comprise one or more portions provided on an inner surface of the vacuum layer such that the vacuum layer is between the inner surface and the conductive layer.

[0015] The conductive layer may cover a majority of the inner surface of the vacuum layer. In this way, it can be ensured that currents can be conducted for a majority of the path of the electron beam within the first section of the beam pipe.

[0016] The conductive layer may comprise one or more discrete portions provided on the vacuum layer and arranged such that one or more portions of the vacuum layer are not covered by the conductive layer.

[0017] The conductive layer comprises one more stripes of conductive material. The stripes of conductive material may be disposed radially around an inner surface of the vacuum layer.

[0018] The vacuum layer may provide an anti-diffusion barrier. The vacuum layer may comprise a glass metal material.

[0019] The vacuum layer may provide surface pumping within the first section. The vacuum layer may comprise a non-evaporable getter.

5 [0020] The vacuum layer may be a coating that has been applied to the inner surface of beam pipe.

[0021] The conductive layer may comprise a coating applied to the inner surface of the vacuum layer. The conductive layer may have a thickness of the order of tens of microns or less.

10 [0022] The beam pipe may be a single channel beam pipe. That is, the electron beam may travel through the single channel of the beam pipe, both the vacuum layer and the conductive layer being provided in the single channel.

[0023] According to a second aspect, there is provided an undulator for a free electron laser comprising a beam pipe according to the first aspect.

15 [0024] According to a third aspect, there is provided a free electron laser comprising an undulator according to the second aspect.

[0025] According to a fourth aspect, there is provided a lithographic system comprising a free electron laser according to the third aspect, and at least one lithographic apparatus, each of the at least one lithographic apparatus being arranged to receive at least a portion of at least one radiation beam produced by the free electron laser.

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[0026] Features of one or more aspects described above may be combined with features of others of the aspects described above.

BRIEF DESCRIPTION OF THE DRAWINGS

25 [0027] 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 lithographic system comprising a radiation source and a plurality of lithographic apparatus;

- Figure 2 is a schematic illustration of a lithographic apparatus that may form part of a lithographic system described herein;

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- Figure 3 is a schematic illustration of a free electron laser comprising a beam pipe in accordance with an embodiment of the invention;

- Figure 4 is a schematic illustration of a beam pipe arrangement;

- Figure 5 is a schematic illustration of an alternative beam pipe arrangement;

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- Figure 6 is a schematic illustration of an alternative beam pipe arrangement; and

- Figure 7 is a schematic illustration of a further alternative beam pipe arrangement.

DETAILED DESCRIPTION

[0028] The term “beam delivery system” as used herein may be used to refer to any combination of optical elements used to provide a beam produced by a source to a tool, such as a lithographic apparatus.

5 **[0029]** Figure 1 shows a lithographic system LS, comprising: a radiation source SO, a beam splitting apparatus 20 and a plurality of tools. In Figure 1 twenty tools LA1-LA20 are provided. Each of the tools may be any tool which receives a radiation beam. The tools LA1-LA20 are generally referred to herein as lithographic apparatuses, although it will be appreciated that the tools are not so limited. For example, the tools may comprise
10 lithographic apparatuses, mask inspection apparatuses, Aerial Image Measurement Systems (AIMS).

[0030] The radiation source SO comprises at least one free electron laser and is configured to generate an extreme ultraviolet (EUV) radiation beam B (which may be referred to as a main beam). The main radiation beam B is split into a plurality of radiation
15 beams B1-B20 (which may be referred to as branch beams), each of which is directed to a different one of the lithographic apparatus LA1-LA20, by the beam splitting apparatus 20. The branch radiation beams B1-B20 may be split off from the main radiation beam B in series, with each branch radiation beam being split off from the main radiation beam B downstream from the preceding branch radiation beam. The beam splitting apparatus may,
20 for example, comprise a series of mirrors (not shown) which are each configured to split off a portion of the main radiation beam B into a branch radiation beam B1-B20.

[0031] The branch radiation beams B1-B20 are depicted in Figure 1 as being split off from the main radiation beam B such that the branch radiation beams B1-B20 propagate in directions which are approximately perpendicular to the direction of propagation of the main
25 radiation beam B. However, in some embodiments the branch radiation beams B1-B20 may instead be split off from the main radiation beam B such that an angle between the direction of propagation of each branch radiation beam B1-B20 and the direction of propagation of the main radiation beam is substantially less than 90 degrees. This may allow mirrors of the beam splitting apparatus to be arranged such that the main radiation beam B is incident on
30 the mirrors at an angle of incidence which is less than normal. This may advantageously decrease the amount of radiation which is absorbed by the mirrors and therefore increase the amount of radiation which is reflected from the mirrors and which is provided to the lithographic apparatus LA1-LA20 via the branch radiation beams B1-B20. Additionally, it may be desirable to direct one or more branch radiation beams at an angle with respect to the
35 entrance of the illuminator (as illustrated in Figure 2). This may allow for the branch radiation beam to be supplied to the illuminator with fewer mirrors and hence less power loss/higher transmission.

[0032] As will be apparent from the description below, although in Figure 1 the branch beams B1-B20 are shown to originate directly from the main radiation beam B it will be appreciated that the main radiation beam B may be split into one or more sub-beams and one or more of the sub-beams may then be further split, at least one more time, to produce the branch radiation beams B1-B20.

[0033] The lithographic apparatus LA1-LA20 may all be positioned on the same vertical level. The vertical level on which the lithographic apparatus LA1-LA20 are positioned may be substantially the same vertical level as the vertical level on which the beam splitting apparatus 20 is positioned and on which the main beam B is received from the radiation source SO. Alternatively, the beam splitting apparatus 20 may direct at least some of the branch radiation beams B1-B20 to one or more different vertical levels on which at least some of the lithographic apparatus LA1-LA20 are positioned. For example, the main radiation beam B may be received by the beam splitting apparatus on a basement or ground floor vertical level. The beam splitting apparatus 20 may direct at least some branch radiation beams B1-B20 to a vertical level which is positioned above the beam splitting apparatus and on which at least some of the lithographic apparatus LA1-LA20 are positioned. The lithographic apparatus LA1-LA20 may be positioned on multiple vertical levels and as such the beam splitting apparatus 20 may direct the branch radiation beams B1-B20 to different vertical levels in order to be received by the lithographic apparatus LA1-LA20.

[0034] The radiation source SO, beam splitting apparatus 20 and lithographic apparatus LA1-LA20 may all be constructed and arranged such that they can be isolated from the external environment. A vacuum may be provided in at least part of the radiation source SO, beam splitting apparatus 20 and lithographic apparatus LA1-LA20 so as to minimise the absorption of EUV radiation. Different parts of the lithographic system LS may be provided with vacuums at different pressures (i.e. held at different pressures which are below atmospheric pressure) and different gas compositions (in which different gas mixtures are supplied to different locations within SO and beam splitting apparatus 20).

[0035] Figure 2 is a schematic depiction of a lithographic apparatus LA1 of the lithographic system LS shown in Figure 1. The lithographic apparatus LA1 comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g. a mask), a projection system PS and a substrate table WT configured to support a substrate W. The illumination system IL is configured to condition the branch radiation beam B1 that is received by the lithographic apparatus LA1 before it is incident upon the patterning device MA. The projection system PS is configured to project the branch radiation beam B1 (now patterned by the mask MA) onto the substrate W. The substrate W may include

previously formed patterns. Where this is the case, the lithographic apparatus aligns the patterned radiation beam B1 with a pattern previously formed on the substrate W.

[0036] The branch radiation beam B1 that is received by the lithographic apparatus LA1 passes into the illumination system IL from the beam splitting apparatus 20 through an opening 8 in an enclosing structure of the illumination system IL. Optionally, the branch radiation beam B1 may be focused to form an intermediate focus at or near to the opening 8.

[0037] The illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 together provide the radiation beam B1 with a desired cross-sectional shape and a desired angular distribution. The radiation beam B1 passes from the illumination system IL and is incident upon the patterning device MA held by the support structure MT. The patterning device MA reflects and patterns the radiation beam to form a patterned beam B1'. The illumination system IL may include other mirrors or devices in addition to or instead of the faceted field mirror device 10 and faceted pupil mirror device 11. The illumination system IL may for example include an array of independently moveable mirrors. The independently moveable mirrors may for example measure less than 1mm across. The independently moveable mirrors may for example be MEMS devices.

[0038] Following reflection from the patterning device MA the patterned radiation beam B11 enters the projection system PS. The projection system comprises a plurality of mirrors 13, 14 which are configured to project the radiation beam B11 onto a substrate W held by the substrate table WT. The projection system PS may apply a reduction factor to the radiation beam, forming an image with features that are smaller than corresponding features on the patterning device MA. A reduction factor of 4 may for example be applied. Although the projection system PS has two mirrors 13, 14 in Figure 2, the projection system may include any number of mirrors.

[0039] In some embodiments a lithographic system LS may include one or more mask inspection apparatus (not shown). A mask inspection apparatus may include optics (e.g. mirrors) configured to receive a branch radiation beam B1-B20 from the beam splitting apparatus 20 and direct the branch radiation beam at a mask MA. The mask inspection apparatus may further include optics (e.g. mirrors) configured to collect radiation reflected from the mask and form an image of the mask at an imaging sensor. The image received at the imaging sensor may be used to determine one or more properties of the mask MA. The mask inspection apparatus may, for example, be similar to the lithographic apparatus LA1 shown in Figure 2, with the substrate table WT replaced with an imaging sensor.

[0040] In some embodiments a lithographic system LS may include one or more Aerial Image Measurement System (AIMS) which may be used to measure one or more properties of a mask MA. An AIMS may, for example, be configured to receive a branch radiation

beam B1-B20 from the beam splitting apparatus 20 and use the branch radiation beam B1-B20 to determine one or more properties of a mask MA.

[0041] The radiation source SO may comprise a free electron laser FEL which is operable to produce a beam of EUV radiation. Optionally, the radiation source SO may comprise more than one free electron laser FEL.

[0042] A free electron laser comprises an electron source, which is operable to produce a bunched relativistic electron beam, and a periodic magnetic field through which the bunches of relativistic electrons are directed. The periodic magnetic field is produced by an undulator and causes the electrons to follow an oscillating path about a central axis. As a result of the acceleration caused by the magnetic fields the electrons spontaneously radiate electromagnetic radiation generally in the direction of the central axis. The relativistic electrons interact with radiation within the undulator. Under certain conditions, this interaction 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.

[0043] Figure 3 is a schematic depiction of a free electron laser FEL comprising an electron source 21, a linear accelerator 22, a steering unit 23 and an undulator 24. The electron source 21 may alternatively be referred to as an injector and the undulator 24 may alternatively be referred to as a wiggler.

[0044] The electron source 21 is operable to produce a beam of electrons E. The electron source 21 may, for example, comprise a photo-cathode or a thermionic cathode and an accelerating electric field. The electron beam E is a bunched electron beam E which comprises a series of bunches of electrons. Electrons in the beam E are further accelerated by the linear accelerator 22. In an example, the linear accelerator 22 may comprise a plurality of radio frequency cavities, which are axially spaced along a common axis, 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.

[0045] The final energy of the beam E can be reached over several acceleration steps. For example, the beam E may be sent through a plurality of linear accelerator modules, which are separated by beam transport elements (bends, drift spaces, etc.). Alternatively, or

additionally, the beam E may be sent through the same linear accelerator module repeatedly, with gains and/or losses of energy in the beam E corresponding to the number of repetitions. Other types of linear accelerators may also be used. For example, laser wakefield accelerators or inverse free electron laser accelerators may be used.

5 **[0046]** The relativistic electron beam E which exits the linear accelerator 22 enters the steering unit 23. The steering unit 23 is operable to alter the trajectory of the relativistic electron beam E so as to direct the electron beam E from the linear accelerator 22 to the undulator 24. The steering unit 23 may, for example, comprise one or more electromagnets and/or permanent magnets configured to generate a magnetic field in the steering unit 23.
10 The magnetic field exerts a force on the electron beam E which acts to alter the trajectory of the electron beam E. The trajectory of the electron beam E upon leaving the linear accelerator 22 is altered by the steering unit 23 so as to direct the electrons to the undulator 24.

[0047] In embodiments in which the steering unit 23 comprises one or more
15 electromagnets and/or permanent magnets, the magnets may be arranged to form one or more of a magnetic dipole, a magnetic quadrupole, a magnetic sextupole and/or any other kind of multipole magnetic field arrangement configured to apply a force to the electron beam E. The steering unit 23 may additionally or alternatively comprise one or more electrically charged plates, configured to create an electric field in the steering unit 23 such
20 that a force is applied to the electron beam E. In general the steering unit 23 may comprise any apparatus which is operable to apply a force to the electron beam E to alter its trajectory.

[0048] The steering unit 23 directs the relativistic electron beam E to the undulator 24. The undulator 24 is operable to guide the relativistic electrons along a periodic path so that
25 the electron beam E interacts with radiation within the undulator 24 so as to stimulate emission of coherent radiation. Generally the undulator 24 comprises a plurality of magnets, which are operable to produce a periodic magnetic field which causes the electron beam E to follow a periodic path. As a result the electrons emit electromagnetic radiation generally in the direction of a central axis of the undulator 24. The undulator 24 may comprise a
30 plurality of sections (not shown), each section comprising a periodic magnet structure. The undulator 24 may further comprise a mechanism for refocusing the electron beam E such as, for example, a quadrupole magnet in between one or more pairs of adjacent sections. The mechanism for refocusing the electron beam E may reduce the size of the electron bunches, which may improve the coupling between the electrons and the radiation within the undulator
35 24, increasing the stimulation of emission of radiation.

[0049] As electrons move through the undulator 24, they interact with the electric field of the electromagnetic radiation in the undulator 24, 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, given by:

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

where λ_{em} is the wavelength of the radiation, λ_u is the undulator period, 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 $A=1$, whereas for a planar undulator $A=2$. For a helical undulator which produces a light which is not circularly polarized, but elliptically polarized A will be in the range of 1 to 2. In practice, each bunch of electrons will have a spread of energies although this spread may be minimised 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:

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

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.

[0050] The resonant wavelength λ_{em} is equal to the first harmonic wavelength spontaneously radiated by electrons moving through the undulator 24. 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 the undulator 24. 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.

[0051] Electrons moving through the undulator 24 may cause the amplitude of radiation to increase, i.e. the free electron laser FEL may have a non-zero gain. Maximum gain may be achieved when the resonance condition is met or when conditions are close to but slightly off resonance.

[0052] A region around a central axis of each undulator module may be considered to be a "good field region". The good field region may be a volume around the central axis wherein, for a given position along the central axis of the undulator module, the magnitude and direction of the magnetic field within the volume are substantially constant. An electron bunch propagating within the good field region may satisfy the resonant condition of Eq. (1) and will therefore amplify radiation. Further, an electron beam E propagating within the good

field region should not experience significant unexpected disruption due to uncompensated magnetic fields.

[0053] Each undulator module may have a range of acceptable initial trajectories. Electrons entering an undulator module with an initial trajectory within this range of acceptable initial trajectories may satisfy the resonant condition of Eq. (1) and interact with radiation in that undulator module to stimulate emission of coherent radiation. In contrast, electrons entering an undulator module with other trajectories may not stimulate significant emission of coherent radiation.

[0054] For example, generally, for helical undulator modules the electron beam E should be substantially aligned with the central axis of the undulator module. A tilt or angle between the electron beam E and the central axis of the undulator module (in radians) should generally not exceed $p/10$, where p is the FEL Pierce parameter. Otherwise the conversion efficiency of the undulator module (i.e. the portion of the energy of the electron beam E which is converted to radiation in that module) may drop below a desired amount (or may drop almost to zero). In an embodiment, the FEL Pierce parameter of an EUV helical undulator module may be of the order of 0.001, indicating that the tilt of the electron beam E with respect to the central axis of the undulator module should be less than 100 μrad .

[0055] For a planar undulator module, a greater range of initial trajectories may be acceptable. Provided the electron beam E remains substantially perpendicular to the magnetic field of a planar undulator module and remains within the good field region of the planar undulator module, coherent emission of radiation may be stimulated.

[0056] As electrons of the electron beam E move through a drift space between each undulator module, the electrons do not follow a periodic path. Therefore, in this drift space, although the electrons overlap spatially with the radiation, they do not exchange any significant energy with the radiation and are therefore effectively decoupled from the radiation.

[0057] The bunched electron beam E has a finite emittance and will therefore increase in diameter unless refocused. Therefore, the undulator 24 further comprises a mechanism for refocusing the electron beam E in between one or more pairs of adjacent modules. For example, a quadrupole magnet may be provided between each pair of adjacent modules. The quadrupole magnets reduce the size of the electron bunches and keep the electron beam E within the good field region of the undulator 24. This improves the coupling between the electrons and the radiation within the next undulator module, increasing the stimulation of emission of radiation.

[0058] An electron which meets the resonance condition as it enters the undulator 24 will lose (or gain) energy as it emits (or absorbs) radiation, so that the resonance condition is no longer satisfied. Therefore, in some embodiments the undulator 24 may be tapered.

That is, the amplitude of the periodic magnetic field and/or the undulator period λ_u may vary along the length of the undulator 24 in order to keep bunches of electrons at or close to resonance as they are guided through the undulator 24. Note that the interaction between the electrons and radiation within the undulator 24 produces a spread of energies within the electron bunches. The tapering of the undulator 24 may be arranged to maximise the number of electrons at or close to resonance. For example, the electron bunches may have an energy distribution which peaks at a peak energy and the tapering may be arranged to keep electrons with this peak energy at or close to resonance as they are guided through the undulator 24.

[0059] The interaction between the electrons and radiation within the undulator 24 produces a spread of energies within the electron bunches. The tapering of the undulator 24 may be arranged to maximise the number of electrons at or close to resonance. For example, the electron bunches may have an energy distribution which peaks at a peak energy and the tapering may be arranged to keep electrons with this peak energy at or close to resonance as they are guided through the undulator 24. Advantageously, tapering of the undulator 24 has the capacity to significantly increase conversion efficiency. For example, the use of a tapered undulator 24 may increase the conversion efficiency by a factor of more than 2. Tapering of the undulator 24 may be achieved by reducing the undulator parameter K along its length. This may be achieved by matching the undulator period λ_u and/or the magnetic field strength B_0 along the axis of the undulator to the electron bunch energy to ensure that they are at or close to the resonance condition. Meeting the resonance condition in this manner increases the bandwidth of the emitted radiation.

[0060] After leaving the undulator 24, the electromagnetic radiation is emitted as a radiation beam B'. The radiation beam B' comprises EUV radiation and may form all or part of the radiation beam B which is provided to the beam splitting apparatus 20 (depicted in Figure 1) and which forms the branch radiation beams B1-20 which are provided to the lithographic apparatus LA1-20.

[0061] In the embodiment of a free electron laser which is depicted in Figure 3, the electron beam E' which leaves the undulator 24 enters a second steering unit 25. The second steering unit 25 alters the trajectory of the electron beam E' which leaves the undulator 24 so as to direct the electron beam E' back through the linear accelerator 22. The second steering unit 25 may be similar to the steering unit 23 and may, for example, comprise one or more electromagnets and/or permanent magnets. The second steering unit 25 does not affect the trajectory of the radiation beam B' which leaves the undulator 24. The steering unit 25 therefore decouples the trajectory of the electron beam E' from the radiation beam B'. In some embodiments, the trajectory of the electron beam E' may be decoupled

from the trajectory of the radiation beam B' (e.g. using one or more magnets) before reaching the second steering unit 25.

[0062] The second steering unit 25 directs the electron beam E' to the linear accelerator 22 after leaving the undulator 24. Electron bunches which have passed through the undulator 24 may enter the linear accelerator 22 with a phase difference of approximately 180 degrees relative to accelerating fields in the linear accelerator 22 (e.g. radio frequency fields). The phase difference between the electron bunches and the accelerating fields in the linear accelerator 22 causes the electrons to be decelerated by the fields. The decelerating electrons E' pass some of their energy back to the fields in the linear accelerator 22 thereby increasing the strength of the fields which accelerate the electron beam E arriving from the electron source 21. This arrangement therefore recovers some of the energy which was given to electron bunches in the linear accelerator 22 (when they were accelerated by the linear accelerator) in order to accelerate subsequent electron bunches which arrive from the electron source 21. Such an arrangement may be known as an energy recovering LINAC.

[0063] Electrons E' which are decelerated by the linear accelerator 22 are absorbed by a beam dump 26. The steering unit 23 may be operable to decouple the trajectory of the electron beam E' which has been decelerated by the linear accelerator 22 from the trajectory of the electron beam E which has been accelerated by the linear accelerator 22. This may allow the decelerated electron beam E' to be absorbed by the beam dump 26 whilst the accelerated electron beam E is directed to the undulator 24.

[0064] The free electron laser FEL may comprise a beam merging unit (not shown) which substantially overlaps the trajectories of the beam E coming from the source 21 and the beam E' coming from the steering unit 25. The merging is possible due to the fact that prior to acceleration by the accelerator 22, the energy of the beam E is significantly smaller than the energy of the beam E'. The trajectory of the accelerated electron beam E may be decoupled from the trajectory of the decelerated electron beam E' by generating a substantially constant magnetic field. The difference in energies between the accelerated electron beam E and the decelerated electron beam E' causes the trajectories of the two electron beams to be altered by different amounts by the constant magnetic field. The trajectories of the two electron beams will therefore become decoupled from each other.

[0065] Alternatively, the steering unit 23 may, for example, be operable to generate a periodic magnetic field which has a substantially constant phase relationship with the electron bunches which form the accelerated electron beam E and the decelerated electron beam E'. For example at times at which electron bunches from the accelerated electron beam E enter the steering unit 23, the steering unit 23 may generate a magnetic field which acts to direct the electrons to the undulator 24. At times at which electron bunches from the

decelerated electron beam E' enter the steering unit 23, the steering unit 23 may generate a magnetic field which acts to direct the electrons to the beam dump 26. Alternatively, at times at which electron bunches from the decelerated electron beam E' enter the steering unit 23, the steering unit 23 may generate little or no magnetic field such that the electrons pass out of the steering unit 23 and to the beam dump 26.

[0066] Alternatively the free electron laser FEL may comprise a beam splitting unit (not shown) which is separate from the steering unit 23 and which is configured to decouple the trajectory of the accelerated electron beam E from the trajectory of the decelerated electron beam E' upstream of the steering unit 23. The beam splitting unit may, for example, be operable to generate a periodic magnetic field which has a substantially constant phase relationship with the electron bunches which form the accelerated electron beam E and the decelerated electron beam E'.

[0067] The beam dump 26 may, for example, include a large amount of water or a material with a high threshold for radioactive isotope generation by high energy electron impact. For example, the beam dump 26 may include aluminium with a threshold for radioactive isotope generation of approximately 15MeV. By decelerating the electron beam E' in the linear accelerator 22 before it is incident on the beam dump 26, the amount of energy the electrons have when they are absorbed by the beam dump 26 is reduced. This reduces the levels of induced radiation and secondary particles produced in the beam dump 26. This removes, or at least reduces, the need to remove and dispose of radioactive waste from the beam dump 26. This is advantageous since the removal of radioactive waste requires the free electron laser FEL to be shut down periodically and the disposal of radioactive waste can be costly and can have serious environmental implications.

[0068] When operating as a decelerator, the linear accelerator 22 may be operable to reduce the energy of the electrons E' to below a threshold energy. Electrons below this threshold energy may not induce any significant level of radioactivity in the beam dump 26.

[0069] In some embodiments a decelerator (not shown) which is separate to the linear accelerator 22 may be used to decelerate the electron beam E' which has passed through the undulator 24. The electron beam E' may be decelerated by the decelerator in addition to being decelerated by the linear accelerator 22 or instead of being decelerated by the linear accelerator 22. For example, the second steering unit 25 may direct the electron beam E' through a decelerator prior to the electron beam E' being decelerated by the linear accelerator 22. Additionally or alternatively the electron beam E' may pass through a decelerator after having been decelerated by the linear accelerator 22 and before being absorbed by the beam dump 26. Alternatively the electron beam E' may not pass through the linear accelerator 22 after leaving the undulator 24 and may be decelerated by one or more decelerators before being absorbed by the beam dump 26.

[0070] Optionally, the free electron laser FEL may comprise one or more bunch compressors. Bunch compressors may be disposed downstream or upstream of the linear accelerator 22. A bunch compressor is configured to bunch electrons in the electron beams E, E' and spatially compress or stretch existing bunches of electrons in the electron beams E, E'. Compression may be used to increase the conversion efficiency in the undulator 24 by providing a high peak current. Stretching of the bunches may be used to enable transport bunches with low peak current.

[0071] One type of bunch compressor comprises a radiation field directed transverse to the electron beam E. An electron in the electron beam E interacts with the radiation and bunches with other electrons nearby. Another type of bunch compressor comprises a magnetic chicane, wherein the length of a path followed by an electron as it passes through the chicane is dependent upon its energy. This type of bunch compressor may be used to compress a bunch of electrons which have been accelerated in a linear accelerator 22 by a plurality of conductors whose potentials oscillate at, for example, radio frequencies.

[0072] It may be desirable for electron bunches entering the undulator 24 to be tightly bunched and therefore have a higher peak current than in other locations within the accelerator. It may therefore be desirable to compress the electron bunches before they pass into the undulator 24 using one or more bunch compressors. A separate bunch compressor (not shown) may therefore be disposed between the steering unit 23 and the undulator 24. Alternatively, or additionally, the steering unit 23 itself may act to bunch the electrons in the electron beam E. An electron bunch which is accelerated by the linear accelerator 22 may have a correlated spread of energies which is a gradient of mean energy along the length of the bunch. For example, some electrons in an electron bunch may have energies which are higher than an average energy of the electron bunch and some electrons in the bunch may have energies which are lower than the average energy. The alteration of the trajectory of an electron which is caused by the steering unit 23 may be dependent on the energy of the electrons (e.g. when the trajectory is altered by a magnetic field). Electrons of different energies may therefore have their trajectories altered by different amounts by the steering unit 23, which may be difference in trajectories may be controlled to result in a compression of an electron bunch.

[0073] The beam line (i.e. the path of propagation) of the beams E and E' are defined with respect to a beam pipe 27 through which the electron beam propagates. Generally, the beam pipe is of circular cross-section. It will be appreciated, however that the beam pipe 27 may take any appropriate form. The beam pipe 27 may comprise a plurality of sections and that the different sections may have different properties. The properties of a particular section of the beam pipe 27 may be dependent upon the conditions required for the electron

beam E, E' within that particular section. The beam pipe 27 may be made from, for example, stainless steel, aluminium (Al) or copper (Cu).

[0074] The free electron laser FEL shown in Figure 3 is housed within a building 31. The building 31 may comprise walls which do not substantially transmit radiation which is generated in the free electron laser FEL whilst the free electron laser FEL is in operation. For example, the building 31 may comprise thick concrete walls (e.g. walls which are approximately 4 metres thick). The walls of the building 31 may be further provided with radiation shielding materials such as, for example, lead and/or other materials which are configured to absorb neutrons and/or other radiation types. Radiation shielding may comprise both materials with high density and high content of heavy elements (e.g. materials having a high Z value) in order to intercept electrons and gamma-photons and in materials with high content of light elements (e.g. materials having a low Z value, such as Hydrogen or Boron) to intercept neutrons. Providing walls of a building 31 with radiation absorbing materials may advantageously allow the thickness of the walls of the building 31 to be reduced. However adding radiation absorbing materials to a wall may increase the cost of constructing the building 31. A relatively cheap material which may be added to a wall of the building 31 in order to absorb radiation may, for example, be a layer of earth or sand.

[0075] In addition to providing walls of the building 31 which have radiation shielding properties. The building 31 may also be configured to prevent radiation generated by the free electron laser FEL from contaminating ground water below the building 31. For example, the base and/or foundations of the building 31 may be provided with radiation shielding materials or may be sufficiently thick to prevent radiation from contaminating ground water below the building 31. In an embodiment the building 31 may be positioned at least partly underground. In such an embodiment ground water may surround portions of the exterior of the building 31 as well as being below the building 31. Radiation shielding may therefore be provided around the exterior of the building 31 in order to prevent radiation from contaminating ground water which surrounds the building 31.

[0076] In addition to or as an alternative to shielding radiation at the exterior of the building 31, radiation shielding may also be provided inside of the building 31. For example, radiation shielding may be provided inside the building 31 at locations proximate to portions of the free electron laser FEL which emit large amounts of radiation.

[0077] It will be appreciated that while an FEL having a particular layout is shown in Figure 3, the FEL may be otherwise arranged. For example, in other embodiments, the accelerator 22 and the undulator 24 may be arranged in-line. In other embodiments the electron beam which exits the undulator may not be directed back to the accelerator. Generally, therefore, it is to be understood that the FEL may be arranged in any appropriate way.

[0078] It is desirable to create vacuum conditions within the beam pipe 27. As such, one or more vacuum pumps (not shown) may be connected, at intervals, to the beam pipe 27 in order to help provide a vacuum environment within the beam pipe 27. Different vacuum conditions may be required at different points of the beam line. That is, the amount of gas that can be tolerated within the beam pipe 27 may differ at different positions within the beam pipe 27.

[0079] For example, as described above, within the undulator 24, it is desirable that the electron beam E be tightly bunched and has a low emittance. In one embodiment, to obtain a sufficient conversion efficiency (CE) of the power in the electron beam E to EUV radiation (for example, a CE of greater than 0.1%), it is desirable for the electron beam E to have an emittance of less than 1 mm mRad in both the X- and Y- directions of the Cartesian coordinates depicted in Figure 3 (that is in the directions transverse to the direction of beam propagation).

[0080] Interaction between the electron beam with residual gas within the beam pipe within the undulator 24 can result in ion generation through collisional ionization. The, generated ions are attracted by the electron beam and may disturb the trajectories of electrons within the electron beam E, leading to non-linear focussing and an increase in the emittance of the electron beam E beyond the desired parameters. In one embodiment, it may be desirable to maintain a residual gas pressure below approximately 10^{-6} Pa to provide sufficiently low steady state concentration of ions within the beam pipe.

[0081] Given outgassing, obtaining a desired residual gas pressure may be difficult to achieve using external pumps alone. Providing specified pressure for the electron beam within the undulator 24 is especially difficult due to limited gas conduction achievable within what is a relatively long and narrow pipe. One way to provide a specified pressure is to reduce outgassing from the bulk material of the beam pipe and/or to introduce "surface pumping" through application of a coating onto an inner surface of the beam pipe 27, the coating being made from a material that is different to that from which the beam pipe 27 is made. Coatings providing anti-diffusion and/or surface pumping properties are referred to herein as vacuum layers. For example, one type of vacuum layer is what is generally known as a "Non-evaporable Getter" (NEG) layer.

[0082] Figure 4 schematically illustrates, in cross-section through the Y-Z plane, a section 28 of the beam pipe 27. The section 28 is a section of beam pipe 27 that passes through the undulator 24. The section 28 comprises a central, tubular, portion 29 with two connection means, in the form of flanges, at each end for connection with the other parts of the FEL (e.g. to other sections of the beam pipe 27). The section 28 may be constructed by any suitable means, such as extrusion. The section 28 has an internal diameter D (which may be, for example, 10 mm) and a length L.

[0083] A portion of the inner surface 28a of the section 28 extending for a length L1 is completely covered by a single continuous vacuum layer 30.. In the embodiment illustrated in Figure 4, the continuous vacuum layer 30 comprises coating having a generally consistent thickness along all points of the inner surface 28a of the section 28 along the length L1. The length L1 extends along a majority of the length L. While not shown in Figure 4, an interface layer may be provided between the inner surface 28a of the section 28 and the vacuum layer 30. By single continuous layer it is to be understood that the layer 30 is unbroken such that between a beginning and end of the vacuum layer 30 no part of the inner surface 28a of the section 28 is exposed to the electron beam E during use.

[0084] The vacuum layer 30 can enable establishment and maintenance of vacuum conditions within the beam pipe 27 by providing a diffusion barrier (or anti-diffusion layer), reducing outgassing from the beam pipe 27 itself, and through surface pumping. When molecules within the beam pipe 27 strike the vacuum layer 30, the molecules are adsorbed by the vacuum layer material. The vacuum layer 30 may be provided, for example, by a NEG layer, that is applied to the inner surface 28a of the section 28 (e.g. by sputtering). Different NEG materials are known in the art, such as those made from co-deposits of Titanium (Ti), Vanadium (V), and Zirconium (Zr), and those made from co-deposits of Ti, V, Zr and Hafnium (Hf).

[0085] Use of the vacuum layer 30 may, however, create additional difficulties. In particular, a beam pipe with the vacuum layer 30 may have a much higher electrical resistance than a beam pipe without such a layer. This is because, the compressed electron bunches (each electron bunch having a length such that the time each electron bunch takes to pass a point in space is approximately 100 fs) sent through the beam pipe 27 induce currents within the beam pipe 27 through wakefields. The currents are localized in the thin (1 micron or less) layer close to the inner surface of beam pipe 27 due to what is known as the "skin-effect". For example, NEG coatings in particular have a higher resistance than materials (such as aluminium or copper) that are often used for beam pipes.

[0086] Energy lost by the electron beam E due to wakefields is dissipated as Joule heating of the beam pipe 27. For example, within the undulator 24, for a section 28 constructed solely from aluminium, Joule heating may be of the order of 100 W/m (assuming a section 28 with a 10 mm internal diameter and an electron beam of approximately 100 fs bunches, repeated at frequency of the order of 100 MHz with average current of the order of 10 mA). In contrast, within the undulator 24, for a section 28 constructed from aluminium and comprising the NEG layer 30, Joule heating may be of the order of 1 -2 kW/m (again, assuming a section 28 with a 10 mm internal diameter and an electron beam of approximately 100 fs bunches, repeated at frequency of the order of 100 MHz with average current of the order of 10 mA). Cooling the beam pipe 27 where the vacuum layer 30 is

provided is therefore significantly more difficult than for a beam pipe 27 without such a vacuum layer 30.

[0087] Further, the presence of a vacuum layer within the section 28 may cause up to half of the electrons in each electron bunch (particularly electrons near to the head and tail of each electron bunch) within the electron beam E to fall out of resonance within the undulator 24, leading to a 2x (or greater) reduction in the conversion efficiency of the FEL. While it is described above that tapering of the undulator 24 may be used to increase the number of electrons within each bunch that meet the resonance condition, tapering may be insufficient to overcome the resonance issues that result from use of the barrier layer 30.

[0088] Figure 5 illustrates an alternative arrangement of a section 28 of a beam pipe within the undulator 24. Like components have been provided with like reference numerals. In the arrangement of Figure 5, a vacuum layer 32 is provided on an internal surface of the section 28. Unlike the vacuum layer 30, the vacuum layer 32 of Figure 5 is provided in the form of one or more discrete portions 32a of a barrier material (such as a NEG material). The vacuum layer 32 of Figure 5 is provided as three stripes 32a, separated by gaps 33 such that the inner surface 28a of the section 28 is exposed to the electron beam E. It will be appreciated that while stripes 32a of a barrier material are depicted in Figure 5, other arrangements which leave portions of the inner surface 28a exposed may be used (e.g. repeating blocks of a barrier material).

[0089] The discrete portions 32a of barrier material provide for surface pumping to occur within the section 28, the amount of surface pumping being dependent upon the surface area of the discrete portions 32a. In this way, by selecting an appropriate combined surface area of the discrete portions 32a of the vacuum layer 32, an amount of surface pumping can be provided that is sufficient to maintain a desired vacuum within the section 28. Meanwhile, although the same surface current is present around the circumference of the beam pipe, the dissipation is less in the discrete portions 32a having a high electrical conductivity so that Joule heating of the section 28 is reduced in comparison to the arrangement of Figure 4.

[0090] The discrete portions 32a may be applied to the inner surface 28a by any suitable technique including, for example, the application of a mask during the sputter deposition process used to apply the discrete portions 32a. The mask may then be removed to expose the inner surface 28a of the section 28.

[0091] An alternative arrangement of a section of a beam pipe within an undulator 24 is schematically illustrated in Figure 6, with like features having like reference numerals. In the arrangement of Figure 6 a vacuum layer 35 is provided along a length L1 within the inner surface 28a of the section 28. The vacuum layer 35 may be a NEG layer, but may be made from any suitable anti-diffusion material. For example, the vacuum layer 35 may be an

amorphous metal (also known as a metallic glass), or more generally an alloy of two or more metals with a significant difference in nuclei size.

[0092] The vacuum layer 35, like the vacuum layer 30, is a single continuous layer having a generally consistent thickness at all points along L1. The length L1 extends along a majority of the length L. While not shown in Figure 6, an interface layer may be provided between the inner surface 28a of the section 28 and the vacuum layer 35.

[0093] A conductive layer 36 is provided along a length L2 on an inner surface 28a of the vacuum layer. In Figure 6, the length L2 extends along a majority of the length L1 of the vacuum layer 35 and the length L of the section 28. The conductive layer 36 is provided as a single continuous layer covering the entire inner surface 28a of the section 28 along the length L2. The conductive layer 36 comprises a highly conductive material (such as aluminium, silver, gold, copper, other alloys, etc.). The conductive layer 36 may have a thickness that is, for example, of the order of 10s of microns or less. Preferably, the conductive layer 36 has a thickness that is at least in the order of the skin depth of the highly conductive material, e.g. in the order of 30nm for the above mentioned highly conductive materials.

[0094] While the conductive layer 36 will outgas into the section 28, the thinness of the conductive layer 36 in combination with the vacuum layer 35 is such that the available gas-forming molecules will be depleted after a short period of time of use. After depletion, the conductive layer 36 ensures that currents are sufficiently conducted along the section 28 to reduce cooling requirements below that required in the arrangement of Figure 4.

[0095] Figure 7 schematically illustrates an alternative arrangement of a beam pipe section 28 within the undulator 24. The arrangement of Figure 7 is generally similar to the arrangement of Figure 6 in that it comprises the vacuum layer 35. In the arrangement of Figure 7, however, a conducting layer 37 is provided on the anti-diffusion layer 35 in the form of one or more discrete portions 37a. In comparison to the arrangement of Figure 6, therefore, gaps in the conducting layer 37 are such that portions of the anti-diffusion layer 35 are exposed to the electron beam E during use. Where the anti-diffusion layer comprises, for example, a NEG material, the anti-diffusion layer 35 can therefore provide surface pumping.

[0096] An important advantage of the arrangement of Figure 7 is that the vacuum layer or anti-diffusion layer 35 covers the entire internal surface of the beam pipe section 28, thereby blocking outgassing from the beam pipe material, while surface pumping of the vacuum layer 35 is still partially enabled due to the gaps in the conducting layer 37. Hence, the arrangement of Figure 7 combines a relatively high pump speed and a relatively reduced heat load on the beam pipe wall.

[0097] In Figure 7, the discrete portions 37a take the form of three stripes (arranged similarly to the discrete portions 32a in the arrangement of Figure 5). It will be appreciated,

however, that any suitable arrangement may be used which provides for a conductive path along the section 28.

[0098] In each of the arrangements of Figures 5 to 7, therefore, an anti-diffusion and/or surface pumping vacuum layer is provided within a beam pipe together with a conductive layer comprising one or more conductive portions, such that currents can be conducted. In this way, the benefits of the vacuum layer (providing an anti-diffusion and/or surface pumping action) in helping to establish and maintain a vacuum can be realized while preventing excessive Joule heating of the beam pipe.

[0099] It will be appreciated that while the arrangements of Figures 5 to 7 are described with reference to a portion 28 of the beam pipe that forms a part of the undulator 24, that the concepts described herein are more generally applicable. For example, the concepts described above may be applied to any suitable portion of a beam pipe. Further, while the embodiments described above are generally concerned with a beam pipe of a FEL, it will be readily apparent to the skilled person that other applications in which beam pipes are utilized (such as, for example, synchrotrons) may similarly benefit from the concepts described herein. Further still, it will be appreciated that the concepts described herein are applicable to any application in which it is desired to provide a vacuum layer, such as a NEG layer, while providing a desired conductivity within a material on which the vacuum layer is applied.

[00100] Further, although embodiments of a free electron laser have been described above as comprising a linear accelerator 22, it should be appreciated that a linear accelerator 22 is merely an example of a type of particle accelerator which may be used to accelerate electrons in a free electron laser. A linear accelerator 22 may be particularly advantageous since it allows electrons having different energies to be accelerated along the same trajectory. However in alternative embodiments of a free electron laser other types of particle accelerators may be used to accelerate electrons to relativistic energies.

[00101] Embodiments of a free electron laser have been described in which an electron beam propagates along a first path and substantially in a first direction and along a second path and substantially in a second direction, wherein the first path and the second path are vertically separated from one another. Whilst embodiments have been described and depicted in which the first and second paths are substantially parallel with each other and are substantially parallel with a horizontal direction, other arrangements may instead be used. For example, in some embodiments the first path and/or the second path may be disposed at a non-zero angle with respect to the horizontal whilst remaining vertically separated from each other. In some embodiments the first and second paths may form different angles with respect to the horizontal and may therefore be disposed at a non-zero angle with respect to each other.

[00102] Whilst embodiments of a radiation source SO have been described and depicted as comprising two free electron lasers 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 a single free electron laser FEL or may comprise a number of free electron lasers (e.g. two or more).

[00103] Embodiments of a lithographic system may also include one or more mask inspection apparatus MIA and/or one or more Aerial Image Measurement Systems (AIMS). In some embodiments, the lithographic system may comprise two mask inspection apparatuses to allow for some redundancy. This may allow one mask inspection apparatus to be used when the other mask inspection apparatus is being repaired or undergoing maintenance. Thus, one mask inspection apparatus is always available for use. A mask inspection apparatus may use a lower power radiation beam than a lithographic apparatus. Further, it will be appreciated that radiation generated using a free electron laser of the type described herein may be used for applications other than lithography or lithography related applications.

[00104] The term "relativistic electrons" should be interpreted to mean electrons which relativistic energies, which they may obtain through acceleration by a particle accelerator. 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 practice a particle accelerator which forms part of a free electron laser may accelerate electrons 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.

[00105] Embodiments of the invention have been described in the context of free electron lasers which output an EUV radiation beam. However a free electron laser may be configured to output radiation having any wavelength. Some embodiments of the invention may therefore comprise a free electron which outputs a radiation beam which is not an EUV radiation beam.

[00106] 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.

[00107] The lithographic apparatuses described herein may be used in the manufacture of ICs. Alternatively, the lithographic apparatuses 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.

[00108] 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. Other aspects of the invention are set-out as in the following numbered clauses.

1. A beam pipe for an electron beam, comprising:
a first section having an inner surface;
a vacuum layer provided on a portion of the inner surface; and
a conductive layer;
wherein the vacuum layer is arranged such that at least a portion of the conductive layer is exposed to an electron beam during use;
wherein the conductive layer has a lower electrical resistance than the vacuum layer.

2. The beam pipe of clause 1, wherein the conductive layer is provided by the inner surface or is disposed between the inner surface and the vacuum layer.

3. The beam pipe of clause 2, wherein the vacuum layer comprises one or more discrete portions provided on the conductive layer and arranged such that one or more portions of the conductive layer are not covered by the vacuum layer.

4. The beam pipe of clause 3, wherein the vacuum layer comprises a plurality of stripes disposed radially around the inner surface.

5. The beam pipe of clause 3 or 4, wherein at least one of the discrete portions extends for a majority of a length of the first section.

6. The beam pipe of clause 1, wherein the conductive layer comprises one or more portions provided on an inner surface of the vacuum layer such that the vacuum layer is between the inner surface and the conductive layer.

7. The beam pipe of clause 6, wherein the conductive layer covers a majority of the inner surface of the vacuum layer.

8. The beam pipe of clause 6, wherein the conductive layer comprises one or more discrete portions provided on the vacuum layer and arranged such that one or more portions of the vacuum layer are not covered by the conductive layer.

9. The beam pipe of any of clauses 6 to 8, wherein the conductive layer comprises one more stripes of conductive material.
- 5 10. The beam pipe of clause 9, wherein the stripes of conductive material are disposed radially around an inner surface of the vacuum layer.
11. The beam pipe of any preceding clause, wherein the vacuum layer provides an anti-diffusion barrier.
- 10 12. The beam pipe of any preceding clause, wherein the vacuum layer comprises a glass metal material.
13. The beam pipe of any preceding clause, wherein the vacuum layer provides surface pumping within the first section.
- 15 14. The beam pipe of any preceding clause, wherein the vacuum layer comprises a non-evaporable getter.
- 20 15. The beam pipe of any preceding clause, wherein the vacuum layer is a coating that has been applied to the inner surface of beam pipe.
16. The beam pipe of clause 6 or any clause dependent thereon, wherein the conductive layer comprises a coating applied to the inner surface of the vacuum layer and having a thickness of the order of tens of microns or less.
- 25 17. The beam pipe of any preceding clause, wherein the beam pipe is a single channel beam pipe.
- 30 18. An undulator for a free electron laser comprising a beam pipe according to any preceding clause.
19. A free electron laser comprising an undulator according to clause 18.
- 35 20. A lithographic system comprising:
a free electron laser according to clause 19; and

at least one lithographic apparatus, each of the at least one lithographic apparatus being arranged to receive at least a portion of at least one radiation beam produced by the free electron laser.

CLAIMS

1. A beam pipe for an electron beam, comprising:
a first section having an inner surface;
a vacuum layer provided on a portion of the inner surface; and
5 a conductive layer;
wherein the vacuum layer is arranged such that at least a portion of the conductive layer is exposed to an electron beam during use;
wherein the conductive layer has a lower electrical resistance than the vacuum layer.
- 10 2. The beam pipe of claim 1, wherein the conductive layer is provided by the inner surface or is disposed between the inner surface and the vacuum layer.
3. The beam pipe of claim 2, wherein the vacuum layer comprises one or more discrete portions provided on the conductive layer and arranged such that one or more portions of
15 the conductive layer are not covered by the vacuum layer.
4. The beam pipe of claim 3, wherein the vacuum layer comprises a plurality of stripes disposed radially around the inner surface.
- 20 5. The beam pipe of claim 3 or 4, wherein at least one of the discrete portions extends for a majority of a length of the first section.
6. The beam pipe of claim 1, wherein the conductive layer comprises one or more portions provided on an inner surface of the vacuum layer such that the vacuum layer is
25 between the inner surface and the conductive layer.
7. The beam pipe of claim 6, wherein the conductive layer covers a majority of the inner surface of the vacuum layer.
- 30 8. The beam pipe of claim 6, wherein the conductive layer comprises one or more discrete portions provided on the vacuum layer and arranged such that one or more portions of the vacuum layer are not covered by the conductive layer.
9. The beam pipe of any of claims 6 to 8, wherein the conductive layer comprises one
35 more stripes of conductive material.

10. The beam pipe of claim 9, wherein the stripes of conductive material are disposed radially around an inner surface of the vacuum layer.

5 11. The beam pipe of claim 6 or any claim dependent thereon, wherein the conductive layer comprises a coating applied to the inner surface of the vacuum layer and having a thickness of the order of tens of microns or less.

10 12. The beam pipe of any preceding claim, wherein the beam pipe is a single channel beam pipe.

13. An undulator for a free electron laser comprising a beam pipe according to any preceding claim.

15 14. A free electron laser comprising an undulator according to claim 13.

15 15. A lithographic system comprising:
a free electron laser according to claim 14; and
at least one lithographic apparatus, each of the at least one lithographic apparatus being arranged to receive at least a portion of at least one radiation beam produced by the
20 free electron laser.

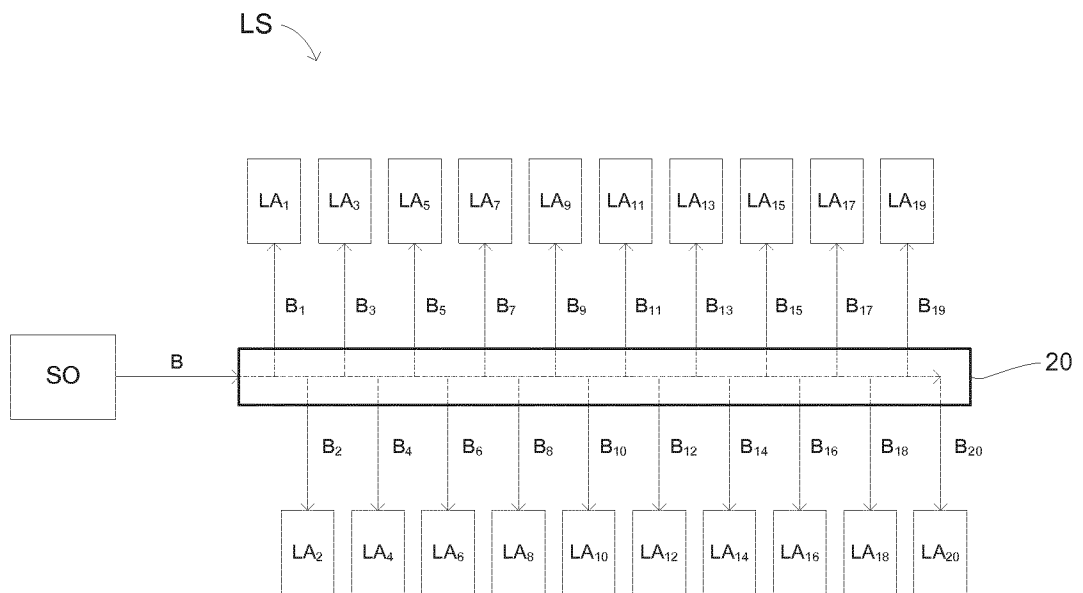


FIG. 1

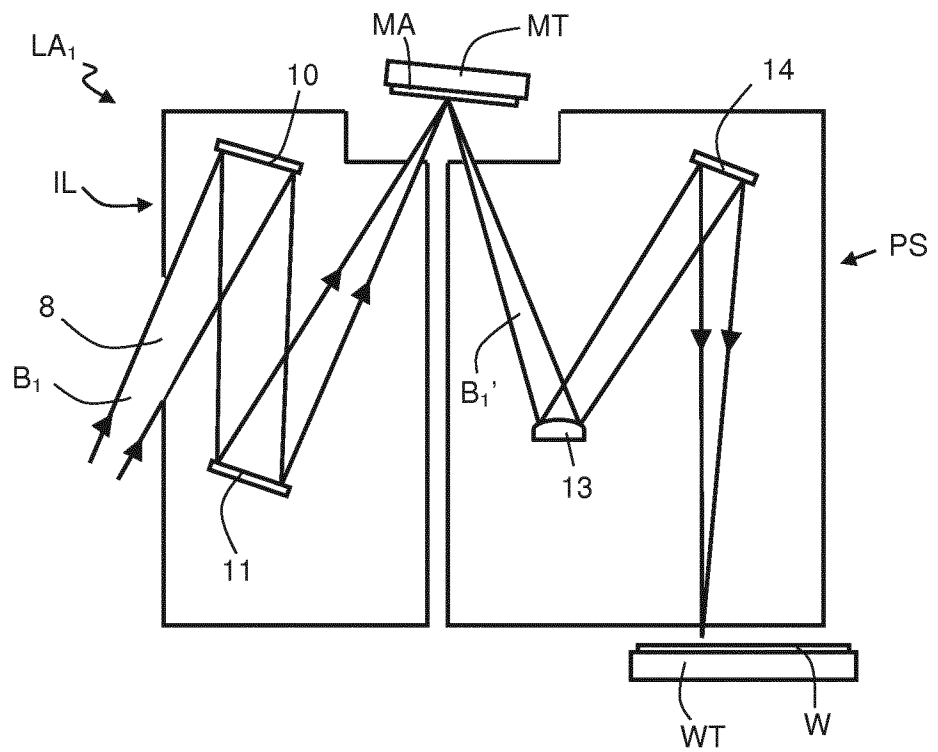


FIG. 2

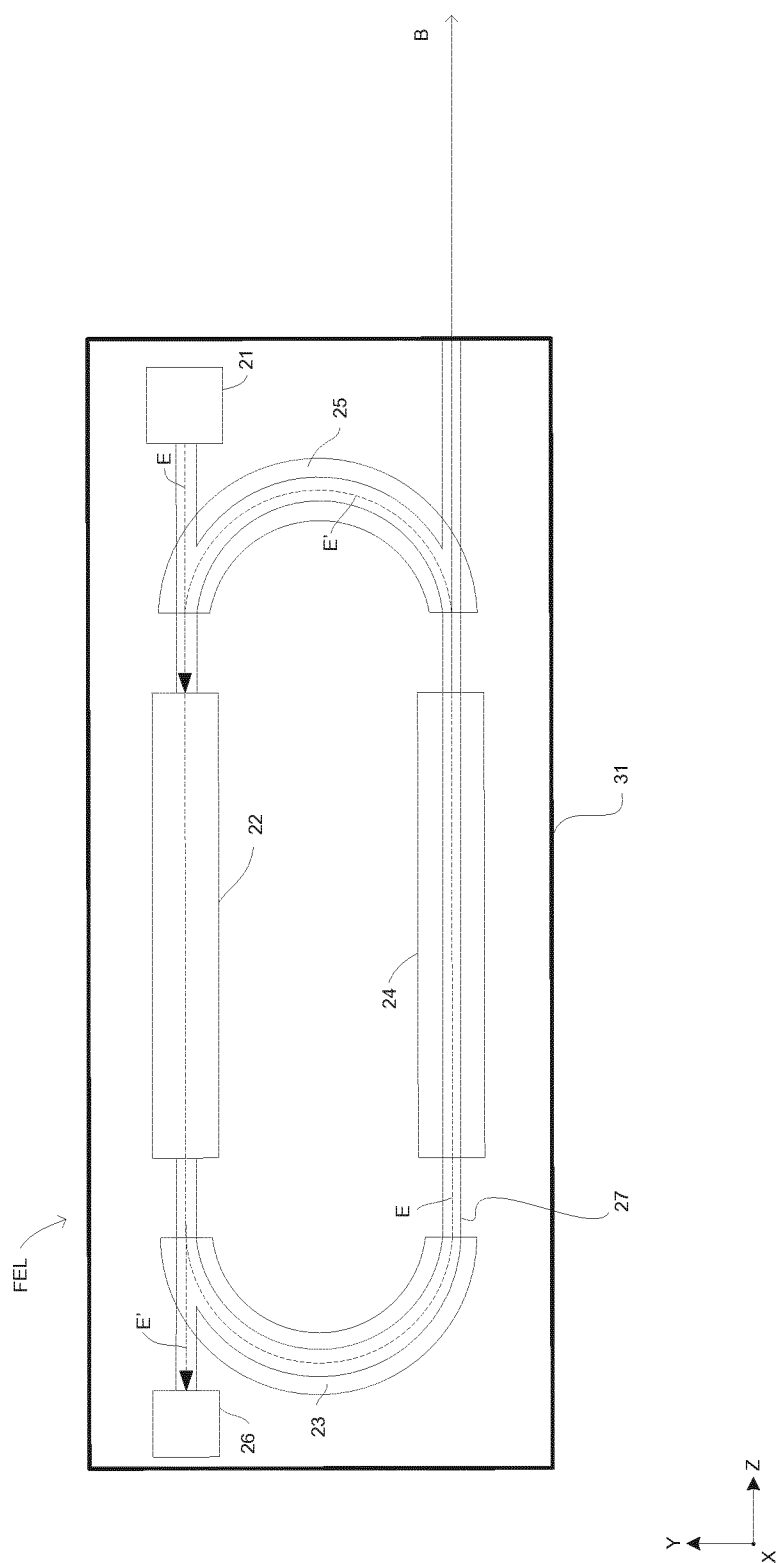


FIG. 3

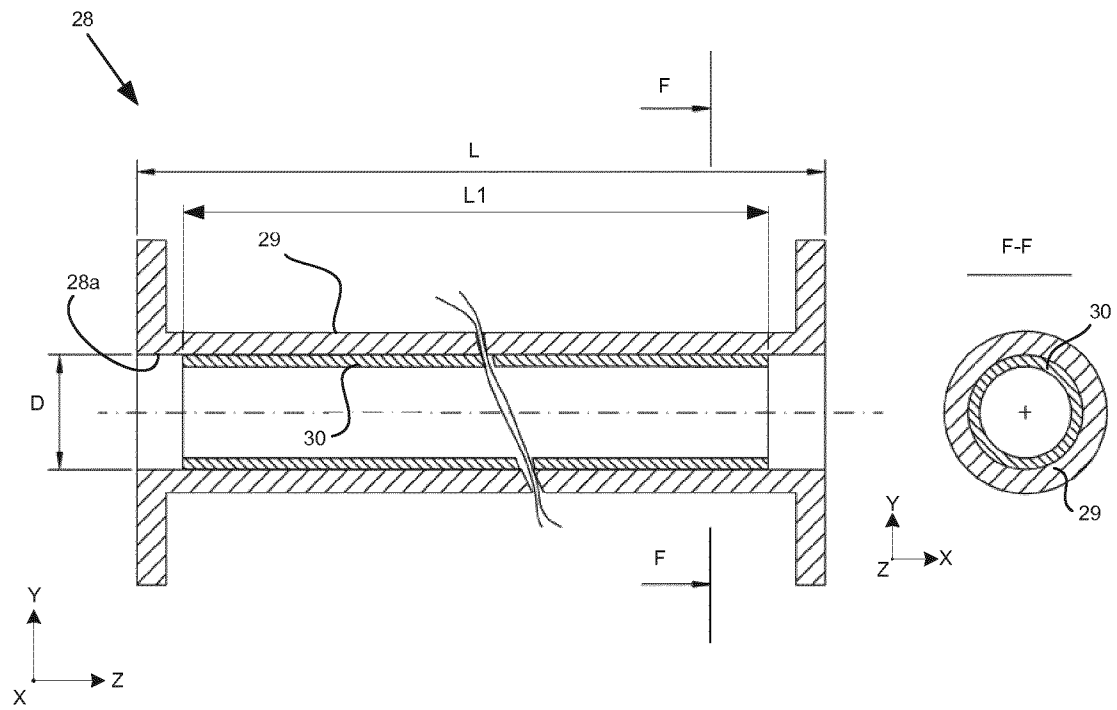


FIG. 4

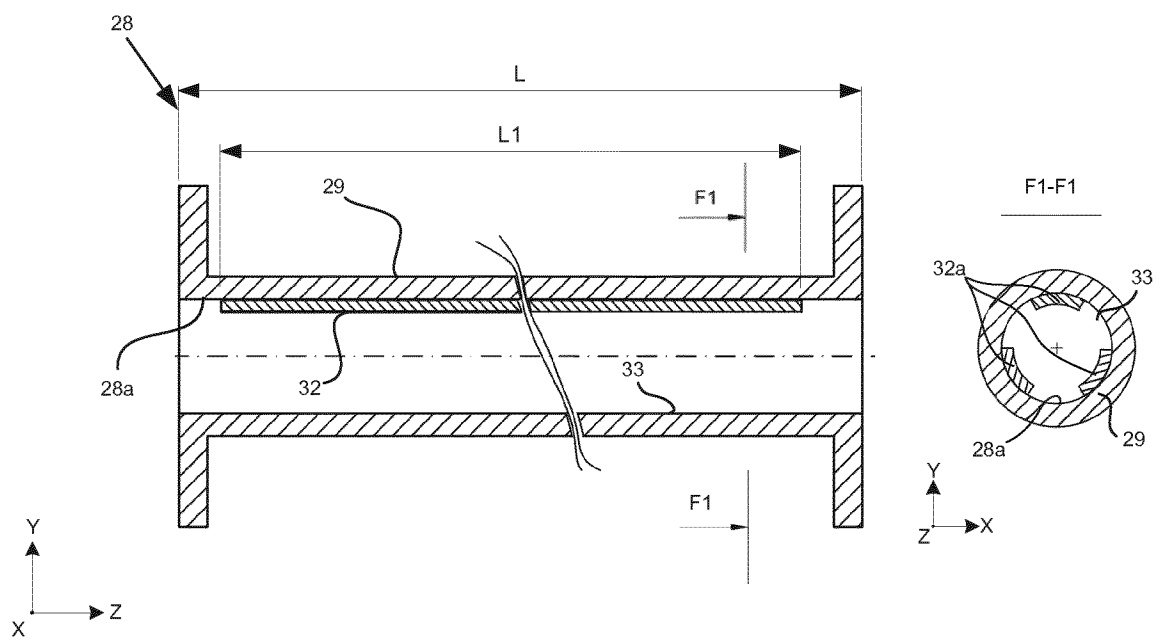


FIG. 5

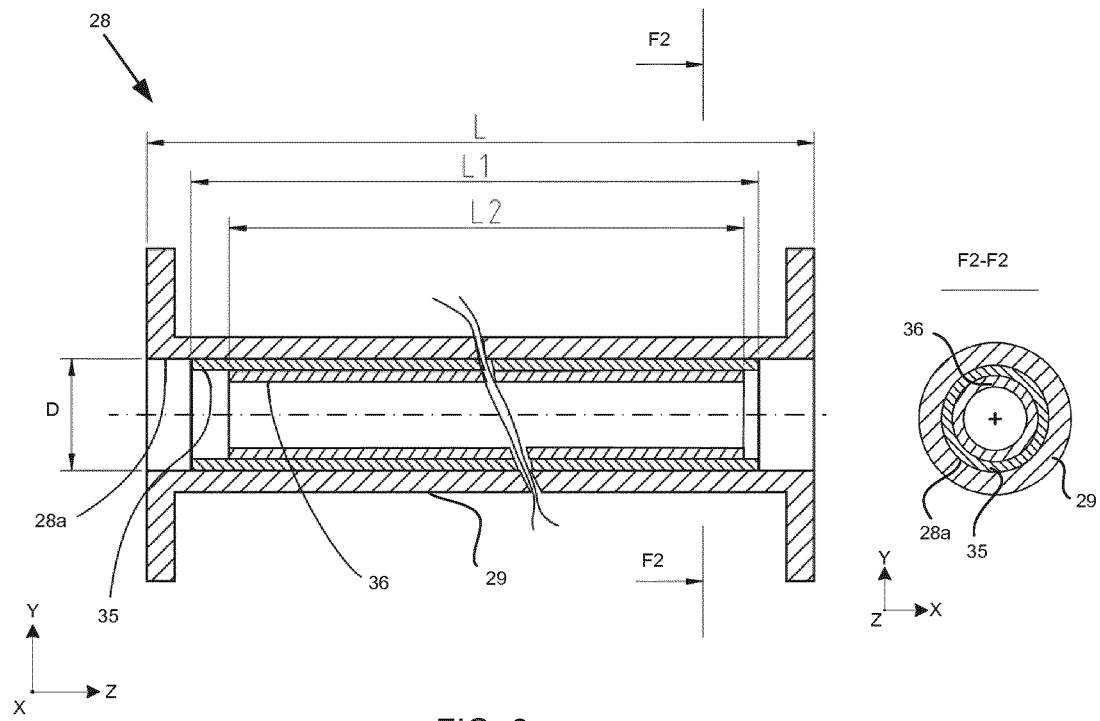


FIG. 6

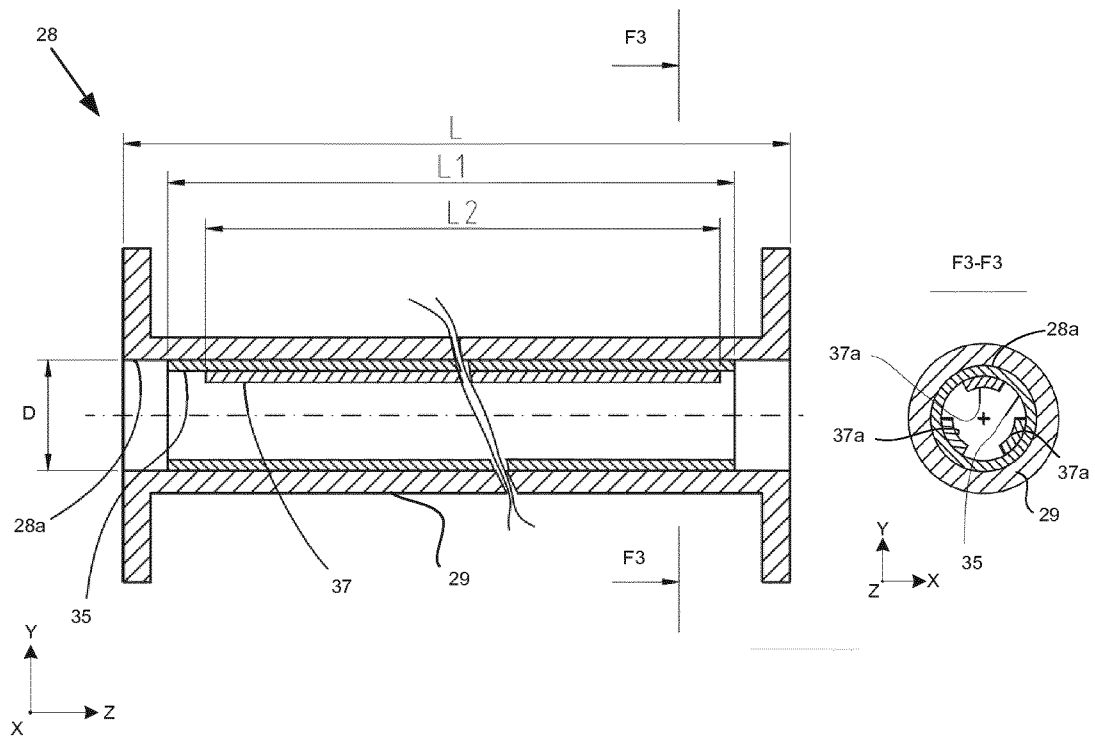


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/050731

A. CLASSIFICATION OF SUBJECT MATTER
INV. H05H7/14
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)
H05H H01J

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)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 4 712 074 A (HARVEY ALEXANDER [US]) 8 December 1987 (1987-12-08) figure 2	1,6-12 2-5, 13-15
X	----- US 5 376 792 A (SCHAMBER FREDERICK H [US] ET AL) 27 December 1994 (1994-12-27) figure 6	1
X	----- US 2 852 686 A (MACKENZIE KENNETH R) 16 September 1958 (1958-09-16) figure 1 -----	1



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

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Date of the actual completion of the international search

22 March 2016

Date of mailing of the international search report

04/04/2016

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/050731

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 4712074	A	08-12-1987	NONE	
US 5376792	A	27-12-1994	NONE	
US 2852686	A	16-09-1958	NONE	