



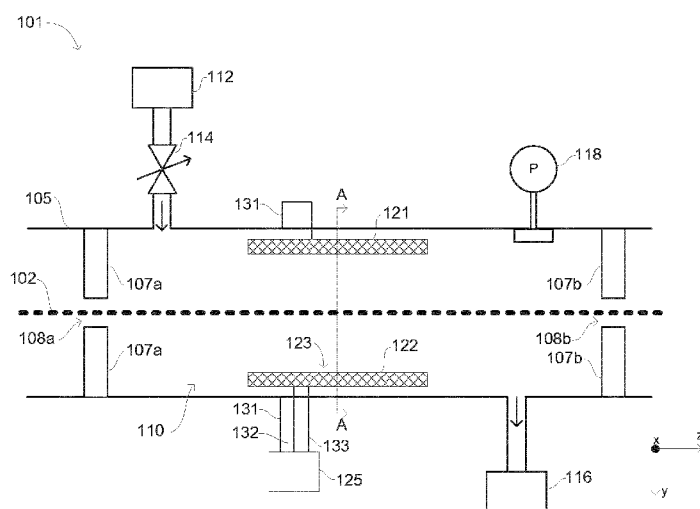
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(54) **Title:** RADIATION SENSOR**FIG. 4**

(57) **Abstract:** A radiation sensor comprising a chamber (110) for containing a gas, the chamber having a first opening (108a) and a second opening (108b) such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening, a gas supply mechanism (112, 114, 116, 118) configured to supply hydrogen or helium into the chamber, a first electrode (121) situated in the chamber, a second electrode (122) situated in the chamber, a voltage source (141) configured to maintain a potential difference between the first electrode and the second electrode, an electrical sensor (143a, 145a, 143b, 145b) configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the hydrogen or helium in the chamber caused by a radiation beam propagating through the chamber and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

Radiation Sensor

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 15154468.1 which was filed on
5 February 10, 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a radiation sensor for determining a position and/or a
power of a radiation beam. In particular, but not exclusively, the radiation beam may propagate
10 in a lithographic system.

BACKGROUND

[0003] 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
15 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
20 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] For lithography and other applications, it may be desirable to measure one or more
properties of a radiation beam.

[0006] It is an object of the present invention to obviate or mitigate at least one problem of prior
25 art techniques.

SUMMARY

[0007] According to a first aspect of the invention there is provided a radiation sensor
30 comprising a chamber for containing a gas, the chamber having a first opening and a second
opening such that a radiation beam can enter the chamber through the first opening, propagate
through the chamber and exit the chamber through the second opening, a gas supply
mechanism configured to supply hydrogen or helium into the chamber, a first electrode situated
in the chamber, a second electrode situated in the chamber, a voltage source configured to

maintain a potential difference between the first electrode and the second electrode, an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the hydrogen or helium in the chamber caused by a radiation beam propagating through the chamber and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

[0008] A radiation beam which propagates through the chamber causes ionization of the gas in the chamber thereby leading to the production of ions and electrons in an interaction region through which the radiation beam propagates. The potential difference which is maintained between the electrodes in the chamber causes the ions to be attracted to one of the electrodes and the ions to be attracted to the other of the electrodes thereby inducing an electrical current to flow through the electrodes. The production of ions in the interaction region through which the radiation beam propagates and their subsequent transport to an electrode causes a reduction in the amount of gas which is present in the interaction region. Hydrogen and helium both have relatively low ionization cross-sections. In particular hydrogen and helium have relatively low ionization cross-sections at wavelengths at which it may be desirable to measure radiation using the radiation sensor. For example, hydrogen and helium have relatively low ionization cross-sections at EUV wavelengths.

[0009] Using a gas which has a relatively low ionization cross-section reduces the number or ionization events which result from a radiation beam having a given power and therefore advantageously reduces the amount of gas which is removed from the interaction region as a result of ionization. Reducing the amount of gas which is removed from the interaction region increases the amount of gas which is present in the interaction region for subsequent ionization and reduces any depletion of gas in the interaction region. Reducing depletion of gas in the interaction region advantageously allows continuous measurement of the radiation beam to be made without significantly reducing the accuracy with which the measurement is made.

[0010] The use of hydrogen or helium which have a relatively low ionization cross section may in particular be advantageous for the measurement of a pulse radiation beam having a relatively high repetition rate.

[0011] The gas supply mechanism may be configured to maintain a desired pressure of hydrogen or helium in the chamber.

[0012] The gas supply mechanism may be configured to maintain a pressure of hydrogen or helium in the chamber which is greater than about 0.01 Pascals.

[0013] The gas supply mechanism may be configured to maintain a pressure of hydrogen or helium in the chamber which is less than about 100 Pascals.

[0014] According to a second aspect of the invention there is provided a radiation sensor comprising a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening, a gas supply mechanism configured to maintain a gas in the chamber at a pressure which is greater than about 0.01 Pascals, a first electrode situated in the chamber, a second electrode situated in the chamber, a voltage source configured to maintain a potential difference between the first electrode and the second electrode, an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the gas in the chamber caused by a radiation beam propagating through the chamber and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

[0015] Maintaining a pressure inside the chamber which is greater than about 0.01 Pascals advantageously increases the current which flows through the electrodes as a result of a radiation beam having a given power propagating through the chamber. An increase in the current which flows through the electrodes increases the signal on which a determination of the power and/or the position of the radiation beam is made thereby advantageously increasing the signal to noise ratio with which the determination is made. Increasing the signal to noise ratio with which a determination of the power and/or the position of a radiation beam is made may allow the determination to be made even when the radiation beam causes partial depletion of the amount of gas which is present in an interaction region through which the radiation beam propagates.

[0016] The gas supply mechanism may be configured to maintain a gas in the chamber at a pressure which is greater than about 0.1 Pascals.

[0017] The gas supply mechanism may be configured to maintain a gas in the chamber at a pressure which is less than about 100 Pascals.

[0018] The gas supply mechanism may be configured to maintain hydrogen or helium in the chamber.

[0019] The radiation sensor may further comprise a third electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the first electrode and the third electrode and wherein the electrical sensor is configured to measure an

electrical current flowing through the second electrode and to measure an electrical current flowing through the third electrode, wherein the first, second and third electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the second electrode and
5 a change in the electrical current flowing between through the third electrode.

[0020] Providing the third electrode in the chamber and arranging the electrodes such that a change in the position of a radiation beam in the chamber causes a change in the electrical currents which flow through the electrodes advantageously allows for an accurate determination of the position of the radiation beam to be made.

10 **[0021]** The processor may be operable to compare the electrical current flowing through the second electrode with the electrical current flowing through the third electrode and determine from the comparison a position, in the first direction, of a radiation beam propagating through the chamber.

[0022] The voltage source may be configured to maintain the first electrode at a higher voltage
15 than the second electrode and at a higher voltage than the third electrode.

[0023] The voltage source may be configured to maintain a potential difference between the first electrode and the second electrode and a potential difference between the first electrode and the third electrode, the potential differences being substantially the same as each other.

[0024] The radiation sensor may further comprise a fourth electrode situated in the chamber,
20 wherein the voltage source is configured to maintain a potential difference between the fourth electrode and the second electrode and is configured to maintain a potential difference between the fourth electrode and the third electrode, wherein the first and fourth electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the first electrode and a
25 change in the electrical current flowing between through the fourth electrode.

[0025] The electrical sensor may be configured to measure an electrical current flowing through the first electrode and an electrical current flowing through the fourth electrode.

[0026] The processor may be operable to compare the electrical current flowing through the first electrode and the electrical current flowing through the fourth electrode and determine from
30 the comparison a position, in the first direction, of a radiation beam propagating through the chamber.

[0027] The radiation sensor may further comprising a fifth electrode situated in the chamber, a sixth electrode situated in the chamber, and a seventh electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the fifth

electrode and the sixth electrode and maintain a potential difference between the fifth electrode and the seventh electrode and wherein the electrical sensor is configured to measure an electrical current flowing through the sixth electrode and to measure an electrical current flowing through the seventh electrode and wherein the fifth electrode, the sixth electrode and the seventh electrode are arranged such that a change in the position, in a second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the sixth electrode and a change in the electrical current flowing through the seventh electrode.

[0028] The processor may be operable to compare the electrical current flowing through the sixth electrode with the electrical current flowing through the seventh electrode and determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

[0029] The first and second directions may extend perpendicular to the direction of propagation of the radiation beam through the chamber.

[0030] The first and second directions may extend perpendicular to each other.

[0031] The radiation sensor may further comprise an eighth electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the eighth electrode and the sixth electrode and is configured to maintain a potential difference between the eighth electrode and the seventh electrode, wherein the fifth and eighth electrodes are arranged such that a change in the position, in the second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the fifth electrode and a change in the electrical current flowing between through the eighth electrode.

[0032] The electrical sensor may be configured to measure an electrical current flowing through the fifth electrode and an electrical current flowing through the eighth electrode.

[0033] The processor may be operable to compare the electrical current flowing through the fifth electrode and the electrical current flowing through the eighth electrode and determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

[0034] The radiation sensor may further comprise a beam splitter arranged to receive a radiation beam and split the radiation beam into a first portion and a second portion and direct the second portion to propagate through the chamber.

[0035] The beam splitter may comprise a grating.

[0036] According to a third aspect of the invention there is provided a radiation sensor comprising a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening, a gas supply mechanism configured to supply a gas into the chamber a first electrode situated in the chamber, a second electrode situated in the chamber, a third electrode situated in the chamber, a voltage source configured to maintain a potential difference between the first electrode and the second electrode and maintain a potential difference between the first electrode and the third electrode, and an electrical sensor configured to measure an electrical current flowing through the second electrode and an electrical current flowing the third electrode, the electrical currents resulting from ionization of the gas in the chamber caused by a radiation beam propagating through the chamber wherein the first, second and third electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the second electrode and a change in the electrical current flowing through the third electrode, the radiation sensor further comprising a processor operable to determine, from the measured electrical current flowing through the second electrode and the measured electrical current flowing through the third electrode a position in the first direction of a radiation beam propagating through the chamber.

[0037] The chamber may be arranged to receive a radiation beam generally along a beam axis extending between the first opening and the second opening and wherein the second and third electrodes are arranged such that a projection of the beam axis onto the second and third electrodes coincides with the third electrode for a first portion of the projection and coincides with the second electrode for a second portion of the projection and wherein the electrodes are configured such that a change in the position of the beam axis in the first direction causes a change in the length of the first portion of the projection relative to the length of the second portion of the projection.

[0038] The second electrode may comprise a first straight edge which is arranged to intersect the projection of the beam axis onto the second electrode and the third electrode may comprise a second straight edge which is arranged to intersect the projection of the beam axis onto the third electrode.

[0039] The first straight edge and the second straight edge may be parallel to each other.

[0040] The processor may be operable to compare the electrical current flowing through the second electrode with the electrical current flowing through the third electrode in order to

determine from the comparison the position, in the first direction, of a radiation beam propagating through the chamber.

[0041] The voltage source may be configured to maintain the first electrode at a higher voltage than the second electrode and at a higher voltage than the third electrode.

5 **[0042]** The processor may be further operable to determine from at least one of the measured electrical current flowing through the second electrode, and the measured electrical current flowing through the third electrode a power of a radiation beam propagating through the chamber.

10 **[0043]** The radiation sensor may further comprise a fifth electrode situated in the chamber, a sixth electrode situated in the chamber and a seventh electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the fifth electrode and the sixth electrode and maintain a potential difference between the fifth electrode and the seventh electrode, wherein the electrical sensor is configured to measure an electrical current flowing through the sixth electrode and an electrical current flowing through the seventh
15 electrode, wherein the fifth electrode, the sixth electrode and the seventh electrode are arranged such that a change in the position, in a second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the sixth electrode and a change in the electrical current flowing through the seventh electrode, and wherein the processor is operable to determine from the measured electrical current flowing
20 through the sixth electrode, and the measured electrical current flowing through the seventh electrode a position in the second direction of a radiation beam propagating through the chamber.

[0044] The sixth and seventh electrodes may be arranged such that a projection of the beam axis onto the sixth and seventh electrodes coincides with the sixth electrode for a first portion of
25 the projection and coincides with the seventh electrode for a second portion of the projection and wherein the sixth and seventh electrodes are arranged such that a change in the position of the beam axis in the second direction causes a change in the length of the first portion of the projection relative to the length of the second portion of the projection.

[0045] The processor may be operable to compare the electrical current flowing through the
30 sixth electrode with the electrical current flowing through the seventh electrode in order to determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

[0046] The first and second directions may extend perpendicular to the direction of propagation of the radiation beam through the chamber.

[0047] The first and second directions may extend perpendicular to each other.

[0048] According to a fourth aspect of the invention there is provided a radiation sensor system comprising a first radiation sensor according to any of first, second or third aspects arranged to determine at least one of a position and a power of a radiation beam at a first location, a second
5 radiation sensor according to any of the first, second or third aspects arranged to determine at least one of a position and a power of the radiation beam at a second location.

[0049] The first radiation sensor may be configured to determine a position of the radiation beam at the first location and the second radiation sensor may be configured to determine a position of the radiation beam at the second location. The radiation sensor system may further
10 comprises a processor configured to compare the determined position of the radiation beam at the first location with the determined position of the radiation beam at the second location and determine from the comparison a direction of propagation of the radiation beam between the first radiation sensor and the second radiation sensor.

[0050] The first radiation sensor may be configured to determine a position of the radiation
15 beam at the first location and the second radiation sensor may be configured to determine a power of the radiation beam at the second location.

[0051] The radiation sensor system may further comprise a beam splitter arranged to receive the radiation beam between the first location and the second location, split the radiation beam into a first portion and a second portion and direct the second portion to the second location.

[0052] According to a fifth aspect of the invention there is provided a lithographic system comprising a radiation source configured to provide a main radiation beam, a plurality of lithographic apparatus, a beam delivery system configured to split the main radiation beam into at least one branch radiation beam and direct the at least one branch radiation beam to at least one lithographic apparatus and a radiation sensor according to any of the first, second or third
20 aspects or a radiation sensor system according to the fourth aspect, the radiation sensor or radiation sensor system being arranged to determine at least one of a power and a position of the main radiation beam and/or a branch radiation beam.

[0053] The radiation source may be configured to provide an EUV main radiation beam.

[0054] The radiation source may be configured to provide a pulsed main radiation beam having
30 a repetition rate which is greater than about 100 Hz.

[0055] The radiation source may comprise at least one free electron laser.

[0056] According to a sixth aspect of the invention there is provided a method of measuring at least one of a position and a power of a radiation beam, the method comprising providing a chamber for containing a gas, the chamber having a first opening and a second opening such

that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening, supplying hydrogen or helium into the chamber, maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber, directing a radiation beam to propagate through the chamber, measuring an electrical current flowing between through at least one of the electrodes, the electrical current resulting from ionization of hydrogen or helium in the chamber caused by the radiation beam propagating through the chamber and determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

[0057] The method may further comprise maintaining the hydrogen or helium in the chamber at a desired pressure.

[0058] The hydrogen or helium may be maintained at a pressure which is greater than about 0.01 Pascals.

[0059] The hydrogen or helium may be maintained at a pressure which is less than about 100 Pascals.

[0060] A method of measuring at least one of a position and a power of a radiation beam, the method comprising providing a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening, supplying a gas into the chamber and maintaining the gas at a pressure which is greater than about 0.01 Pascals, maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber, directing a radiation beam to propagate through the chamber, measuring an electrical current flowing through at least one of the electrodes, the electrical current resulting from ionization of the gas in the chamber caused by the radiation beam propagating through the chamber and determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

[0061] The gas may be maintained at a pressure which is greater than about 100 Pascals.

[0062] 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

[0063] 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 free electron laser according to an embodiment of the invention;
- 5 - Figure 2 is a schematic illustration of a lithographic apparatus that forms part of the lithographic system of Figure 1;
- Figure 3 is a schematic illustration of a free electron laser that forms part of the lithographic system of Figure 1;
- Figure 4 is a schematic illustration of a radiation sensor according to an embodiment of
10 the invention;
- Figure 5 is a schematic illustration of electrodes which form part of the radiation sensor of Figure 4;
- Figure 6 is a schematic illustration of electrodes and electronics which form part of the radiation sensor of Figure 4;
- 15 - Figure 7 is a schematic illustration of a projection of a radiation beam in three different positions onto the electrodes of Figure 5;
- Figure 8 is a schematic illustration of electrodes which form part of an alternative embodiment of a radiation sensor;
- Figure 9 is a schematic illustration of an alternative embodiment of electronics which
20 may form part of a radiation sensor;
- Figure 10 is a schematic representation of a steady state gas pressure inside a radiation sensor as a function of the repetition rate of a radiation beam propagating through the gas sensor;
- Figure 11 is a schematic illustration of a radiation sensor and a beam splitter arranged to
25 determine at least one property of a radiation beam; and
- Figure 12 is a schematic illustration of a radiation sensor system according to an embodiment of the invention.

DETAILED DESCRIPTION

- 30 **[0064]** Figure 1 shows a lithographic system LS according to one embodiment of the invention. The lithographic system LS comprises a radiation source SO, a radiation sensor RS, a beam delivery system BDS and a plurality of lithographic apparatus LA_a-LA_n (e.g. eight lithographic apparatus). The radiation source SO is configured to generate an extreme ultraviolet (EUV) radiation beam B (which may be referred to as a main beam).

[0065] The beam delivery system BDS comprises beam splitting optics and may optionally also comprise beam expanding optics and/or beam shaping optics. The main radiation beam B is split into a plurality of radiation beams B_a - B_n (which may be referred to as branch beams), each of which is directed to a different one of the lithographic apparatus LA_a - LA_n , by the beam delivery system BDS. The radiation sensor RS which is shown in Figure 1 is configured to measure one or more properties (e.g. the power and/or the position) of the main beam B. Additionally or alternatively a radiation sensor RS may be configured to measure one or more properties of a branch radiation beam B_a - B_n .

[0066] The optional beam expanding optics (not shown) are arranged to increase the cross sectional area of the radiation beam B. Advantageously, this decreases the heat load on mirrors downstream of the beam expanding optics. This may allow the mirrors downstream of the beam expanding optics to be of a lower specification, with less cooling, and therefore less expensive. Additionally or alternatively, it may allow the downstream mirrors to be nearer to normal incidence. For example, the beam expanding optics may be operable to expand the main beam B from a diameter of approximately 100 μ m to a diameter of more than 10 cm before the main beam B is split by the beam splitting optics.

[0067] In an embodiment, the branch radiation beams B_a - B_n are each directed through a respective attenuator (not shown). Each attenuator may be arranged to adjust the intensity of a respective branch radiation beam B_a - B_n before the branch radiation beam B_a - B_n passes into its corresponding lithographic apparatus LA_a - LA_n .

[0068] The radiation source SO, beam delivery system BDS and lithographic apparatus LA_a - LA_n 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 delivery system BDS and lithographic apparatuses LA_a - LA_n so as to reduce 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).

[0069] Referring to Figure 2, a lithographic apparatus LA_a 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 B_a that is received by that lithographic apparatus LA_a before it is incident upon the patterning device MA. The projection system PS is configured to project the radiation beam B_a' (now patterned by the patterning device 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 B_a' with a pattern previously formed on the substrate W.

[0070] The branch radiation beam B_a that is received by the lithographic apparatus LA_a passes into the illumination system IL from the beam delivery system BDS through an opening 8 in an enclosing structure of the illumination system IL. Optionally, the branch radiation beam B_a may be focused to form an intermediate focus at or near to the opening 8.

[0071] 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 B_a with a desired cross-sectional shape and a desired angular distribution. The radiation beam B_a 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 B_a' . 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 1 mm across. The independently moveable mirrors may, for example, be microelectromechanical systems (MEMS) devices.

[0072] Following redirection (e.g. reflection) from the patterning device MA the patterned radiation beam B_a' enters the projection system PS. The projection system PS comprises a plurality of mirrors 13, 14 which are configured to project the radiation beam B_a' 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 in Figure 2, the projection system may include any number of mirrors (e.g. six mirrors).

[0073] The lithographic apparatus LA_a is operable to impart a radiation beam B_a with a pattern in its cross-section and project the patterned radiation beam onto a target portion of a substrate thereby exposing a target portion of the substrate to the patterned radiation. The lithographic apparatus LA_a may, for example, be used in a scan mode, wherein the support structure MT and the substrate table WT are scanned synchronously while a pattern imparted to the radiation beam B_a' is projected onto a substrate W (i.e. a dynamic exposure). The velocity and direction of the substrate table WT relative to the support structure MT may be determined by the demagnification and image reversal characteristics of the projection system PS.

[0074] Referring again to Figure 1, the radiation source SO is configured to generate an EUV radiation beam B with sufficient power to supply each of the lithographic apparatus LA_a-LA_n. As noted above, the radiation source SO may comprise a free electron laser.

[0075] Figure 3 is a schematic depiction of a free electron laser FEL comprising an injector 21, a linear accelerator 22, a bunch compressor 23, an undulator 24, an electron decelerator 26 and a beam dump 100.

[0076] The injector 21 is arranged to produce a bunched electron beam E and comprises an electron source (for example a thermionic cathode or a photo-cathode) and an accelerating electric field. Electrons in the electron 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 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.

[0077] Optionally, the electron beam E passes through a bunch compressor 23, disposed between the linear accelerator 22 and the undulator 24. The bunch compressor 23 is configured to spatially compress existing bunches of electrons in the electron beam E. One type of bunch compressor 23 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 23 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 bunches of electrons which have been accelerated in a linear accelerator 22 by a plurality of resonant cavities.

[0078] The electron beam E then passes through the undulator 24. Generally, the undulator 24 comprises a plurality of modules (not shown). Each module comprises a periodic magnet structure, which is operable to produce a periodic magnetic field and is arranged so as to guide the relativistic electron beam E produced by the injector 21 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.

[0079] 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.

[0080] 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:

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

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 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:

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

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.

[0081] 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 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
5 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.

[0082] 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
10 achieved when the resonance condition is met or when conditions are close to but slightly off resonance.

[0083] 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
15 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. The tapering may be achieved by varying the amplitude of the periodic magnetic field and/or the undulator period λ_u within each undulator module and/or from module to module. Additionally or alternatively tapering may be achieved by varying the helicity
20 of the undulator 24 (by varying the parameter A) within each undulator module and/or from module to module.

[0084] Radiation produced within the undulator 24 is output as a radiation beam B_{FEL} .

[0085] After leaving the undulator 24, the electron beam E is absorbed by a dump 100. The dump 100 may comprise a sufficient quantity of material to absorb the electron beam E. The
25 material may have a threshold energy for induction of radioactivity. Electrons entering the 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 may comprise aluminium (Al), which has a threshold energy of around 17 MeV. It may be desirable to reduce
30 the energy of electrons in the electron beam E before they enter the dump 100. This removes, or at least reduces, the need to remove and dispose of radioactive waste from the dump 100. 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.

[0086] The energy of electrons in the electron beam E may be reduced before they enter the dump 100 by directing the electron beam E through a decelerator 26 disposed between the undulator 24 and the beam dump 100.

5 [0087] In an embodiment the electron beam E which exits the undulator 24 may be decelerated by passing the electrons back through the linear accelerator 22 with a phase difference of 180 degrees relative to the electron beam produced by the injector 21. 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 injector 21. As the electrons decelerate in the linear accelerator 22 some of their energy is transferred to the RF fields in the linear accelerator 22.
10 Energy from the decelerating electrons is therefore recovered by the linear accelerator 22 and may be used to accelerate the electron beam E output from the injector 21. Such an arrangement is known as an energy recovery linear accelerator (ERL).

[0088] In some embodiments of a lithographic system LS the radiation source SO may comprise a single free electron laser FEL. In such embodiments the main beam B which is
15 emitted from the radiation source SO may be a laser beam B_{FEL} which is emitted from the free electron laser FEL. In other embodiments, a lithographic system LS may comprise a plurality of free electron lasers. A plurality of laser beams B_{FEL} emitted from the free electron lasers may be combined to form a single main beam B comprising radiation emitted from the plurality of free electron lasers FEL.

20 [0089] It is desirable in a lithographic system LS to regulate a dose of radiation which is provided to a substrate W by a lithographic apparatus LA_a . The dose of radiation which is provided to a substrate W is dependent on the power of a branch radiation beam B_a which is provided to a lithographic apparatus LA_a . The dose of radiation may therefore be controlled by controlling the power of a branch radiation beam B_a . In order to control the power of a branch
25 radiation beam B_a , the power of the branch radiation beam B_a and/or the main beam B may be measured using one or more radiation sensors RS (such as the radiation sensor RS shown in Figure 1). A radiation sensor RS may form part of a feedback system which is configured to control the power of the main beam B and/or the power of a branch radiation beam B_a so as to regulate the dose provided at a substrate W. For example, the power of the main beam B and/or the power of a branch radiation beam B_a may be adjusted in response to a measurement
30 made by one or more radiation sensors RS so as to provide a branch radiation beam having a desired power. The power of the main beam B and/or the power of a branch radiation beam B_a may be adjusted, for example, by arranging one or more attenuators in the path of the main beam B and/or a branch beam B_a . An attenuator may be controlled so as to adjust the intensity

of the main beam B and/or a branch beam B_a in response to a measurement made by a radiation sensor RS so as to provide a branch radiation beam B_a having a desired power.

[0090] It is further desirable in a lithographic system LS to measure the position of radiation beams propagating through the lithographic system LS. For example, the position of one or more radiation beams may be measured with a radiation sensor RS in order to check the alignment of the radiation beams. A radiation sensor RS which measures the position of a radiation beam may form part of a feedback system which is configured to control the alignment of the radiation beam. For example, the alignment and/or the orientation of one or more optical components of the lithographic system LS may be controlled in response to a measurement of the position of a radiation beam. A radiation sensor RS may, for example, be arranged to measure the position of a branch radiation beam B_a prior to the branch radiation beam B_a being provided to a lithographic apparatus LA_a . In the event that the position of the branch radiation beam B_a deviates from a desired position of the beam the alignment and/or orientation of, for example, one or more optical components in the beam delivery system BDS may adjusted so as to correct the deviation in position of the branch radiation beam B_a .

[0091] Figure 4 is a schematic illustration of a radiation sensor 101 which is suitable for use in a lithographic system LS. The radiation sensor 101 is configured to measure the power and/or the position of a radiation beam 102. The radiation beam 102 may, for example, be a main beam B emitted from a radiation source SO or may be a branch radiation beam B_a . Figure 4 is provided with Cartesian coordinates in which the z-direction represents the direction of propagation of the radiation beam 102.

[0092] The radiation sensor 101 incorporates a portion of a beam pipe 105 along which the radiation beam 102 propagates. The beam pipe 105 is provided with a first aperture plate 107a which includes a first opening 108a and a second aperture plate 107b which includes a second opening 108b. The aperture plates 107a, 107b and the beam pipe 105 together form a chamber 110 through which the radiation beam 102 propagates. The radiation beam 102 enters the chamber 110 through the first opening 108a, propagates through the chamber 110 and exits the chamber 110 through the second opening 108b.

[0093] The chamber 110 is suitable for containing a gas. Gas is introduced into the chamber 110 by a gas supply 112. Gas passes into the chamber 110 from the gas supply 112 via a valve 114. The valve 114 may be a variable valve operable to adjust the rate at which gas is introduced into the chamber 110. The chamber 110 is further provided with a pump 116 which is configured to pump gas out of the chamber 110. The pump 116 may be operable to adjust the rate at which gas is pumped out of the chamber 110. A pressure sensor 118 is arranged to

measure the pressure inside the chamber 110. The gas supply 112, the valve 114 and/or the pump 116 may be controlled in response to measurements of the pressure inside the chamber 110 (made by the pressure sensor 118) so as to maintain a desired pressure inside the chamber 110.

5 **[0094]** The gas supply 112, the valve 114, the pump 116 and the pressure sensor 118 may together be considered to be an example of a gas supply mechanism configured to supply gas into the chamber 110. The gas supply mechanism may be configured to maintain a desired pressure inside the chamber 110. A gas supply mechanism may take other forms and may include more and/or different components than the gas supply mechanism which is shown in
10 Figure 4. In general a gas supply mechanism may comprise any apparatus configured to supply gas into a chamber and/or maintain a desired pressure of gas in the chamber.

[0095] The aperture plates 107a, 107b serve to restrict any gas flow into and/or out of the chamber 110 along the beam pipe 105 by restricting any gas flow to the openings 108a and 108b in the aperture plates 107a, 107b. Restriction of the gas flow into and/or out of the
15 chamber 110 along the beam pipe 105 may assist in maintaining a desired composition and/or a desired pressure of the gas in the chamber 110. The first and second openings 108a, 108b remain open in order to allow the radiation beam 102 to propagate through the chamber 110.

[0096] The gas flow into and/or out of the chamber 102 through the beam pipe 105 may be further restricted by covering the openings 108a with an impermeable material which
20 substantially transmits the radiation beam 102. However, impermeable materials typically absorb a relatively large portion of EUV radiation. In embodiments in which the radiation beam 102 is an EUV radiation beam, covering the first and second openings 108a, 108b with an impermeable material may therefore lead to an undesirable loss of EUV radiation from the radiation beam 102 by absorption. Furthermore, typically an EUV radiation beam in a
25 lithographic system LS has a relatively high power. A high amount of absorption of a relatively high power EUV radiation beam by a material covering the openings 108a, 108b may therefore lead to excessive heating of the material and/or damage to the material.

[0097] The gas flow into and/or out of the chamber 102 through the beam pipe 105 may be further restricted by providing further aperture plates in the beam pipe 105. For example, a third
30 aperture plate (not shown) may be positioned in the beam pipe 105 and to the left of the first aperture plate 107a as viewed in Figure 4 and a fourth aperture plate (not shown) may be positioned in the beam pipe 105 and to the right of the second aperture plate 107b as viewed in Figure 4. The pressure of gas between the first aperture plate 107a and the third aperture plate and between the second aperture plate 107b and the fourth aperture plate may, for example, be

controlled with one or more pumps and/or gas supplies in order to restrict gas flow into and/or out of the chamber 110. For example, the pressure in the volume between the first aperture plate 107a and the third aperture plate and the volume between the second aperture plate 107b and the fourth aperture plate may be controlled so as to reduce pressure differences across the first aperture plate 107a and the second aperture plate 107b thereby reducing any gas flow through the first and second openings 108a, 108b.

[0098] As will be described in more detail further below, in some embodiments a desired pressure and composition of gas in the chamber 110 of the radiation sensor 101 may be the same as a desired pressure and composition of gas in the rest of the beam pipe 105. In such embodiments, first and second aperture plates 107a, 107b may not be present since gas flow along the beam pipe 105 need not be restricted. In such embodiments the beam pipe 105 alone may be considered to form a chamber 110 which forms part of the radiation sensor 101. A gas supply mechanism may be provided to supply gas into the beam pipe 105 and/or maintain a desired pressure of gas inside the beam pipe 105, thereby supplying gas into a chamber 110 of the radiation sensor RS and/or maintaining a desired pressure inside the chamber 110 of the radiation sensor RS.

[0099] The radiation sensor 101 further comprises a first electrode 121, a second electrode 122 and a third electrode 123 each situated in the chamber 110. The third electrode 123 is not visible in Figure 4 since it is situated behind the second electrode 122 as viewed in Figure 4. The arrangement of the second 122 and third electrodes 123 will be explained below with reference to Figures 5 and 6.

[00100] The radiation sensor 101 includes electronics 125. The first electrode 121 is electronically connected to the electronics 125 via a first connection 131, the second electrode 122 is electronically connected to the electronics 125 via a second connection 132 and the third electrode is electronically connected to the electronics 125 via a third connection 133. The electronics 125 is shown in more detail in Figure 6 and will be described further below.

[00101] Figure 5 is a schematic illustration of the second electrode 122 and the third electrode 123 as viewed along the y-axis. Also shown in Figure 5 is a projection of the radiation beam 102 onto the second and third electrodes. The second electrode 122 and the third electrode 123 are arranged such that the projection of the radiation beam 102 coincides with the third electrode 123 for a first portion 135 of the path of the radiation beam 102 and coincides with the second electrode 122 for a second portion 137 of the path of the radiation beam 102.

[00102] Figure 6 is a schematic illustration of the first, second and third electrodes 121, 122, 123 as viewed along the z-axis. Also shown in Figure 6 is an embodiment of the

electronics 125 and the first 131, second 132 and third 133 connections between the electrodes and the electronics 125. The electronics 125 includes a voltage source 141, a first voltmeter 143a, a second voltmeter 143b, a first resistor 145a and a second resistor 145b. The voltage source 141 is configured to maintain a potential difference between the first electrode 121 and the second electrode 122 and is configured to maintain a potential difference between the first electrode 121 and the third electrode 123. For example a potential difference of the order of approximately 100-1000 V may be maintained between the first electrode 121 and the second and third electrodes 122, 123. The voltage source may be configured to maintain the first electrode 121 at a higher voltage than the second electrode 122 and the third electrode 123 (as is indicated by the + and – symbols in Figure 6). The voltage source may be configured to maintain a potential difference between the first electrode 121 and the second electrode 122 which is substantially the same as the potential difference which is maintained between the first electrode 121 and the third electrode 123.

[00103] The electronics 125 may include a connection (not shown) to an electrical ground. For example, the electronics 125 may include a connection to the beam pipe 105. The beam pipe 105 may be connected to earth. A connection to the beam pipe 105 ensures that the voltages of the electrodes in the chamber 110 are maintained relative to the beam pipe 105 and avoids uncontrolled charge build up on components of the radiation sensor RS. A connection to the beam pipe 105 may, for example, be made to a negative terminal of the voltage source 141.

[00104] The first voltmeter 143a is configured to measure the voltage drop across the first resistor 145a from which a second electrical current I_2 flowing between the first electrode 121 and the second electrode 122 can be derived. The second voltmeter 143b is configured to measure the voltage drop across the second resistor 145b from which a third electrical current I_3 flowing between the first electrode 121 and the third electrode 123 can be derived. In the embodiment which is shown in Figure 6, the second current I_2 is the electrical current which flows through the second electrode 122 and the third current I_3 is the electrical current which flows through the third electrode 123. A first current I_1 flows through the first electrode 121 and is equal to the sum of the second I_2 and third I_3 currents.

[00105] The first voltmeter 143a, the first resistor 145a, the second voltmeter 143b and the second resistor 145b together form an electrical sensor 147 which is configured to measure an electrical current I_2 flowing through the second electrode 122 and an electrical current I_3 flowing through the third electrode 123. In other embodiments an electrical sensor 147 may take other forms and may be configured to measure more or less quantities than the electrical sensor 147 which is shown in Figure 6. For example, in some embodiments an electrical

sensor 147 may be configured to directly measure the first current I_1 which flows through the first electrode 121. A direct measurement of the first current I_1 may be made in addition to or as an alternative to the measurement of the second I_2 and/or the third currents I_3 flowing through the second 122 and third 123 electrodes. In general an electrical sensor is configured to measure the electrical current which flows through at least one of the electrodes of a radiation sensor RS.

[00106] As the radiation beam 102 passes through the chamber 110, the radiation beam 102 collides with gas molecules in the chamber and causes ionization of the gas, resulting in the production of positively charged ions and free electrons. The potential difference between the first electrode 121 and the second electrode 122 and the potential difference between the first electrode 121 and the third electrode 123 causes the free electrons to be attracted to the first electrode 121 and the ions to be attracted to the second electrode 122 or the third electrode 123. The flow of electrons to the first electrode 121 and the flow of ions to the second 122 and third electrodes 123 results in a second electrical current I_2 flowing between the first electrode 121 and the second electrode 122 and a third electrical current I_3 flowing between the first electrode 121 and the third electrode 123.

[00107] The second electric current I_2 which flows between the first electrode 121 and the second electrode and the third electric current I_3 which flows between the first electrode 121 and the third electrode 123 depends on the rate at which ions and electrons are formed by ionization of the gas in the chamber 110. The rate at which ions and electrons are formed by ionization of the gas in the chamber 110 depends on the ionization cross section of the gas in the chamber and the power of the radiation beam 102. An increase in the power of the radiation beam will lead to an increase in the rate at which ions and electrons are formed by ionization of the gas in the chamber 110 thereby leading to an increase in the first, second and third currents flowing through the electrodes. Measurements of the second and third currents I_2, I_3 flowing between the electrodes which are made by the electrical sensor 147 are therefore indicative of the power of the radiation beam 102 and may be used to determine the power of the radiation beam 102. In other embodiments the first current I_1 which flows through the first electrode 101 may be measured and may be used to determine the power of the radiation beam 102.

[00108] The power of the radiation beam 102 may be determined by a processor 151 which is operable to determine from a measurement of the first electric current I_1 , the second electric current I_2 and/or the third electric current I_3 (made by the electrical sensor 147) the power of the radiation beam 102. Whilst the embodiment of a radiation sensor RS which is shown in Figures 4, 5 and 6 includes three electrodes, it will be appreciated that at least the power of the

radiation beam 102 may be determined with an arrangement of just two electrodes between which a potential difference is held and a current flow is measured. Some embodiments of the invention may therefore only comprise a first electrode, a second electrode, a voltage source configured to maintain a potential difference between the first and second electrodes, an electrical sensor configured to measure an electrical current flowing through at least one of the first and second electrodes and a processor operable to determine from the measured electrical current flowing between the first electrode and the second electrode the power of the radiation beam 102.

[00109] Referring again to Figure 5, it will be appreciated that the number of ions which arrive at the second electrode 122 relative to the number of ions which arrive at the third electrode 123 depends on the relative lengths of the first portion 135 of the path of the radiation beam 102 and the second portion 137 of the path of the radiation beam 102. For example, if the length of the first portion 135 decreases and the length of the second portion 137 increases then the number of ions which arrive at the third electrode 123 will decrease and the number of ions which arrive at the second electrode 122 will increase. The second current I_2 flowing through the second electrode 122 will therefore increase and the third current I_3 flowing through the third electrode 123 will decrease. A comparison of the second current I_2 and the third current I_3 is therefore indicative of the relative lengths of the first portion 135 of the path of the radiation beam 102 and the second portion 137 of the path of the radiation beam 102.

[00110] Figure 7 is a schematic illustration of the second electrode 122 and the third electrode 123, on which projections of the radiation beam 102 onto the electrodes 122, 123 are shown for three different positions of the radiation beam 102 in the x-direction. A first position of the radiation beam in the x-direction forms a first projection 102a of the radiation beam onto the electrodes 122, 123, a second position of the radiation beam in the x-direction forms a second projection 102b of the radiation beam onto the electrodes 122, 123 and a third position of the radiation beam in the x-direction forms a third projection 102c of the radiation beam onto the electrodes 122, 123.

[00111] The first projection 102a of the radiation beam coincides with the third electrode 123 for a first portion 135a of the path of the radiation beam and coincides with the second electrode 122 for a second portion 137a of the path of the radiation beam. The first position of the radiation beam is such that the first portion 135a of the first projection 102a is approximately the same length as the second portion 137a of the first projection 102a. This may result in the first current I_1 flowing between the first electrode 121 and the second electrode 122 being

approximately equal to the second current I_2 flowing between the first electrode 121 and the third electrode 123.

[00112] The second position of the radiation beam which forms the second projection 102b onto the electrodes 122, 123 is shifted in the negative x-direction relative to the first position of the radiation beam. This results in a first portion 135b of the second projection 102b which is longer than the first portion 135a of the first projection 102a and a second portion 137b of the second projection 102b which is shorter than the first portion 135a of the first projection 102a. A shift in position in the x-direction of the radiation beam 102 from the first position to the second position therefore results in an increase in the third current I_3 flowing through the third electrode 123 and a decrease in the second current I_2 flowing through the second electrode 122.

[00113] The third position of the radiation beam which forms the third projection 102c onto the electrodes 122, 123 is shifted in the positive x-direction relative to the first position of the radiation beam. This results in a first portion 135c of the second projection 102c which is shorter than the first portion 135a of the first projection 102a and a second portion 137c of the second projection 102b which is longer than the first portion 135a of the first projection 102a. A shift in position in the x-direction of the radiation beam 102 from the first position to the third position therefore results in a decrease in the third current I_3 flowing through the third electrode 123 and an increase in the second current I_2 flowing through the second electrode 122.

[00114] As has been described above the size of the second current I_2 which flows through the second electrode 122 relative to the size of the third current I_3 which flows through the third electrode 123 is dependent on the position of the radiation beam in the x-direction. A measurement of the second current I_2 may therefore be compared to a measurement of the third current I_3 in order to determine the position of the radiation beam 102 in the x-direction. The position x of the radiation beam 102 in the x-direction may be given by:

$$x = k(I_3 - I_2)/(I_2 + I_3) \quad (3)$$

where k is a proportionality constant.

[00115] The position x of the radiation beam 102 may be determined by the processor 151 which may be operable to compare the second I_2 and third I_3 electrical currents and determine from the comparison the position of the radiation beam 102 in the x-direction (for example by using equation (3)).

[00116] In practice the radiation beam 102 has a diameter which extends in the x-direction and thus the radiation beam 102 is not confined to a single position in the x-direction. The electrons and ions which arrive at the electrodes are not therefore confined to a single

position in the x-direction. The position x of the radiation beam 102 given by equation (3) is the average position of the radiation beam 102 in the x-direction.

[00117] Since the radiation beam 102 has a diameter which extends in the x-direction which causes the electrons and ions which arrive at the electrodes to not be confined to a single position in the x-direction, the electrons and ions which arrive at the electrodes have a spread Δx in the x-direction. In addition to the spread of electrons and ions which is caused by the diameter of the radiation beam 102, the electrons and ions may be further spread in the x-direction before arriving at the electrodes. A spread $\Delta x'$ in the x-direction of the electrons and ions which occurs after ionization and before the electrons and ions arrive at the electrodes is given by:

$$\Delta x' = v \sqrt{H m / 2 E e} \quad (4)$$

where H is the separation in the y-direction between the first electrode 121 and the second and third electrodes, m is the mass of an ion or electron, E is the strength of the electric field between the electrodes, e is the charge of an ion or electron and v is the initial velocity of the ions or electrons after ionization.

[00118] All the variables which determine the spread $\Delta x'$ in the x-direction given by equation (4) are the same for ions and electrons except for the mass m of the ions and electrons and the initial velocity v of the ions and electrons after ionization. The mass of an electron is 9.1×10^{-31} kg. The mass of an ion depends on the chemical element which has been ionized but is always orders of magnitude heavier than an electron. For example, in an embodiment the gas in the chamber 110 comprises hydrogen which leads to the formation of hydrogen ions which have a mass of approximately 1.7×10^{-27} kg. The initial velocity of an ion after ionization is a combination of the thermal velocity before ionization and a recoil velocity which results from collision with a photon in the radiation beam 102. The initial velocity of an electron after ionization depends on the energy which is absorbed from a photon which ionizes the electron from an atom. Due to the higher mass of an ion when compared to an electron and the requirement that momentum is conserved during an ionization event, in general the initial velocity of ions after ionization is less than the initial velocity of electrons after ionization. For example, in an embodiment the initial velocity of ions after ionization may be approximately $3.5 \times 10^{-3} \text{ m s}^{-1}$ and the initial velocity of electrons after ionization may be approximately $5 \times 10^6 \text{ m s}^{-1}$.

[00119] In general, the result of the higher initial velocity of electrons after ionization (when compared to the initial velocity of ions) and the larger mass of ions (when compared to the mass of electrons) is that the spread $\Delta x'$ in the x-direction is less for ions than for electrons.

For example, in an embodiment the separation H in the y-direction between the first electrode 121 and the second and third electrodes is approximately 1 cm, the strength of the electric field E between the electrodes is approximately $1 \times 10^5 \text{ V m}^{-1}$, the initial velocity of ions after ionization is approximately $3.5 \times 10^{-3} \text{ m s}^{-1}$, the initial velocity of electrons after ionization is approximately $5 \times 10^6 \text{ m s}^{-1}$, the mass of the electrons is $9.1 \times 10^{-31} \text{ kg}$ and the mass of the ions is approximately $1.7 \times 10^{-27} \text{ kg}$. In such an embodiment the spread $\Delta x'$ in the x-direction which is caused by the electrostatic repulsion of the ions is approximately 0.08 mm and the spread $\Delta x'$ in the x-direction which is caused by the electrostatic repulsion of the electrons is approximately 2.7 mm.

[00120] The smaller spread $\Delta x'$ in the x-direction of ions when compared to the spread $\Delta x'$ in the x-direction of electrons means that the position of the radiation beam 102 in the x-direction may be measured to a better accuracy by measuring the position of ions in the x-direction than by measuring the position of electrons in the x-direction. It will be appreciated that the arrangement of electrodes which is shown in Figures 4-6 results in a measurement of the position in the x-direction of charged particles which arrive at the second and third electrodes 122, 123. Since the second and third electrodes 122, 123 are held at a lower voltage than the first electrode 121, ions are incident on the second and third electrodes 122, 123 and thus it is the position of the ions in the x-direction which is determined by comparing the second I_2 and third I_3 currents. It is therefore advantageous to hold the second and third electrodes 122, 123 which lead to a determination of the position of the radiation beam 102 at a lower voltage (i.e. a voltage which is more negative and less positive) than the first electrode 121 in order to improve the accuracy with which the position of the radiation beam 102 is determined.

[00121] Whilst the spread of ions (in the x-direction) which arrive at the second and third electrodes 122, 123 may be approximately 0.1 mm or greater (due to the combined effects of the diameter of the radiation beam and the spread $\Delta x'$ of ions before they arrive at the electrodes), measuring the second I_2 and third currents I_3 is equivalent to averaging over many ions which arrive at the second and third electrodes. The resolution of a determination of the position of the radiation beam 102 in the x-direction may therefore in practice be less than 0.1 mm, since the determination of the position is a result of averaging over many ions.

[00122] The first current I_1 which flows through the first electrode 121 (i.e. the sum of the second I_2 and third currents I_3) is given by:

$$I_1 = (e\epsilon L p P \lambda) / (hc) \quad (5)$$

where e is the charge of an electron ($1.6 \times 10^{-19} \text{ C}$), ϵ is the absorption coefficient of the radiation beam 102 in the chamber 110, L is the length of the electrodes in the z-direction, p is the pressure in the chamber 110, P is the power of the radiation beam 102, λ is wavelength of the

radiation beam 102, h is the Planck constant ($6.63 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1}$) and c is the speed of light in a vacuum ($3 \times 10^8 \text{ m s}^{-1}$). In an embodiment the gas in the chamber may comprise hydrogen at a pressure of approximately 0.05 Pa, the length L of the electrodes in the z-direction may be approximately 5 cm, the wavelength λ of the radiation beam 102 may be approximately 13.5 nm, the power P of the radiation beam 102 may be approximately 30 kW and the absorption coefficient ε of the radiation beam 102 in the chamber 110 may be approximately $1.2 \times 10^{-3} \text{ Pa}^{-1} \text{ m}^{-1}$. In such an embodiment the first current I_1 may be approximately 1 mA. A current of this magnitude may easily be measured with an accuracy sufficient to derive the power and/or the position of the radiation beam 102 from the measurement.

[00123] The range across which the position of the radiation beam 102 may be measured and the resolution with which the measurement is made depends on the configuration of the second 122 and third 123 electrodes. For example, in the arrangement of the second 122 and third electrodes 123 which is shown in Figure 5, the second electrode 122 has a first straight edge 122a and the third electrode 123 has a second straight edge 123a. The first 122a and second 123a straight edges are arranged so as to intersect a projection of the radiation beam 102 onto the second and third electrodes. In the arrangement which is shown in Figure 5, the first 122a and second 123a straight edges are parallel and intersect a projection of the radiation beam 102 onto the electrodes so as to form an angle α between the first and second edges and the projection of the radiation beam 102. The extent of the electrodes in the x-direction of the second and third electrodes is equal to $L \tan \alpha$, where L is the length of the electrodes in the direction of propagation of the radiation beam (the z-direction). The range across which the position of the radiation beam 102 may be measured is therefore approximately $L \tan \alpha$ (assuming that the gap between the first edge 122a and the second edge 123a is relatively small). The range across which the position of the radiation beam 102 may be measured may therefore be increased by increasing the length L of the electrodes and/or increasing the angle α .

[00124] The resolution with which a measurement of the position of the radiation beam 102 (in the x-direction) is made depends on the size of the change in the length of the first portion 135 of the path of the radiation beam 102 which coincides with the third electrode 123 and the change in the length of the second portion 137 of the path of the radiation beam 102 which coincides with the second electrode 122, which results from a given change in the position of the radiation beam 102 in the x-direction. That is, the resolution of the measurement depends on the sensitivity of the lengths of the first portion 135 and the second portion 137 to changes in the position of the radiation beam 102 in the x-direction. The sensitivity of the

lengths of the first portion 135 and the second portion 137 to changes in the position of the radiation beam 102 in the x-direction is proportional to $\frac{1}{L \tan \alpha}$. The resolution of the measurement may therefore be increased by decreasing the angle α . The angle α and the length L of the electrodes may be set determined so as to bring about a desired resolution and range of the measurement of the position of the radiation beam 102.

[00125] In some embodiments more or less than three electrodes may be arranged in a radiation sensor RS. Figure 8 is a schematic illustration of an embodiment of a radiation sensor (as viewed along the z-axis) which include four electrodes. The radiation sensor which is shown in Figure 8 includes a second electrode 122 and a third electrode 123 which are the same as the second 122 and third 123 electrodes which are the same as the second 122 and third 123 electrodes which are depicted in Figure 4-6. However the radiation sensor which is shown in Figure 8 differs from the embodiment shown in Figures 4-6 in that the first electrode 121 is split into a separate first electrode 121 and fourth electrode 124.

[00126] The first electrode 121 is provided with a first electrical connection 131 to electronics 125 and the fourth electrode 124 is provided with a fourth electrical connection 134 to the electronics 125. The electronics 125 comprises a voltage source (not shown in Figure 8) which is configured to maintain a potential difference between the first electrode 121 and the second 122 and third 123 electrodes and configured to maintain a potential difference between the fourth electrode 124 and the second 122 and third 123 electrodes. The electronics 125 further comprises an electrical sensor (not shown in Figure 8) which is configured to measure at least one electrical current flowing through at least one of the electrodes 121, 122, 123, 124. The electronics 125 which is used in conjunction with the embodiment which is shown in Figure 8 may be configured similarly to the electronics 125 which is shown in Figure 6 or may include a different configuration of electrical components.

[00127] The first electrode and the fourth electrode may be configured in a similar fashion to the second 122 and third 123 electrodes. That is, the first and fourth electrodes may be configured such that a projection of the radiation beam 102 onto the first and fourth electrodes coincides with the first electrode for a first length and coincides with the fourth electrode for a second length, where the first and second lengths vary as a function of the position of the radiation beam 102 in the x-direction. A measurement of a first current I_1 which flows through the first electrode 121 and/or a measurement of a fourth current I_4 which flows through the fourth electrode 124 may therefore be used to determine the position of the radiation beam 102 in the x-direction in an analogous fashion to the determination which was described above with reference to the currents flowing through the second and third electrodes.

[00128] Providing separate first 121 and fourth 124 electrodes may allow for separate determinations of the position of the radiation beam 102 by a comparison of the first I_1 and fourth I_4 currents flowing through the first 121 and fourth 124 electrodes and a comparison of the second I_2 and third I_3 currents flowing through the second 122 and third 123 electrodes. Since the first 121 and fourth 124 electrodes are held at a higher (i.e. more positive or less negative) voltage than the second 122 and third 123 electrodes, the determination of the position of the radiation beam 102 made from the first I_1 and fourth I_4 currents is based upon the arrival of electrons at the first 121 and fourth 124 electrodes whereas the determination of the position of the radiation beam 102 made from the second I_2 and third I_3 currents is based upon the arrival of ions at the second 122 and third 123 electrodes.

[00129] Since the mass of an electron is less than the mass of an ion the electrons produced through ionization will undergo a larger acceleration under the influence of the electric field in between the electrodes than the acceleration which is experienced by the ions. The electrons will therefore arrive at the second 122 and third 123 electrodes before the arrival of the ions at the first 121 and fourth 124 electrodes. A determination of the position of the radiation beam 102 which is based upon the first I_1 and fourth I_4 currents may therefore provide faster feedback concerning the position of the radiation beam 102 than a determination of the position of the radiation beam 102 which is based upon the second I_2 and third I_3 currents. This may be advantageous in an embodiment in which the position of the radiation beam 102 is controlled by a feedback loop which is based upon a measurement of the position of the radiation beam 102. A faster measurement of the position of the radiation beam 102 may allow the position of the radiation beam 102 to be adjusted faster in response to any changes in the position of the radiation beam 102.

[00130] Whilst a measurement of the position of the radiation beam 102 which is based upon the measurement of electrons arriving at electrodes may be faster than a measurement of the position of the radiation beam 102 which is based upon the measurement of ions arriving at the electrodes, as was described above a measurement which is based upon ions may be less accurate than a measurement which is based upon electrons. Separate measurements of the position of the radiation beam 102 which are based on ions and electrons respectively may therefore each be advantageous for different reasons.

[00131] Whilst specific arrangements of electrodes has been described above in connection with the measurement of the position of the radiation beam 102 in the x-direction, in other embodiments electrodes may be arranged differently to the those arrangements which are described above. In general any arrangement of electrodes may be used in which a change in

the position of the radiation beam 102 causes a change in the currents flowing through the electrodes such that a measurement of the currents flowing through the electrodes may be used to determine the position of the radiation beam 102.

[00132] In general a chamber 110 of a radiation sensor RS according to an embodiment of the invention may be considered to be arranged to receive a radiation beam 102 generally along a beam axis extending between the first opening 108a and the second opening 108b of the chamber 110. The beam axis may, for example, coincide with the path of the radiation beam 102 which is shown in Figure 4-6. Electrodes in the radiation sensor may be arranged such that a projection of the beam axis onto the electrodes coincides with different electrodes for different portions of the projection. The electrodes may be arranged such that a change in the position of the beam axis causes a change in the length of the different portions of the projection which coincide with the different electrodes, thereby causing a change in the currents flowing through the electrodes.

[00133] Whilst measurement of the position of the radiation beam 102 in the x-direction by a radiation sensor RS has been described above it will be appreciated that the position of the radiation beam in one or more other directions may be measured by using a similar arrangement of electrodes to the arrangement which is shown in Figures 4-6 or in Figure 8 but arranged to measure the position of the radiation beam in a direction other than the x-direction.

[00134] For example a radiation sensor may further comprise a fifth electrode, a sixth electrode and a seventh electrode arranged in a similar fashion to the first, second and third electrodes but rotated by 90 degrees about the direction of propagation of the radiation beam 102. That is, the fifth, sixth and seventh electrodes may generally extend in the y and z-directions as opposed to the first, second and third electrodes which generally extend in the x and z-directions. A voltage source may be configured to maintain a potential difference between the fifth electrode and the sixth electrode and maintain a potential difference between the fifth electrode and the seventh electrode. The radiation sensor may further comprise an electrical sensor configured to measure an electrical current flowing through the sixth electrode and an electrical current flowing through the seventh electrode. The currents flowing through the sixth and seventh electrodes may be compared in order to determine the position of the radiation beam 102 in the y-direction in an analogous fashion to the comparison of the second I_2 and third currents I_3 in order to determine the position of the radiation beam 102 in the x-direction which was described above. The position of the radiation beam 102 in the y-direction may be determined by the processor 151 which may be operable to compare the currents

flowing through the sixth and seventh electrodes and determine from the comparison the position of the radiation beam 102.

[00135] Whilst an embodiment has been described above in which a fifth, sixth and seventh electrode are arranged to determine the position of the radiation beam 102 in the y-direction, it will be appreciated that more electrodes may be provided in order to determine the position of the radiation beam 102 in the y-direction. For example, a radiation sensor may further include an eighth electrode which may be held at a potential difference with respect to the sixth and seventh electrodes and may be arranged such that a comparison of the current flowing through the fifth and eighth electrodes may allow for a further determination of the position of the radiation beam 102 in the y-direction.

[00136] Whilst the embodiments described above are described with reference to a single voltage source which maintains a potential difference between different electrodes, the voltage source may in practice comprise a plurality of voltage supplies. For example, a first voltage supply may maintain a potential difference between a first and a second electrode, a second voltage supply may maintain a potential difference between a first and a third electrode, a third voltage supply may maintain a potential difference between a fourth and a fifth electrode and a fourth voltage supply may maintain a potential difference between a fourth and a sixth electrode. Alternatively one or more voltage supplies may be configured to maintain a potential difference between more than one pair of electrodes.

[00137] Whilst a specific embodiment of the electronics 125 is depicted in Figure 6 and is described above, the electronics 125 may take other forms. For example, Figure 9 is a schematic illustration of an alternative embodiment of electronics 125'. The embodiment of electronics 125' is configured to be electrically connected to the arrangement of first 121, second 122, third 123 and fourth 124 electrodes which is shown in Figures 7 via the first 131, second 132, third 133 and fourth 134 electrical connections. However, it will be appreciated that the electronics 125' which is shown in Figure 9 may be adapted for connection to a different arrangement of electrodes. For example the electronics 125' which is shown in Figure 9 may be adapted for connection to the first 121, second 122 and third 123 electrodes which are shown in Figures 4-6.

[00138] In the embodiment of the electronics 125' which is shown in Figure 9 electrical connections 131, 132, 133, 134 from the electrodes 121, 122, 123, 124 (not shown in Figure 9) are each held at a potential difference with respect to the beam pipe 105. A first voltage supply 441a is connected between the beam pipe 105 and the first 131 and fourth 134 electrical connections and is configured to maintain a potential difference between the first electrode 121

and the beam pipe 105 and a potential difference between the fourth electrode 124 and the beam pipe 105. A first current sensor 447a is configured to measure a first current I_1 which flows between the first electrode 121 and the beam pipe 105 and therefore measures the current which flows through the first electrode 121. In the embodiment which is shown in Figure 9 the first current sensor 447a takes the form of a first resistor 445a and a first voltmeter 443a which is configured to measure the voltage drop across the first resistor 445a. However in other embodiments the first current sensor 447a may take other forms.

[00139] A fourth current sensor 447d is configured to measure a fourth current I_4 which flows between the fourth electrode 124 and the beam pipe 105 and therefore measures the current which flows through the fourth electrode 124. In the embodiment which is shown in Figure 9 the fourth current sensor 447d takes the form of a fourth resistor 445d and a fourth voltmeter 443d which is configured to measure the voltage drop across the fourth resistor 445d. However in other embodiments the fourth current sensor 447a may take other forms.

[00140] A second voltage supply 441b is connected between the beam pipe 105 and the second and third electrical connections 132, 133 and is configured to maintain a potential difference between the second electrode 122 and the beam pipe 105 and between the third electrode 123 and the beam pipe 105. A second current sensor 447b is configured to measure a second current I_2 which flows between the second electrode 122 and the beam pipe 105 and therefore measures the current which flows through the second electrode 122. In the embodiment which is shown in Figure 9 the second current sensor 447b takes the form of a second resistor 445b and a second voltmeter 443b which is configured to measure the voltage drop across the second resistor 445b. However in other embodiments the second current sensor 447b may take other forms.

[00141] A third current sensor 447c is configured to measure a third current I_3 which flows between the third electrode 123 and the beam pipe 105 and therefore measures the current which flows through the third electrode 123. In the embodiment which is shown in Figure 9 the third current sensor 447c takes the form of a third resistor 445c and a third voltmeter 443c which is configured to measure the voltage drop across the third resistor 445c. However in other embodiments the second current sensor 447c may take other forms.

[00142] The beam pipe 105 functions as an electrical ground and may, for example, be connected to earth. The first voltage supply 441a and the second voltage supply 441b are configured to maintain a potential difference between the first and fourth electrodes 121, 124 and the beam pipe 105 which is different to the potential difference which is maintained between the second and third electrodes 122, 123 and the beam pipe 105. The first and second voltage

supplies 441a and 441b are therefore configured to maintain a potential difference between the first and fourth electrodes 121, 124 and the second electrode 122 and to maintain a potential difference between the first and fourth electrodes 121, 124 and the third electrode 123 by maintaining potential differences between the electrodes and a common ground (which in the embodiment which is shown in Figure 9 is the beam pipe 105). The first voltage supply 441a and the second voltage supply 441b may therefore together be considered to be an example of a voltage source which maintains a potential difference between the electrodes.

[00143] The first 447a, second 447b, third 447c and fourth 447d current sensors may be together be considered to be an example of an electrical sensor which is configured to measure the current flowing through at least one of the electrodes.

[00144] The first 447a, second 447b, third 447c and fourth 447d current sensors which measure the first current I_1 , the second current I_2 , the third current I_3 and the fourth current I_4 flowing through the first 121, second 122, third 123 and fourth 124 electrodes respectively provide inputs to a processor 151. It will be appreciated from the above discussion of the currents which flow between the electrodes in the embodiment shown in Figure 6 that the first current I_1 , the second current I_2 , the third current I_3 and the fourth current I_4 are each indicative of the power of the radiation beam 102 and that a comparison of the second current I_2 and the third current I_3 and/or a comparison of the first current I_1 and the fourth current I_4 is indicative of the position of the radiation beam 102 in the x-direction. The processor 151 is operable to determine from the first, second, third and fourth currents the power of the radiation beam 102 and the position of the radiation beam 102 in the x-direction.

[00145] Other embodiments of a radiation sensor RS may include electronics which are different to those shown in the embodiment of Figure 9 and may include electronics which are different to those shown in Figure 6. In general a voltage source is configured to maintain a potential difference between electrodes in a radiation sensor RS. The potential difference may, for example, be applied directly between the electrodes (as is shown in Figure 6) or may be applied between the electrodes and a common ground such as the beam pipe 105 (as is shown in Figure 9). The voltage source may, for example, comprise a single voltage supply as is shown in Figure 6 or may comprise a plurality of voltage supplies as is shown in Figure 9. At least one electrical sensor is configured to measure the current flowing through at least one of the electrodes. The current flowing through an electrode may, for example, be measured by measuring a current flowing between electrodes (as is shown in Figure 6) or may, for example, be measured by measuring a current flowing between an electrode and a common ground such as the beam pipe 105 (as is shown in Figure 9).

[00146] It will be appreciated that the electronics 125' which are shown in Figure 9 may be adapted for embodiments which do not include a fourth electrode as was described above. The electronics 125' which are shown in Figure 9 may additionally or alternatively be adapted for embodiments which include a fifth, sixth and seventh electrode arranged to determine the position of the radiation beam 102 in the y-direction. The electronics 125' which are shown in Figure 9 may further be adapted for embodiments which further include an eighth electrode arranged to determine the position of the radiation beam in the y-direction.

[00147] It will be appreciated from the described embodiments that electrodes may be arranged in a radiation sensor RS in order to measure at least one of the power of the radiation beam 102, the position of the radiation beam in the x-direction and the position of the radiation beam in the y-direction. In some embodiments, electrodes may be arranged so as to measure all three of these quantities. In such embodiments the power of the radiation beam and the position of the radiation in a plane perpendicular to the direction of propagation of the radiation beam 102 are determined.

[00148] As has been described above, gas in the chamber 110 is ionized by the radiation beam 102 and the resulting ions and electrons travel to one of the electrodes in the chamber 110 under the influence of the electric field in the chamber 110 which results from a potential difference maintained between the electrodes. Ionization of gas in the chamber therefore results in the removal of gas from a region of the chamber 110 through which the radiation beam 102 propagates. The region of the chamber 110 from which gas is removed by ionization and transport of the resulting ions to an electrode may be referred to as an interaction region 153 which is shown generally with a dashed circle in Figure 6.

[00149] The passage of the radiation beam 102 through the chamber 110 therefore leads to a temporary reduction of the amount of gas which is present in the interaction region 153. Typically the radiation beam 102 is a pulsed radiation beam comprising a series of pulses of radiation. The passage of a pulse of radiation through the chamber 110 causes a reduction of the amount of gas in the interaction region 153. In between pulses of radiation the amount of gas in the interaction region 153 may be at least partially replenished due to gas from regions surrounding the interaction region 153 travelling into the interaction region 153. The amount of gas which is present in the interaction region 153 for a subsequent pulse of radiation (after a reduction of the gas in the interaction region 152 caused by ionization and a subsequent replenishment of the gas from regions surrounding the interaction region 153) depends on the ionization cross section of the gas in the chamber 110, the composition of the gas, the power of the radiation beam and the time interval in between successive pulses of radiation.

[00150] Known radiation sensors typically utilize a gas which has a relatively high ionization cross section so as to ensure that the amount of gas which is ionized by a radiation beam of a given power is relatively large and thus the resulting current which flows through electrodes in a radiation sensor is relatively large. For example, a gas such as xenon may be used in a radiation sensor. Xenon has a relatively high ionization cross section and is typically used in a radiation sensor at relatively low pressures such as pressures of 1×10^{-4} Pa.

[00151] For some applications the use of a gas with a relatively high ionization cross section at a relatively low pressure may be suitable. However in, for example, a lithographic system LS a radiation beam 102 which is measured by a radiation sensor RS may have a relatively high power and may be pulsed at a relatively high repetition rate. For example, the radiation beam 102 may have a power of the order of 30 kW. The radiation beam 102 may, for example, have a pulse repetition rate of approximately 375 MHz. A radiation beam having a relatively high power may cause a relatively large amount of gas to be ionized by each pulse of the radiation beam and thus a relatively large amount of gas is removed from the interaction region 153 by each pulse. A radiation beam having a relatively high repetition rate results in a relatively short time interval in between each pulse of the radiation beam and thus there is a relatively short time interval during which the interaction region 153 can be replenished with gas in between pulses of the radiation beam 102.

[00152] The large amount of gas which is removed from the interaction region 153 by each pulse of the radiation beam 102 and the small time interval during which the gas can be replenished between pulses may result in the interaction region 153 not being sufficiently replenished in between pulses of the radiation beam 102. For example, after a first pulse of the radiation beam has passed through the interaction region 153 the amount of gas in the interaction region 153 is reduced and may not be fully replenished before a second pulse of the radiation beam passes through the interaction region such that less gas is present in the interaction region 153 during the propagation of the second pulse through the interaction region 153 than during the propagation of the first pulse through the interaction region 153. Further subsequent pulses of radiation may further reduce the amount of gas which is present in the interaction region 153 which may lead to a depletion of gas in the interaction region 153.

[00153] A reduction of the amount of gas which is present in the interaction region 153 reduces the number of ionization events which are caused by a pulse of radiation passing through the interaction region 153. Reducing the number of ionization events results in a reduction in the number of ions and electrons which are formed due to ionization of the gas and thus the current which flows between the electrodes in the radiation sensor is reduced. A

reduction in the current which flows between the electrodes amounts to a reduction of the signal from which the power and/or the position of a radiation beam is measured by a radiation sensor RS. The signal to noise ratio with which the power and/or the position is determined by the radiation sensor RS is therefore reduced thereby reducing the accuracy of the determinations.

5 The current which flows between the electrodes may, for example, be reduced by depletion of gas in the interaction region 153 to such an extent that a determination of the power and/or the position of the radiation beam is no longer possible.

[00154] Furthermore, depletion of gas in the interaction region 153 may not be spatially uniform across the interaction region 153. Variations in the intensity of the radiation beam 102
10 across its cross-section may lead to variations in the quantity of gas which is ionized at different positions in the interaction region 153. For example, a radiation beam 102 which propagates through a radiation sensor may have an approximately Gaussian cross-sectional intensity distribution whose intensity is greater at the centre of the beam cross-section than at its edges. Such a radiation beam 102 may lead to a greater degree of depletion at the centre of the
15 interaction region 153 than at the edges. Consequently a determination of the position of the radiation beam 102 may be weighted towards the edges of the extent of the radiation beam 102 where there is more gas available for ionization, thereby reducing the accuracy of the determination.

[00155] In order to overcome the above mentioned problems associated with the
20 measurement of a radiation beam having a relatively high power and/or a relatively high repetition rate, one aspect of the invention contemplates the use of a radiation sensor in which hydrogen is introduced into the chamber 110 of the radiation sensor RS. In some applications the radiation beam 102 which is measured by a radiation sensor RS is an EUV radiation beam. At EUV wavelengths, the ionization cross-section of hydrogen is less than the ionization cross-
25 section of gases which are typically used in known radiation sensors. For example, at EUV wavelengths the ionization cross-section of hydrogen is approximately 400 times less than the ionization cross-section of xenon. The relatively small ionization cross-section of hydrogen means that less ionization events occur as a result of a pulse of radiation of a given power passing through the interaction region 153. The amount of gas which is removed from the
30 interaction region 153 by each pulse of radiation is therefore reduced and more gas remains in the interaction region 153 for ionization by a subsequent pulse of radiation.

[00156] In addition to the reduced ionization cross section of hydrogen, hydrogen is also lighter than gases used in known radiation sensors. The reduced mass of hydrogen (when compared to other gases) means that at a given temperature and pressure hydrogen has a

higher velocity than other gases. For example, at a given temperature and pressure the velocity of hydrogen may be approximately 8 times larger than the velocity of xenon. The increased velocity of hydrogen when compared to other gases means that after a pulse of radiation passes through the interaction region 153 and gas is removed from the interaction region 153, the interaction region 153 is replenished at an increased rate when compared to other gases. The extent to which the amount of gas in the interaction region 153 is replenished in between pulses of radiation passing through the interaction region 153 is therefore increased in the case of hydrogen when compared to other gases (such as, for example, xenon).

[00157] As has been described above using hydrogen in a radiation sensor RS results in a reduced amount of gas being removed from the interaction region 153 by each pulse of radiation and increases the rate at which gas in the interaction region 153 is replenished in between pulses of radiation which pass through the interaction region 153. This advantageously allows radiation beams having higher powers and repetition rates to be measured by a radiation sensor RS without the gas in the interaction region 153 being depleted to the extent that the accuracy of the measurement is significantly reduced.

[00158] Figure 10 is a schematic representation of the steady state gas pressure in the interaction region 153 as a function of the repetition rate of a radiation beam 102 passing through the interaction region in a radiation sensor RS which includes a chamber 110 into which hydrogen is introduced. The gas pressure in the interaction region 153 is shown in Figure 10 as a percentage of the gas pressure in the rest of the chamber 110. The dashed line which is shown in Figure 10 represents a repetition rate of 375 MHz which may, for example, be the repetition rate of an EUV radiation beam in a lithographic system LS. It can be seen from Figure 10 that the steady state gas pressure at a repetition rate of 375 MHz is close to 100% of the pressure in the rest of the chamber (and may, for example, be approximately 99.5%). The gas which is removed from the interaction region 153 due to ionization is therefore almost all replenished in between pulses of the radiation beam such that the pressure in the interaction region 153 is not significantly reduced for subsequent pulses of radiation passing through the interaction region 153. The use of a radiation sensor RS in which hydrogen is introduced to a chamber in the radiation sensor RS therefore advantageously allows for measurement of the position and/or the power of a radiation beam having a relatively large power and/or repetition rate.

[00159] As was explained above hydrogen has a smaller ionization cross section than gases used in known radiation sensors. The reduced ionization cross section of hydrogen means that at a given pressure of gas and for a given power of a radiation beam the number of

ionization events which result from a single pulse of radiation is reduced when compared to other gases and thus the current which flows between electrodes in the sensor is reduced. However, as was described above the use of hydrogen advantageously reduces the extent to which gas is depleted by a pulse of radiation and thus for subsequent pulses of radiation more ionization events may occur when hydrogen is used than when other gases are used. The current which flows between electrodes as a result of subsequent pulses of radiation is therefore advantageously increased.

[00160] An additional advantage of the use of hydrogen in a radiation sensor is that hydrogen may serve other useful purposes in a beam pipe through which a radiation beam propagates. For example, hydrogen may be introduced into a beam pipe in order to clean contamination from optical components in the beam pipe. A radiation beam propagating through hydrogen may lead to the formation of hydrogen ions and/or hydrogen radicals. If hydrogen ions are subjected to an electric field as is the case in between the electrodes in a radiation sensor RS then the hydrogen ions are attracted to one of the electrodes and recombine with electrons at one of the electrodes. However in other locations in the beam pipe the hydrogen ions are not subjected to an electric field and are not attracted to an electrode. The passage of a radiation beam 102 through a beam pipe 105 containing hydrogen may therefore lead to the presence of free hydrogen ions and/or radicals in the beam pipe 105.

[00161] Hydrogen ions and radicals are highly reactive and thus may react with other substances within the beam pipe 105. For example, particles may be present in the beam pipe 105 which may become deposited onto an optical component in the beam pipe 105 (e.g. a mirror) causing undesirable contamination of the optical component. Hydrogen ions or radicals present in the beam pipe 105 may react with the contamination to form a gaseous compound with the hydrogen. The gaseous compound which includes the contamination may then be drawn out of the beam pipe 105 by a pump so as to remove the contamination from the beam pipe 105. Hydrogen may therefore be usefully introduced into a beam pipe 105 so as to clean components situated in the beam pipe 105.

[00162] In some embodiments, hydrogen may therefore be introduced into a beam pipe 105 for other advantageous purposes. In such an embodiment a separate gas supply mechanism for a radiation sensor RS may not be required and instead a gas supply system which supplies hydrogen to the beam pipe 105 may function as a gas supply system for the radiation sensor. In such embodiments aperture plates may not be required to form a separate chamber in the radiation sensor RS and a chamber of the radiation sensor may be formed

solely from the beam pipe 105. This may advantageously reduce the complexity and/or cost of the radiation sensor RS.

[00163] The pressure of hydrogen within a chamber 110 which forms part of a radiation sensor RS may be controlled by a gas supply mechanism so as to maintain a desired pressure of hydrogen inside the chamber. The desired pressure of hydrogen inside the chamber may depend on a number of factors. For example, increasing the pressure of hydrogen inside the chamber may increase the number of ionization events which occur for each pulse of radiation which passes through the radiation sensor RS. This may lead to a corresponding increase in the current which flows between the electrodes in the radiation sensor RS thereby advantageously increasing the size of the signal on which a determination of the power and/or position of a radiation beam is based.

[00164] In some embodiments a gas supply mechanism may supply hydrogen into a chamber 110 of a radiation sensor RS so as to maintain a pressure in the chamber which is greater than about 0.01 Pascals. In some embodiments the gas supply mechanism may maintain a pressure of hydrogen in the chamber 110 which is greater than about 0.1 Pascals.

[00165] However, at a certain pressure of hydrogen in the chamber 110 the potential difference between electrodes in the chamber may induce a Paschen discharge between the electrodes. An electric discharge between electrodes may induce the formation of ions and electrons which may lead to a conductive pathway being established between electrodes. Paschen discharge may therefore disadvantageously affect measurements made by a radiation sensor RS (and may render any such measurement impossible) and it is thus desirable to maintain a pressure of hydrogen inside the chamber which is less than a pressure at which Paschen discharge occurs.

[00166] The pressure inside the chamber at which Paschen discharge occurs depends on the potential difference between electrodes, the composition of the gas between the electrodes, the separation between the electrodes and the shape of the electrodes. In embodiments in which the gas in the chamber 110 is hydrogen a potential difference between electrodes (or between an electrode and another component e.g. the beam pipe 105) which is greater than approximately 270 V may lead to Paschen discharge for some pressures and electrode arrangements. For example, at a pressure of approximately 10 Pa and a separation between electrodes of approximately 15 cm a potential difference between electrodes of approximately 270 V or larger may lead to Paschen discharge occurring. In some embodiments it may therefore be desirable to maintain a pressure of hydrogen in a chamber which is less than about 10 Pa so as to avoid Paschen discharge in the chamber. In other embodiments (e.g.

in which a different gas is used, in which there is a larger separation between electrodes and/or in which there is a small potential difference between electrodes) a pressure which is greater than 10 Pa may be maintained in a chamber whilst still avoiding Paschen discharge. In some embodiments the pressure inside the chamber may be less than about 100 Pa.

5 [00167] In some embodiments the separation between electrodes may be less than about 15 cm and/or the potential difference between electrodes may be greater than about 270 V. In such embodiments it may be desirable to maintain a pressure which is significantly less than 10 Pa inside the chamber. For example, the pressure in the chamber may be maintained at less than about 1 Pa.

10 [00168] Whilst the advantages of using a gas having a relatively low ionization cross-section have been described above in the context of using hydrogen, other gases having a low ionization cross-section may lead to the same or similar advantageous effects which were described above with reference to hydrogen. For example, helium also has a relatively low ionization cross-section for EUV radiation and may therefore equivalently be used in a radiation
15 sensor RS.

[00169] In some embodiments a radiation sensor may be suitable for measuring a radiation beam 102 having a wavelength of approximately 13.5 nm. At a wavelength of 13.5 nm hydrogen has an ionization cross-section of approximately $4.9 \times 10^{-24} \text{ m}^2$ and helium has an ionization cross-section of approximately $5.1 \times 10^{-23} \text{ m}^2$. By comparison xenon which may be
20 used in some radiation sensors has an ionization cross-section of approximately $2.5 \times 10^{-21} \text{ m}^2$.

[00170] In some embodiments a radiation sensor may be suitable for measuring a radiation beam 102 having a wavelength of approximately 6.75 nm. At a wavelength of 6.75 nm hydrogen has an ionization cross-section of approximately $5.9 \times 10^{-25} \text{ m}^2$ and helium has an ionization cross-section of approximately $7.7 \times 10^{-24} \text{ m}^2$.

25 [00171] Whilst the advantages of using hydrogen or helium in a chamber which forms part of a radiation sensor RS have been described above, other gases may alternatively be advantageously used in a radiation sensor RS. For example, a gas such as xenon which has a relatively high ionization cross section may be used in a radiation sensor RS. As was described above, using a gas with a relatively high ionization cross section may lead to depletion of the
30 gas in an interaction region 153 in which the gas is ionized by a radiation beam 102. In particular a radiation beam 102 having a relatively high power and/or a relatively high repetition rate may cause depletion of the gas in the interaction region 153. Depletion of gas in the interaction region 153 reduces the number of ionization events which are caused by a given pulse of a radiation beam 102 and therefore reduces a resulting current which flows between

electrodes in the radiation sensor RS. A reduction of the current flowing between the electrodes reduces the size of the signal from which the power and/or the position of the radiation beam 102 is determined and therefore reduces the signal to noise ratio with which the determination is made.

5 **[00172]** As was described above, one solution to this problem is to use a gas with a smaller ionization cross section such as hydrogen or helium. An alternative solution to the problem is to increase the pressure of the gas in the chamber 110 which forms part of the radiation sensor RS. Increasing the pressure inside the chamber 110 leads to an increase in the number of ionization events which result from a given pulse of radiation which passes
10 through the chamber 110, thereby increasing the resulting current flow between the electrodes. Since increasing the pressure inside the chamber increases the number of ionization events which result from a given pulse of radiation, the amount of gas which is removed from the interaction region 153 during each pulse is also increased. The interaction region 153 may therefore remain depleted despite increasing the pressure of the gas. However, despite the
15 depletion of gas in the interaction region 153 the current which flows between the electrodes in the radiation sensor RS is increased by increasing the pressure of the gas in the chamber 110. Increasing the pressure therefore leads to an increase in the size of the signal on which the determination of the power and/or the position of the radiation beam is based and thus increases the signal to noise ratio with which the determination is made. For example,
20 increasing the pressure of gas inside the chamber from, for example, a pressure of 1×10^{-3} Pa to a pressure of 0.1 Pa may increase the signal to noise ratio of a determination of the power and/or the position of a radiation beam by a factor of about 100.

[00173] Increasing the pressure inside a chamber 110 in a radiation sensor RS may therefore advantageously allow measurements of the position and/or the power of a radiation
25 beam having a relatively large power and/or repetition rate to be made with the radiation sensor. For example the power and/or the position of a radiation beam which propagates through a lithographic system LS may be measured.

[00174] Increasing the pressure inside a chamber 110 in a radiation sensor RS will however increase the fraction of the radiation beam propagating through the chamber which is
30 absorbed. The pressure inside the chamber 110 may therefore be controlled in order to limit attenuation of the radiation beam by absorption.

[00175] In some embodiments a radiation sensor RS may include a gas supply mechanism which is configured to maintain a gas in a chamber 110 which is greater than about 0.01 Pascals. In some embodiments the gas supply mechanism may be configured to maintain

a gas in the chamber which is greater than about 0.1 Pascals. The gas may be any gas which is ionized by a radiation beam. The gas may, for example, comprise xenon. In some embodiments the gas may comprise any noble gas. For example, the gas may comprise one or more of helium, neon, argon, krypton and/or xenon. In some embodiments a non-noble gas such as nitrogen and/or oxygen may be used.

[00176] As has been explained above with reference to the use of hydrogen in a radiation sensor RS, as the pressure of the gas in the chamber 110 of a radiation sensor RS is increased a pressure may be reached at which Paschen discharge is induced in between the electrodes in the chamber. It is therefore desirable to maintain a gas in the chamber at a pressure below which Paschen discharge is induced.

[00177] As was explained above, the extent to which gas is depleted in a radiation sensor depends on the power of the radiation beam. Gas depletion in a radiation sensor RS may therefore be decreased or avoided by measuring a radiation beam having a reduced power. This may, for example, be achieved by only measuring a portion of a radiation beam and using the measurement to derive one or more properties of the whole radiation beam.

[00178] Figure 11 is a schematic illustration of an arrangement in which a portion of a radiation beam 202 is measured with a radiation sensor RS. A beam splitter 205 is positioned in the path of the radiation beam 202 and is configured to receive the radiation beam 202 and split the radiation beam 202 into a first portion 203 and a second portion 204. The second portion 204 of the radiation beam 202 is directed to the radiation sensor RS which may, for example, take the form of the radiation sensor RS depicted in Figures 4-6. The radiation sensor RS is configured to measure the power and/or the position of the second portion 204 of the radiation beam 202. The power and/or the position of the second portion 204 is indicative of the power and/or the position of the radiation beam 202 and may therefore be used to determine the power and/or the position of the radiation beam 202. The first portion 203 is used for the main application of the radiation beam 202. For example, the first portion 203 or a portion of the first portion 203 may be provided to a lithographic apparatus LA in a lithographic system LS.

[00179] The beam splitter 205 may be configured to direct only a small fraction of the power of the radiation beam 202 to form the second portion 204. For example, the second portion 204 may have a power of less than 1% of the power of the radiation beam 202. In some embodiments the second portion may have a power of approximately 0.1% of the power of the radiation beam 202. Since the power of the second portion 204 is much less than the power of the radiation beam 202 the second portion 204 may be measured by the radiation sensor RS without causing gas depletion in the radiation sensor RS. Measuring only a portion 204 of a

radiation beam 202 may therefore advantageously allow the power and/or the position of a high power radiation beam 202 (such an EUV radiation beam in a lithographic system LS) to be determined without causing gas depletion in the radiation sensor RS.

[00180] The beam splitter 205 may, for example, comprise a diffraction grating which splits the radiation beam 202 into a number of different diffraction orders. The second portion 204 of the radiation beam may represent a first diffraction order and the first portion 203 of the radiation beam may represent a zeroth diffraction order.

[00181] Whilst in Figure 11 the second portion 204 is shown as propagating in a direction which is approximately perpendicular to the direction of propagation of the radiation beam 202 towards the beam splitter 205, in some embodiments the second portion 204 may propagate in a different direction. Furthermore, whilst the first portion 203 of the radiation beam is shown in Figure 11 as propagating in a direction which is substantially the same as the direction of propagation of the radiation beam 202 towards the beam splitter 205, in some embodiments the first portion may propagate in different directions. For example, in some embodiments the beam splitter 205 may comprise a reflective grating. A reflective grating may reflect a zeroth diffraction order which forms the first portion 203 and may reflect a first diffraction order at a non-perpendicular angle which forms the second portion 204.

[00182] In some embodiments one or more measurements of the power and/or the position of a radiation beam may be used to provide input to a feedback loop which controls the power and/or the position of the radiation beam. For example, the power of a radiation beam may be controlled (e.g. using one or more attenuators) in response to a measurement of the power of the radiation beam so as to maintain the power of the radiation beam at a desired power. Similarly, the position of a radiation beam may be controlled (e.g. by controlling the alignment of one or more optical components) in response to a measurement of the position of the radiation beam.

[00183] In some embodiments, multiple radiation sensors RS may be arranged to measure the power and/or the position of a radiation beam at multiple locations (e.g. at multiple locations in a lithographic system LS). For example, a first radiation sensor may be arranged to determine at least one of a power and a position of a radiation beam at a first location and a second radiation sensor may be arranged to determine at least one of a power and a position of a radiation beam at a second location. The first radiation sensor may, for example, be configured to determine a position of the radiation beam at the first location and the second radiation sensor may be configured to determine a position of the radiation beam at the second location. The position of the radiation beam at two or more locations along its propagation path

may be used to determine the direction of propagation of the radiation beam between the two locations. For example, a processor may be configured to compare the determined position of the radiation beam at the first location and the determined position of the radiation beam and may determine from the comparison a direction of propagation of the radiation beam.

5 **[00184]** Figure 12 is a schematic illustration of a radiation sensor system 301 which includes a first radiation sensor RS_1 and a second radiation sensor RS_2 . The first radiation sensor RS_1 is arranged to measure one or more properties of a radiation beam 302 shortly after the radiation beam 302 has been emitted from a radiation source SO. The radiation sensor system 301 also includes a beam splitter 305 which is configured to split the radiation beam 302
10 into a first portion 303 and a second portion 304. The second portion 304 is directed to the second radiation sensor RS_2 .

[00185] Since the first radiation sensor RS_1 is positioned relatively close to the radiation source SO, the radiation beam 302 which propagates through the first radiation sensor RS_1 may have a relatively high power and a relatively small cross section. The high power and relatively
15 small cross section of the radiation beam 302 in the first radiation sensor RS_1 may cause depletion of the gas in the first radiation sensor RS_1 . A measurement of the power of a radiation beam may in particular be sensitive to gas depletion in a radiation sensor whereas a measurement of the position of a radiation beam may be less sensitive to gas depletion in the radiation sensor. Since the first radiation sensor RS_1 may experience gas depletion in the
20 sensor, the first radiation sensor RS_1 may be used to determine the position of the radiation beam 302 but not used to determine the power of the radiation beam 302. Whilst a measurement of the position of a radiation beam may be less sensitive to gas depletion in a radiation sensor, any spatial variability in the gas depletion which occurs in the radiation sensor may reduce the accuracy of the measurement of the position of the radiation beam.

25 **[00186]** The second portion 304 of the radiation beam 302 may represent a relatively small fraction of the power of the radiation beam 302 and thus may cause little or no gas depletion in the second radiation sensor RS_2 . Since there may be little or no gas depletion in the second radiation sensor RS_2 , the second radiation sensor RS_2 may be suitable for determining the power of the second portion 304 of the radiation beam from which the power of the radiation
30 beam 302 may be determined.

[00187] In the radiation sensor system 301 which is shown in Figure 12, the position of the radiation beam 302 may therefore be determined by the first radiation sensor RS_1 and the power of the radiation beam 302 may be determined by the second radiation sensor RS_2 . In some embodiments the second radiation sensor RS_2 may also determine the position of the

second portion 304 of the radiation beam. The position of the radiation beam 302 which is determined by the first radiation sensor RS_1 may be compared with the position of the second portion 304 of the radiation beam which is determined by the second radiation sensor RS_2 in order to determine the direction of propagation of the radiation beam 302.

5 **[00188]** Whilst embodiments have been described above in which a position and/or a power of a radiation beam which propagates in a lithographic system LS is determined by a radiation sensor RS, embodiments of a radiation sensor RS as described herein may be used to determine a radiation beam used in applications other than lithography.

10 **[00189]** Whilst embodiments of a radiation source SO have been described and depicted as comprising a free electron laser FEL, a radiation source SO may include a source of radiation other than a free electron laser FEL.

[00190] It should be appreciated that a radiation source which comprises a free electron laser FEL 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
15 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 is being repaired or undergoing maintenance.

[00191] 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,
20 depend on the amount of radiation which is output from a radiation source 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.

[00192] Embodiments of a lithographic system LS may also include one or more mask
25 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
30 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.

[00193] 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 limited to, lithography.

[00194] 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 therefore comprise a free electron which outputs a radiation beam which is not an EUV radiation beam. As has been explained above the ionization cross-section of a gas is dependent on the wavelength of radiation in question. At wavelengths which are not in the EUV range, the behavior of particular gases which have been described above in the context of EUV radiation may be different than has been described.

[00195] 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.

[00196] 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.

[00197] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

[00198] 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 radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to supply hydrogen or helium into the chamber;

a first electrode situated in the chamber;
a second electrode situated in the chamber;
a voltage source configured to maintain a potential difference between the first electrode and the second electrode;

5 an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the hydrogen or helium in the chamber caused by a radiation beam propagating through the chamber; and

a processor operable to determine, from the measured electrical current, at least
10 one of a power and a position of a radiation beam propagating through the chamber.

2. The radiation sensor of clause 1, wherein the gas supply mechanism is configured to maintain a desired pressure of hydrogen or helium in the chamber.

15 3. The radiation sensor of clause 2, wherein the gas supply mechanism is configured to maintain a pressure of hydrogen or helium in the chamber which is greater than about 0.01 Pascals.

4. The radiation sensor of clause 2 or 3, wherein the gas supply mechanism is
20 configured to maintain a pressure of hydrogen or helium in the chamber which is less than about 100 Pascals.

5. A radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second
25 opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to maintain a gas in the chamber at a pressure which is greater than about 0.01 Pascals;

a first electrode situated in the chamber;

30 a second electrode situated in the chamber;

a voltage source configured to maintain a potential difference between the first electrode and the second electrode;

an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from

ionization of the gas in the chamber caused by a radiation beam propagating through the chamber; and

a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

5

6. The radiation sensor of clause 5, wherein the gas supply mechanism is configured to maintain a gas in the chamber at a pressure which is greater than about 0.1 Pascals.

7. The radiation sensor of clause 5 or 6, wherein the gas supply mechanism is
10 configured to maintain a gas in the chamber at a pressure which is less than about 100 Pascals.

8. The radiation sensor of any of clauses 5-7, wherein the gas supply mechanism is configured to maintain hydrogen or helium in the chamber.

15 9. The radiation sensor of any preceding clause, further comprising a third electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the first electrode and the third electrode and wherein the electrical sensor is configured to measure an electrical current flowing through the second electrode and to measure an electrical current flowing through the third electrode, wherein the first, second and
20 third electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the second electrode and a change in the electrical current flowing between through the third electrode.

25 10. The radiation sensor of clause 9, wherein the processor is operable to compare the electrical current flowing through the second electrode with the electrical current flowing through the third electrode and determine from the comparison a position, in the first direction, of a radiation beam propagating through the chamber.

30 11. The radiation sensor of clause 9 or 10, wherein the voltage source is configured to maintain the first electrode at a higher voltage than the second electrode and at a higher voltage than the third electrode.

12. The radiation sensor of any of clauses 9-11, wherein the voltage source is configured to maintain a potential difference between the first electrode and the second electrode and a potential difference between the first electrode and the third electrode, the potential differences being substantially the same as each other.

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13. The radiation sensor of any preceding clause, further comprising a fourth electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the fourth electrode and the second electrode and is configured to maintain a potential difference between the fourth electrode and the third electrode, wherein the first and
10 fourth electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the first electrode and a change in the electrical current flowing between through the fourth electrode.

14. The radiation sensor of clause 13, wherein the electrical sensor is configured to measure an electrical current flowing through the first electrode and an electrical current flowing through the fourth electrode.

15. The radiation sensor of clause 14, wherein the processor is operable to compare the
20 electrical current flowing through the first electrode and the electrical current flowing through the fourth electrode and determine from the comparison a position, in the first direction, of a radiation beam propagating through the chamber.

16. The radiation sensor of any preceding clause, further comprising:

25 a fifth electrode situated in the chamber;
a sixth electrode situated in the chamber; and
a seventh electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the fifth electrode and the sixth electrode and maintain a potential difference between the fifth electrode and
30 the seventh electrode;
wherein the electrical sensor is configured to measure an electrical current flowing through the sixth electrode and to measure an electrical current flowing through the seventh electrode; and

wherein the fifth electrode, the sixth electrode and the seventh electrode are arranged such that a change in the position, in a second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the sixth electrode and a change in the electrical current flowing through the seventh electrode.

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17. The radiation sensor of clause 16, wherein the processor is operable to compare the electrical current flowing through the sixth electrode with the electrical current flowing through the seventh electrode and determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

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18. The radiation sensor of clause 16 or 17, wherein the first and second directions extend perpendicular to the direction of propagation of the radiation beam through the chamber.

19. The radiation sensor of any of clauses 16-18, wherein the first and second directions extend perpendicular to each other.

15

20. The radiation sensor of any of clauses 16-19, further comprising an eighth electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the eighth electrode and the sixth electrode and is configured to maintain a potential difference between the eighth electrode and the seventh electrode, wherein the fifth and eighth electrodes are arranged such that a change in the position, in the second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the fifth electrode and a change in the electrical current flowing between through the eighth electrode.

25

21. The radiation sensor of clause 20, wherein the electrical sensor is configured to measure an electrical current flowing through the fifth electrode and an electrical current flowing through the eighth electrode.

22. The radiation sensor of clause 21, wherein the processor is operable to compare the electrical current flowing through the fifth electrode and the electrical current flowing through the eighth electrode and determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

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23. The radiation sensor of any preceding clause, further comprising a beam splitter arranged to receive a radiation beam and split the radiation beam into a first portion and a second portion and direct the second portion to propagate through the chamber.

24. The radiation sensor of clause 23, wherein the beam splitter comprises a grating.

25. A radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to supply a gas into the chamber;

a first electrode situated in the chamber;

a second electrode situated in the chamber;

a third electrode situated in the chamber;

a voltage source configured to maintain a potential difference between the first electrode and the second electrode and maintain a potential difference between the first electrode and the third electrode; and

an electrical sensor configured to measure an electrical current flowing through the second electrode and an electrical current flowing through the third electrode, the electrical currents resulting from ionization of the gas in the chamber caused by a radiation beam propagating through the chamber;

wherein the first, second and third electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the second electrode and a change in the electrical current flowing through the third electrode;

the radiation sensor further comprising a processor operable to determine, from the measured electrical current flowing through the second electrode and the measured electrical current flowing through the third electrode a position in the first direction of a radiation beam propagating through the chamber.

26. The radiation sensor of clause 25, wherein the chamber is arranged to receive a radiation beam generally along a beam axis extending between the first opening and the second opening and wherein the second and third electrodes are arranged such that a projection of the beam axis onto the second and third electrodes coincides with the third electrode for a first

portion of the projection and coincides with the second electrode for a second portion of the projection and wherein the electrodes are configured such that a change in the position of the beam axis in the first direction causes a change in the length of the first portion of the projection relative to the length of the second portion of the projection.

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27. The radiation sensor of clause 26, wherein the second electrode comprises a first straight edge which is arranged to intersect the projection of the beam axis onto the second electrode and wherein the third electrode comprises a second straight edge which is arranged to intersect the projection of the beam axis onto the third electrode.

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28. The radiation sensor of clause 27, wherein the first straight edge and the second straight edge are parallel to each other.

29. The radiation sensor of any of clauses 25-28, wherein the processor is operable to compare the electrical current flowing through the second electrode with the electrical current flowing through the third electrode in order to determine from the comparison the position, in the first direction, of a radiation beam propagating through the chamber.

15

30. The radiation sensor of any of clauses 25-29, wherein the voltage source is configured to maintain the first electrode at a higher voltage than the second electrode and at a higher voltage than the third electrode.

20

31. The radiation sensor of any of clauses 25-30, wherein the processor is further operable to determine from at least one of the measured electrical current flowing through the second electrode, and the measured electrical current flowing through the third electrode a power of a radiation beam propagating through the chamber.

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32. The radiation sensor of any of clauses 25-31, further comprising:

a fifth electrode situated in the chamber;

a sixth electrode situated in the chamber; and

a seventh electrode situated in the chamber, wherein the voltage source is configured to maintain a potential difference between the fifth electrode and the sixth electrode and maintain a potential difference between the fifth electrode and the seventh electrode;

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wherein the electrical sensor is configured to measure an electrical current flowing through the sixth electrode and an electrical current flowing through the seventh electrode;

5 wherein the fifth electrode, the sixth electrode and the seventh electrode are arranged such that a change in the position, in a second direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the sixth electrode and a change in the electrical current flowing through the seventh electrode, and wherein the processor is operable to determine from the measured electrical current flowing through the sixth electrode, and the measured electrical current flowing through the seventh
10 electrode a position in the second direction of a radiation beam propagating through the chamber.

33. The radiation sensor of clause 32, wherein the sixth and seventh electrodes are arranged such that a projection of the beam axis onto the sixth and seventh electrodes
15 coincides with the sixth electrode for a first portion of the projection and coincides with the seventh electrode for a second portion of the projection and wherein the sixth and seventh electrodes are arranged such that a change in the position of the beam axis in the second direction causes a change in the length of the first portion of the projection relative to the length of the second portion of the projection.

20 34. The radiation sensor of clause 32 or 33, wherein the processor is operable to compare the electrical current flowing through the sixth electrode with the electrical current flowing through the seventh electrode in order to determine from the comparison a position, in the second direction, of a radiation beam propagating through the chamber.

25 35. The radiation sensor of any of clauses 32-34, wherein the first and second directions extend perpendicular to the direction of propagation of the radiation beam through the chamber.

30 36. The radiation sensor of any of clauses 32-35, wherein the first and second directions extend perpendicular to each other.

37. A radiation sensor system comprising:

a first radiation sensor according to any of clauses 1-36 arranged to determine at least one of a position and a power of a radiation beam at a first location;

a second radiation sensor according to any of clauses 1-36 arranged to determine at least one of a position and a power of the radiation beam at a second location.

38. The radiation sensor system of clause 37, wherein the first radiation sensor is
5 configured to determine a position of the radiation beam at the first location and the second radiation sensor is configured to determine a position of the radiation beam at the second location and wherein the radiation sensor system further comprises a processor configured to compare the determined position of the radiation beam at the first location with the determined position of the radiation beam at the second location and determine from the comparison a
10 direction of propagation of the radiation beam between the first radiation sensor and the second radiation sensor.

39. The radiation sensor system of clause 37 or 38, wherein the first radiation sensor is configured to determine a position of the radiation beam at the first location and the second
15 radiation sensor is configured to determine a power of the radiation beam at the second location.

40. The radiation sensor system of clause 39, further comprising a beam splitter arranged to receive the radiation beam between the first location and the second location, split
20 the radiation beam into a first portion and a second portion and direct the second portion to the second location.

41. A lithographic system comprising:
a radiation source configured to provide a main radiation beam;
25 a plurality of lithographic apparatus;
a beam delivery system configured to split the main radiation beam into at least one branch radiation beam and direct the at least one branch radiation beam to at least one lithographic apparatus; and
a radiation sensor according to any of clauses 1-36 or a radiation sensor system
30 according to any or clauses 37-40, the radiation sensor or radiation sensor system being arranged to determine at least one of a power and a position of the main radiation beam and/or a branch radiation beam.

42. The lithographic system of clause 41, wherein the radiation source is configured to provide an EUV main radiation beam.

43. The lithographic system of clause 41 or 42, wherein the radiation source is configured to provide a pulsed main radiation beam having a repetition rate which is greater than about 100 Hz.

44. The lithographic system of any of clauses 41-43, wherein the radiation source comprises at least one free electron laser.

45. A method of measuring at least one of a position and a power of a radiation beam, the method comprising:

providing a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

supplying hydrogen or helium into the chamber;

maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber;

directing a radiation beam to propagate through the chamber;

measuring an electrical current flowing between through at least one of the electrodes, the electrical current resulting from ionization of hydrogen or helium in the chamber caused by the radiation beam propagating through the chamber; and

determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

46. The method of clause 45, further comprising maintaining the hydrogen or helium in the chamber at a desired pressure.

47. The method of clause 46, wherein the hydrogen or helium is maintained at a pressure which is greater than about 0.01 Pascals.

48. The method of clause 46 or 47, wherein the hydrogen or helium is maintained at a pressure which is less than about 100 Pascals.

49. A method of measuring at least one of a position and a power of a radiation beam, the method comprising:

providing a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

supplying a gas into the chamber and maintaining the gas at a pressure which is greater than about 0.01 Pascals;

maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber;

directing a radiation beam to propagate through the chamber;

measuring an electrical current flowing through at least one of the electrodes, the electrical current resulting from ionization of the gas in the chamber caused by the radiation beam propagating through the chamber; and

determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

50. The method of clause 49, wherein the gas is maintained at a pressure which is greater than about 100 Pascals.

CLAIMS

1. A radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to supply hydrogen or helium into the chamber;

a first electrode situated in the chamber;

a second electrode situated in the chamber;

a voltage source configured to maintain a potential difference between the first electrode and the second electrode;

an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the hydrogen or helium in the chamber caused by a radiation beam propagating through the chamber; and

a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

2. The radiation sensor of claim 1, wherein the gas supply mechanism is configured to maintain a desired pressure of hydrogen or helium in the chamber.

3. The radiation sensor of claim 2, wherein the gas supply mechanism is configured to maintain a pressure of hydrogen or helium in the chamber which is greater than about 0.01 Pascals.

4. The radiation sensor of claim 2 or 3, wherein the gas supply mechanism is configured to maintain a pressure of hydrogen or helium in the chamber which is less than about 100 Pascals.

5. A radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to maintain a gas in the chamber at a pressure which is greater than about 0.01 Pascals;

a first electrode situated in the chamber;

a second electrode situated in the chamber;

5 a voltage source configured to maintain a potential difference between the first electrode and the second electrode;

an electrical sensor configured to measure an electrical current flowing through at least one of the first electrode and the second electrode, the electrical current resulting from ionization of the gas in the chamber caused by a radiation beam propagating through the
10 chamber; and

a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

6. The radiation sensor of claim 5, wherein the gas supply mechanism is configured to
15 maintain a gas in the chamber at a pressure which is greater than about 0.1 Pascals.

7. The radiation sensor of claim 5 or 6, wherein the gas supply mechanism is configured to maintain a gas in the chamber at a pressure which is less than about 100 Pascals.

20 8. The radiation sensor of any of claims 5-7, wherein the gas supply mechanism is configured to maintain hydrogen or helium in the chamber.

9. A radiation sensor comprising:

a chamber for containing a gas, the chamber having a first opening and a second
25 opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

a gas supply mechanism configured to supply a gas into the chamber;

a first electrode situated in the chamber;

a second electrode situated in the chamber;

30 a third electrode situated in the chamber;

a voltage source configured to maintain a potential difference between the first electrode and the second electrode and maintain a potential difference between the first electrode and the third electrode; and

an electrical sensor configured to measure an electrical current flowing through the second electrode and an electrical current flowing the third electrode, the electrical currents resulting from ionization of the gas in the chamber caused by a radiation beam propagating through the chamber;

5 wherein the first, second and third electrodes are arranged such that a change in the position, in a first direction, of a radiation beam propagating through the chamber causes a change in the electrical current flowing through the second electrode and a change in the electrical current flowing through the third electrode;

10 the radiation sensor further comprising a processor operable to determine, from the measured electrical current flowing through the second electrode and the measured electrical current flowing through the third electrode a position in the first direction of a radiation beam propagating through the chamber.

10. The radiation sensor of claim 9, wherein the chamber is arranged to receive a radiation
15 beam generally along a beam axis extending between the first opening and the second opening and wherein the second and third electrodes are arranged such that a projection of the beam axis onto the second and third electrodes coincides with the third electrode for a first portion of the projection and coincides with the second electrode for a second portion of the projection and wherein the electrodes are configured such that a change in the position
20 of the beam axis in the first direction causes a change in the length of the first portion of the projection relative to the length of the second portion of the projection.

11. The radiation sensor of claim 10, wherein the second electrode comprises a first straight
25 edge which is arranged to intersect the projection of the beam axis onto the second electrode and wherein the third electrode comprises a second straight edge which is arranged to intersect the projection of the beam axis onto the third electrode.

12. The radiation sensor of claim 11, wherein the first straight edge and the second straight
30 edge are parallel to each other.

13. The radiation sensor of any of claims 9-12, wherein the processor is operable to compare the electrical current flowing through the second electrode with the electrical current flowing through the third electrode in order to determine from the comparison the position, in the first direction, of a radiation beam propagating through the chamber.

14. The radiation sensor of any of claims 9-13, wherein the voltage source is configured to maintain the first electrode at a higher voltage than the second electrode and at a higher voltage than the third electrode.

5

15. The radiation sensor of any of claims 9-14, wherein the processor is further operable to determine from at least one of the measured electrical current flowing through the second electrode, and the measured electrical current flowing through the third electrode a power of a radiation beam propagating through the chamber.

10

16. A radiation sensor system comprising:

a first radiation sensor according to any of claims 1-15 arranged to determine at least one of a position and a power of a radiation beam at a first location;

15 a second radiation sensor according to any of claims 1-15 arranged to determine at least one of a position and a power of the radiation beam at a second location.

17. The radiation sensor system of claim 16, wherein the first radiation sensor is configured to determine a position of the radiation beam at the first location and the second radiation sensor is configured to determine a position of the radiation beam at the second location and wherein the radiation sensor system further comprises a processor configured to compare the determined position of the radiation beam at the first location with the determined position of the radiation beam at the second location and determine from the comparison a direction of propagation of the radiation beam between the first radiation sensor and the second radiation sensor.

25

18. The radiation sensor system of claim 16 or 17, wherein the first radiation sensor is configured to determine a position of the radiation beam at the first location and the second radiation sensor is configured to determine a power of the radiation beam at the second location.

30

19. The radiation sensor system of claim 18, further comprising a beam splitter arranged to receive the radiation beam between the first location and the second location, split the radiation beam into a first portion and a second portion and direct the second portion to the second location.

20. A lithographic system comprising:

a radiation source configured to provide a main radiation beam;

a plurality of lithographic apparatus;

5 a beam delivery system configured to split the main radiation beam into at least one branch radiation beam and direct the at least one branch radiation beam to at least one lithographic apparatus; and

10 a radiation sensor according to any of claims 1-15 or a radiation sensor system according to any or claims 16-19, the radiation sensor or radiation sensor system being arranged to determine at least one of a power and a position of the main radiation beam and/or a branch radiation beam.

21. A method of measuring at least one of a position and a power of a radiation beam, the method comprising:

15 providing a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

supplying hydrogen or helium into the chamber;

20 maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber;

directing a radiation beam to propagate through the chamber;

measuring an electrical current flowing between through at least one of the electrodes, the electrical current resulting from ionization of hydrogen or helium in the chamber caused by the radiation beam propagating through the chamber; and

25 determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

22. The method of claim 21, further comprising maintaining the hydrogen or helium in the chamber at a desired pressure.

30

23. The method of claim 22, wherein the hydrogen or helium is maintained at a pressure which is greater than about 0.01 Pascals.

24. The method of claim 22 or 23, wherein the hydrogen or helium is maintained at a pressure which is less than about 100 Pascals.

25. A method of measuring at least one of a position and a power of a radiation beam, the method comprising:

providing a chamber for containing a gas, the chamber having a first opening and a second opening such that a radiation beam can enter the chamber through the first opening, propagate through the chamber and exit the chamber through the second opening;

supplying a gas into the chamber and maintaining the gas at a pressure which is greater than about 0.01 Pascals;

maintaining a potential difference between a first electrode situated in the chamber and a second electrode situated in the chamber;

directing a radiation beam to propagate through the chamber;

measuring an electrical current flowing through at least one of the electrodes, the electrical current resulting from ionization of the gas in the chamber caused by the radiation beam propagating through the chamber; and

determining from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber.

26. The method of claim 25, wherein the gas is maintained at a pressure which is greater than about 100 Pascals.

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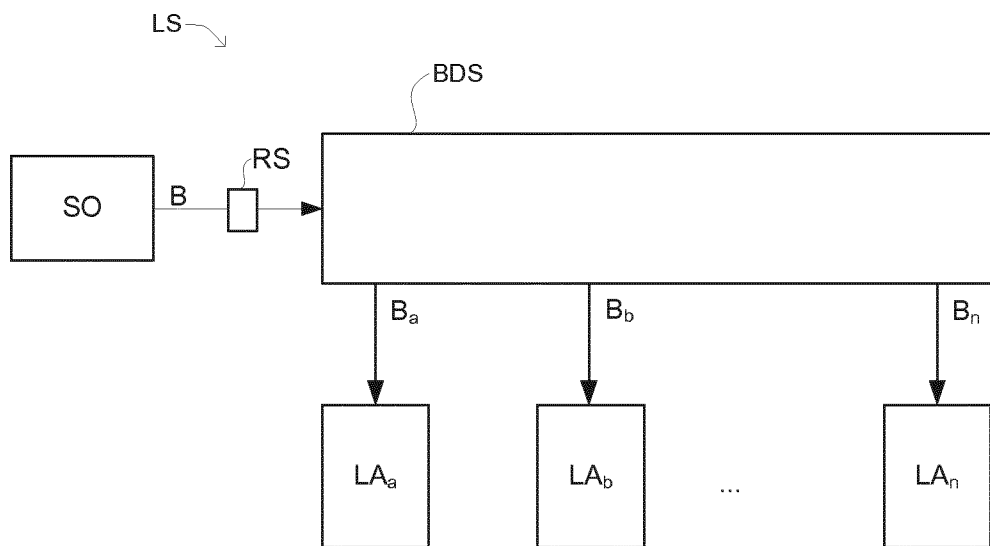


FIG. 1

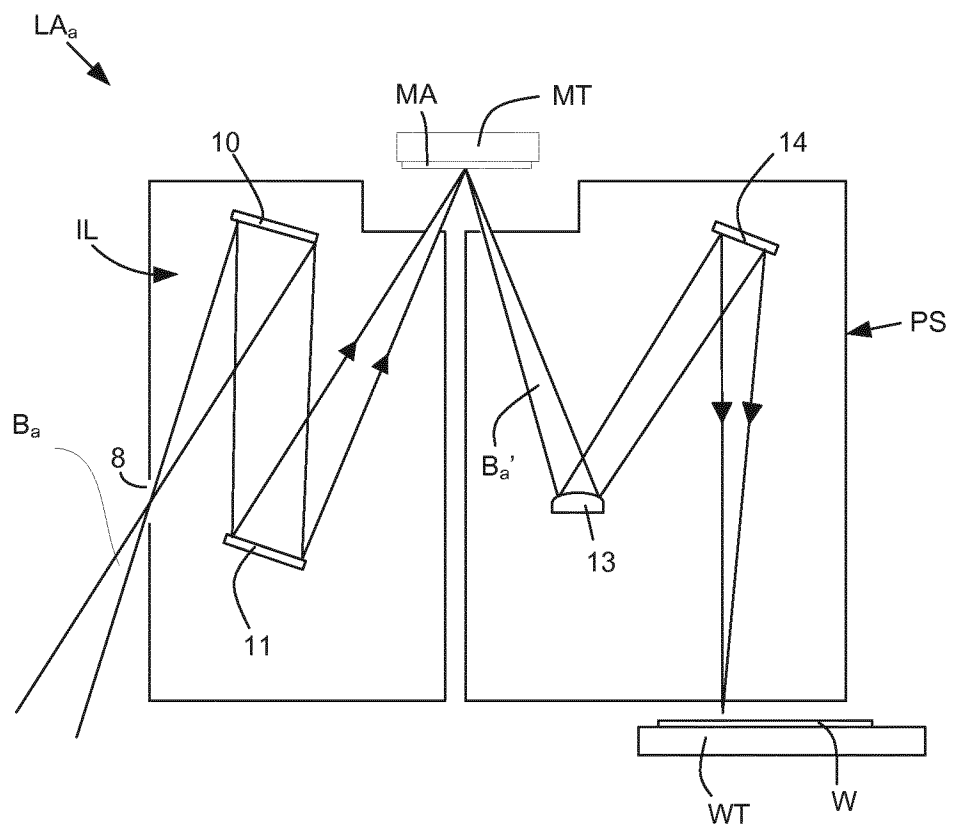


FIG. 2

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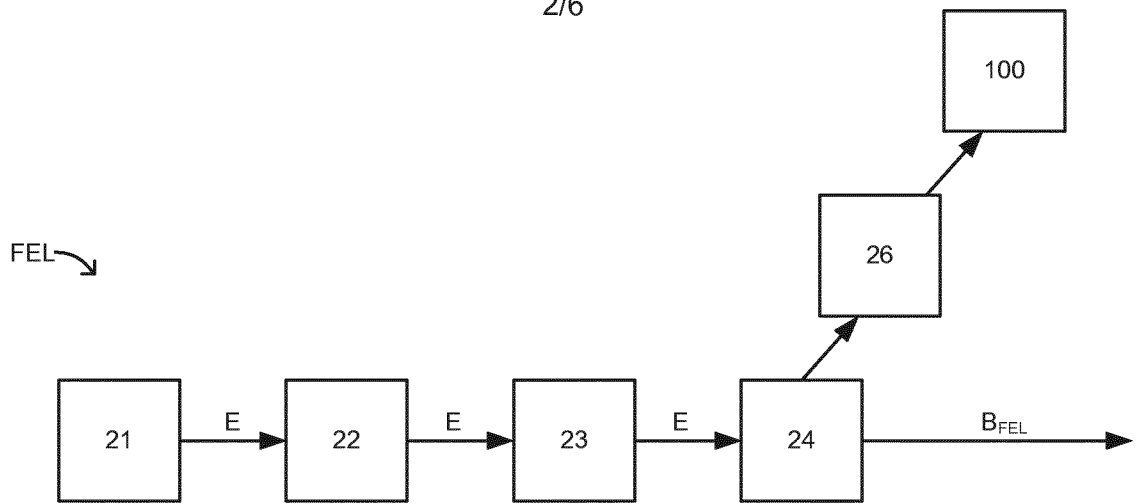


FIG. 3

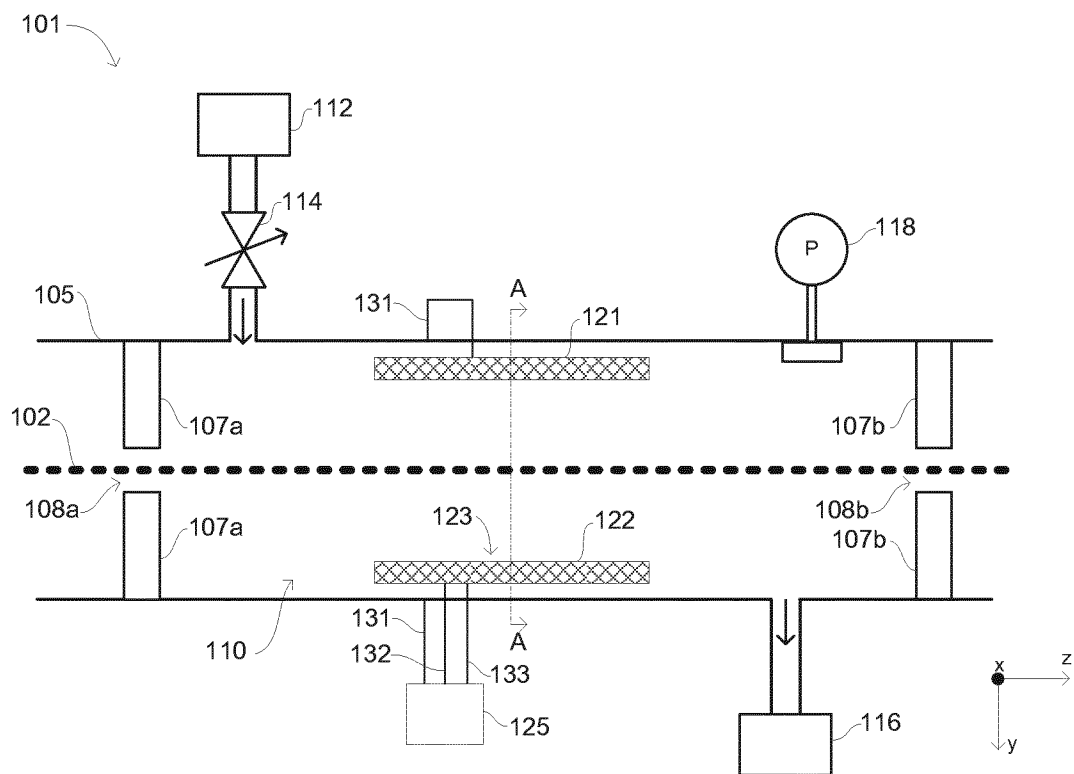


FIG. 4

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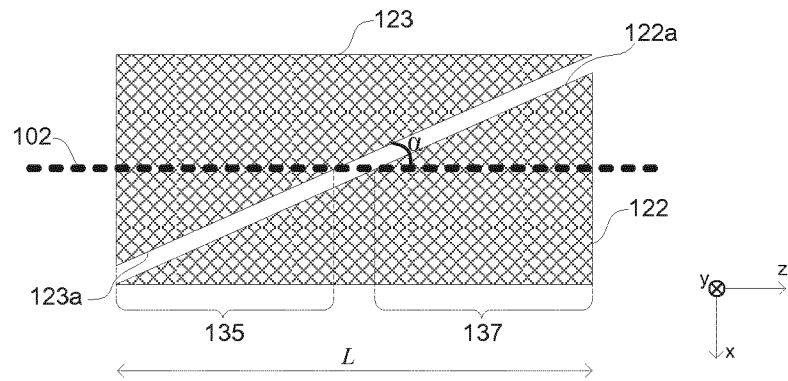


FIG. 5

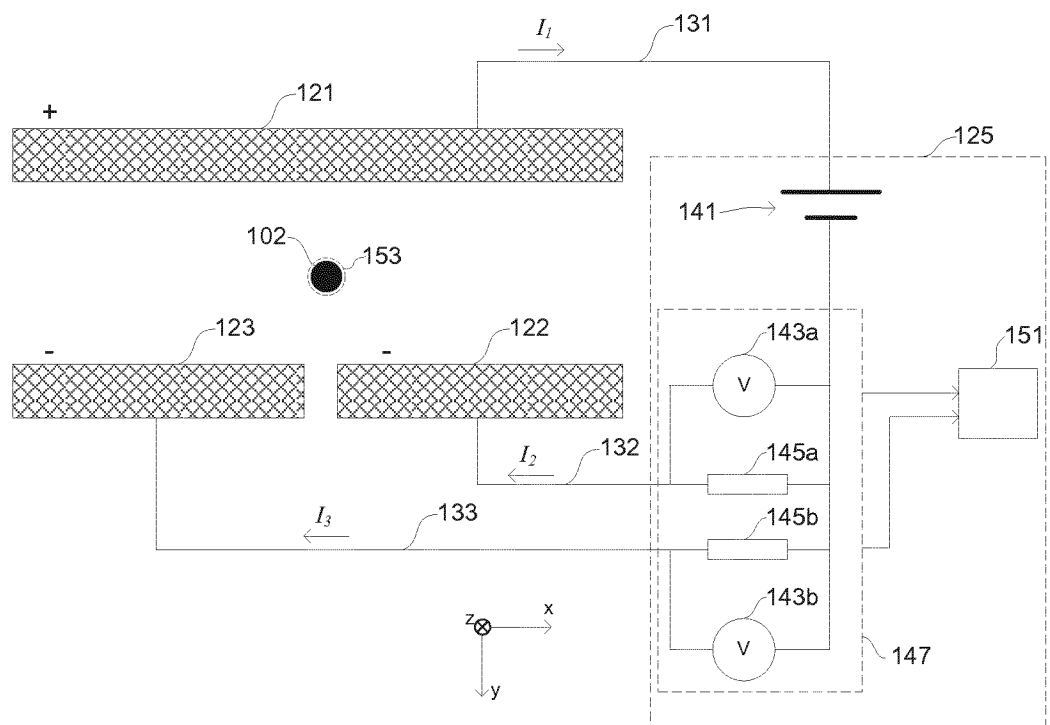


FIG. 6

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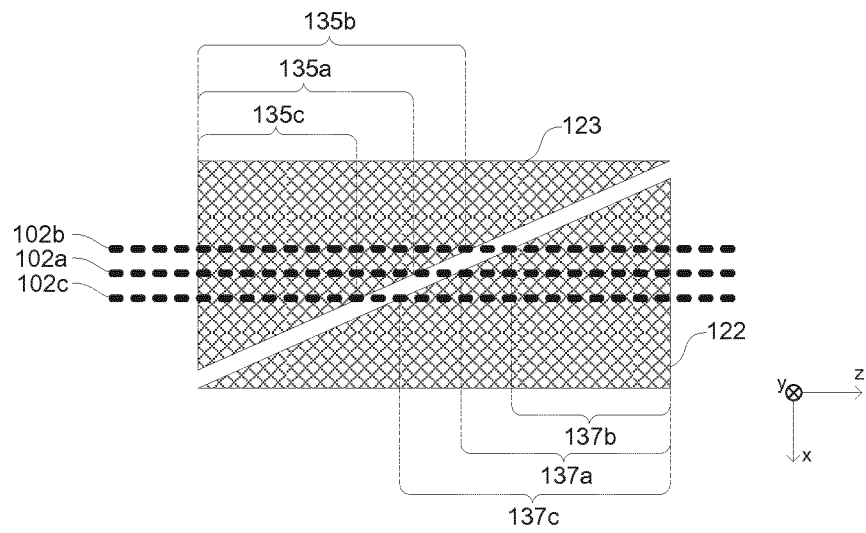


FIG. 7

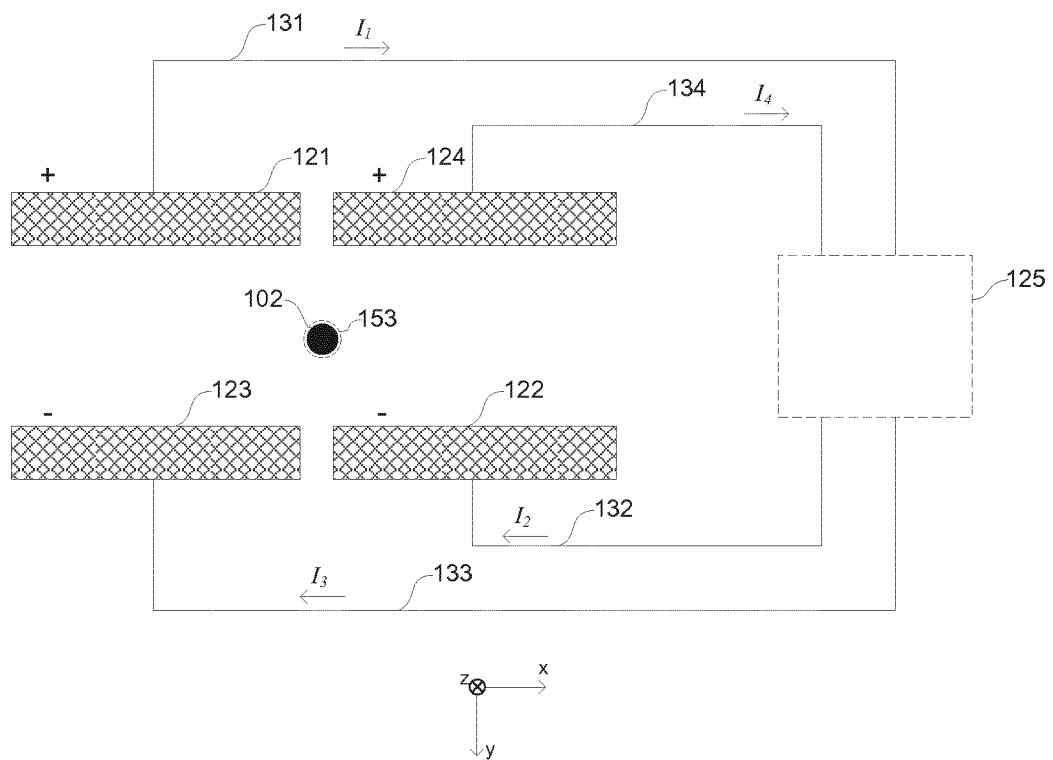


FIG. 8

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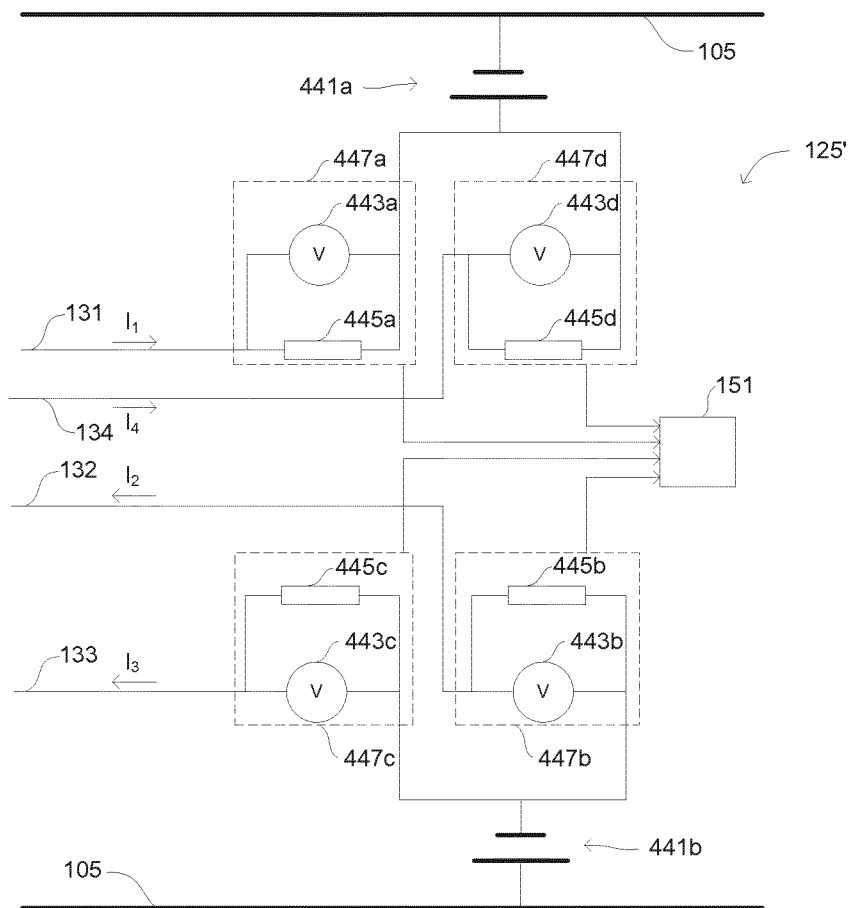


FIG. 9

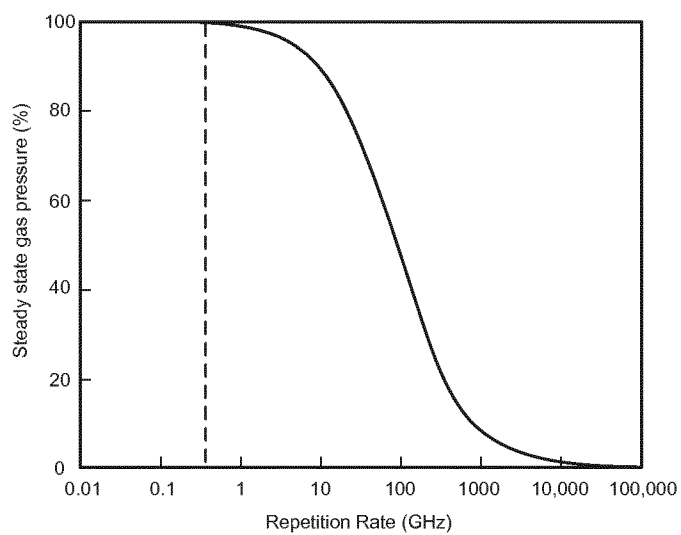


FIG. 10

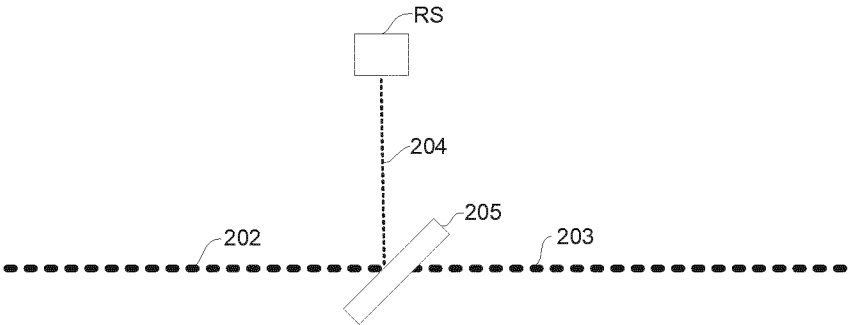


FIG. 11

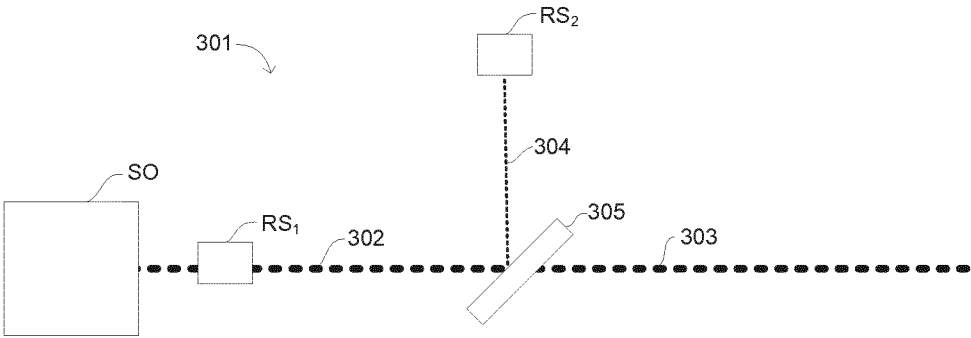


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/050242

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01T1/185 G01J1/42
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)
G01T H01J G01J

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, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JON TISCHLER ET AL: "Photo-electron and ionization chamber position monitors for CHESS", NUCLEAR INSTRUMENTS AND METHODS, vol. 172, no. 1-2, 1 May 1980 (1980-05-01) , pages 67-71, XP055261812, ISSN: 0029-554X, DOI: 10.1016/0029-554X(80)90610-2 abstract; figures page 69, paragraph 3 -----	1-4, 21-24
Y	US 4 590 401 A (GOLDSTEIN NORMAN P [US] ET AL) 20 May 1986 (1986-05-20)	8
A	column 3, line 44 - line 59 ----- -/-	3,23



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

21 June 2016

Date of mailing of the international search report

28/06/2016

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
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Fax: (+31-70) 340-3016

Authorized officer

Eberle, Katja

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2016/050242

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 102 44 303 A1 (BUNDESREP DEUTSCHLAND [DE]) 1 April 2004 (2004-04-01)	5,7,25
Y	paragraph [0005] paragraph [0010] - paragraph [0011] paragraph [0022] - paragraph [0023]; figures	8,20
X	----- HORI M ED - UNNO YOSHINOBU FUKAZAWA YASUSHI HOU SUEN OHSUGI TAKASHI F-W SADROZINSKI HARTMUT: "Parallel plate chambers for monitoring the profiles of high-intensity pulsed antiproton beams", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A: ACCELERATORS, SPECTROMETERS, DETECTORS, AND ASSOCIATED EQUIPMENT, ELSEVIER BV * NORTH-HOLLAND, NL, vol. 522, no. 3, 21 April 2004 (2004-04-21), pages 420-431, XP004502352, ISSN: 0168-9002, DOI: 10.1016/J.NIMA.2003.11.200	5,6,25, 26
Y	abstract page 421, paragraph 2; figures page 424, left-hand column page 425, right-hand column	8,15
X	----- US 2013/112888 A1 (DEYHIM ALEX K [US] ET AL) 9 May 2013 (2013-05-09)	9,14
Y	paragraph [0020] - paragraph [0022]; figures paragraph [0024] - paragraph [0025]	15-20
X	----- WO 01/36998 A1 (MEDICAL RES COUNCIL [GB]; ARNDT ULRICH WOLFGANG [GB]; KYTE MARTIN PAUL) 25 May 2001 (2001-05-25)	9-14
Y	figures page 5 - page 7	20
Y	----- VENKAT SUBRAMANIAN ET AL: "In situ diagnostic capabilities for beam position and beam intensity monitoring at SyLMAND", MICROSYSTEM TECHNOLOGIES ; MICRO AND NANOSYSTEMS INFORMATION STORAGE AND PROCESSING SYSTEMS, SPRINGER, BERLIN, DE, vol. 16, no. 8-9, 11 May 2010 (2010-05-11) , pages 1547-1551, XP019851615, ISSN: 1432-1858 abstract; figures page 1547, right-hand column, paragraph 1. page 1548	16-19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2016/050242

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.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

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

1. claims: 1-4, 21-24

A radiation sensor comprising a chamber for containing a gas; a gas supply mechanism; a first and a second electrode situated in the chamber; a voltage source configured to maintain a potential difference between the first electrode and the second electrode; an electrical sensor; and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber wherein the gas supply mechanism is configured to supply hydrogen or helium into the chamber.

2. claims: 5-8, 25, 26

A radiation sensor comprising a chamber for containing a gas; a gas supply mechanism; a first and a second electrode situated in the chamber; a voltage source configured to maintain a potential difference between the first electrode and the second electrode; an electrical sensor; and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber wherein the gas supply mechanism is configured to maintain a gas in the chamber at a pressure which is greater than about 0.01 Pascals.

3. claims: 9-20

A radiation sensor comprising a chamber for containing a gas; a gas supply mechanism; a first and a second electrode situated in the chamber; a voltage source configured to maintain a potential difference between the first electrode and the second electrode; an electrical sensor; and a processor operable to determine, from the measured electrical current, at least one of a power and a position of a radiation beam propagating through the chamber wherein the radiation sensor further comprises a third electrode.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/050242

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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