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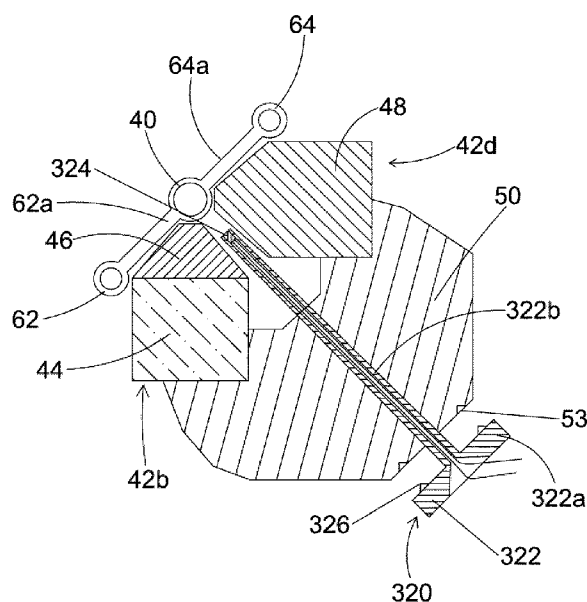


Fig. 7

(57) Abstract: Apparatus and associated methods for de-
termining a magnetic field strength of an undulator module
are disclosed. One such apparatus comprises an undulator
module and a magnetic field sensor. The magnetic field
sensor comprises a body and a sensing element operable to
measure a magnetic field. The undulator module comprises a
support structure and a plurality of periodic magnetic struc-
tures. The periodic structures are supported by the support
structure and being arranged around and extending parallel
to a central axis. The undulator module is provided with at
least one opening for receiving the sensing element of the
magnetic field sensor. The undulator module and the mag-
netic field sensor comprise complementary alignment fea-
tures that provide releasable engagement between the mag-
netic field sensor and the undulator module such that the
sensing element of the magnetic field sensor can be repeat-
ably positioned within the undulator module in substantially
the same position relative to the central axis undulator mod-
ule.

An Undulator

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 15153438.5 which was filed on
5 February 2, 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to apparatus and associated methods for determining a
magnetic field in an undulator. In particular, but not exclusively, the undulator may form part of
10 a free electron laser, which may be used in the generation of radiation for 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
20 having a wavelength within the range 4-20 nm, may be used to form smaller features on a
substrate than a conventional lithographic apparatus (which may for example use
electromagnetic radiation with a wavelength of 193 nm).

[0005] One potential source of a radiation beam for lithography is a free electron laser. A
free electron laser guides a bunched electron beam through a periodic magnetic field within an
25 undulator to stimulate coherent emission of radiation. The output power of a free electron laser
is dependent on the periodic magnetic field produced by an undulator, which may vary over
time. It is therefore desirable to periodically monitor the periodic magnetic field within an
undulator of a free electron laser.

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

SUMMARY

[0007] According to a first aspect of the invention there is provided an apparatus
comprising an undulator module and a magnetic field sensor, the magnetic field sensor

comprising: a body; and a sensing element operable to measure a magnetic field; the undulator module comprising: a support structure; and a plurality of periodic magnetic structures, the periodic structures being supported by the support structure and being arranged around and extending parallel to a central axis; wherein the undulator module is provided with at least one opening for receiving the sensing element of the magnetic field sensor; wherein the undulator module and the magnetic field sensor comprise complementary alignment features that provide releasable engagement between the magnetic field sensor and the undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

[0008] The apparatus of the first aspect allows the sensing element of the magnetic field sensor to be moved between: (a) an accurate position within the undulator module that is in the vicinity of the central axis of the undulator module so that the magnetic field strength and/or direction at that position may be determined; and (b) a location outside of the undulator module, where it is not subject to significant levels of radiation or radioactivity. It will be appreciated that a position within the undulator module that is in the vicinity of the central axis of the undulator module may be any position which is sufficiently close to the central axis to allow a useful determination of the magnetic field (strength and/or direction) on the central axis from a measurement of the magnetic field at that position. The sensing element of the magnetic field sensor may for example be periodically and accurately positioned in the vicinity of the central axis of the undulator module while no electron beam is passing through the undulator module. Further, it may be positioned in the vicinity of the central axis of the undulator module for a relatively short time period, for example just long enough to take a measurement. This allows periodic measurements of the magnetic field in the vicinity of the central axis of the undulator module whilst limiting the level of radioactivity that the sensing element is subject to. Allowing the magnetic field sensor to be removed from the opening defined by the undulator module allows it to be recalibrated in between measurements and limits the amount of damage that it sustains due to radioactivity.

[0009] The undulator module may form part of a free electron laser. The plurality of periodic magnetic structures are operable to produce a periodic magnetic field for guiding an electron beam along a periodic path such that electrons within the electron beam interact with radiation in the undulator module to stimulate emission of coherent radiation to provide a radiation beam. A region around the central axis of an undulator module may be considered to be a "good field region". The good field region may be a volume around the central axis wherein, for a given position along the central axis of the undulator module, the magnitude and direction of the

magnetic field within the volume are substantially constant. The electron beam propagates close to the central axis of the undulator module (i.e. in the good field region) in a region which is maintained at high vacuum (e.g. within an evacuated beam pipe).

[0010] High energy electrons from the electron beam may be scattered by residual gas molecules within this region, for example via Rutherford scattering. Such scattered electrons may be incident upon the periodic magnetic structures of the undulator module, producing an electromagnetic shower or cascade of lower energy electrons and photons, which may cause the magnetic structures to partially demagnetize. Over time, such demagnetization of the magnetic structures leads to a distortion of the trajectory followed by electrons through the undulator module, resulting in a loss of conversion efficiency. It is desirable to periodically monitor the magnetic field strength along the central axis of an undulator module. Once the conversion efficiency of the free electron laser falls below an acceptable level the periodic magnetic structures may be re-tuned (re-magnetised) or replaced.

[0011] From one or more measurements of the magnetic field strength in the vicinity of the axis of the undulator module, the magnetic field strength on the central axis can be determined, for example by modelling or extrapolation. In order to determine the magnetic field strength at the central axis of the undulator module accurately, it is important that the sensing element of the magnetic sensor can be positioned in substantially the same position relative to the undulator module for each measurement. This is achieved by the alignment features.

[0012] The first aspect of the invention allows the magnetic field within the undulator module to be sampled without disassembling the undulator module because the at least one opening allows the sensing element of the magnetic field sensor to be positioned within the undulator. This may be advantageous since disassembly of the undulator module may be time consuming. Furthermore, parts of the undulator module which are closer to the central axis may be radioactive for a time after the electron beam has been switched off. Since disassembly of the undulator module may expose such parts of the undulator module, either the resultant radiation must be contained or the undulator module should be allowed to cool down for a time period before disassembly. This increases the complexity of disassembly of undulator modules and/or increases the down time of the free electron laser. The at least one opening subtends a relatively small solid angle at the central axis of the undulator module and therefore the quantity of radiation that may exit the undulator module through the at least one opening is small.

[0013] The position of the sensing element of the magnetic field sensor may be specified by three co-ordinates in any suitable co-ordinate system.

[0014] The alignment features may be arranged to allow the sensing element of the magnetic field sensor to be positioned within the opening to within a specified tolerance distance of a fixed position relative to the undulator module. The specified tolerance distance may be 10 μm or less, for example 2 μm or less. Each of the three co-ordinates that specify the position of the sensing element relative to the fixed position may be less than the specified tolerance distance.

[0015] The complementary alignment features may comprise one or more projections on one of the magnetic field sensor and the undulator module and one or more complementary recesses on the other of the magnetic field sensor and the undulator module.

[0016] The releasable engagement between the magnetic field sensor and the undulator module provided by the complementary alignment features may be such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module with substantially the same orientation.

[0017] This may be advantageous if, for example, the sensing element is operable to determine a component of the magnetic field in a single sensing direction (relative to the magnetic field sensor). For example, the sensing element may comprise a single Hall probe. In order to determine the magnetic field strength at the central axis of the undulator module accurately, it may be important that the sensing element of the magnetic sensor can be positioned with substantially the same orientation for each measurement of the magnetic field (so that the sensing element determines the same component of the magnetic field for each measurement). This may be achieved by the alignment features. In an alternative embodiment, the sensing element may be operable to determine the magnitude of the magnetic field. For example, the sensing element may comprise a plurality of Hall probes (e.g. three), which may each be operable to determine a different component of the magnetic field, from which the magnitude of the magnetic field may be determined.

[0018] The orientation of the sensing element of the magnetic field sensor may be specified by three angles. The at least one opening for receiving the sensing element of the magnetic field sensor may extend along an opening axis. The orientation of the sensing element of the magnetic field sensor may be specified by: a rotation angle of the body of the magnetic field sensor around the opening axis; and as two tilt angles of the body of the magnetic field sensor relative to the opening axis. The two tilt angles of the body of the magnetic field sensor relative to the opening axis may be well constrained by requiring the position of the sensing element of the magnetic field sensor to be within the specified tolerance distance. The rotation angle of the body of the magnetic field sensor around the opening axis may be less constrained than the two

tilt angles by requiring the position of the sensing element of the magnetic field sensor to be within the specified tolerance distance.

[0019] The alignment features may be arranged to allow the sensing element of the magnetic field sensor to be positioned within the opening to within a specified tolerance orientation of a desired orientation. The specified tolerance orientation may be 1 mrad or less, for example 0.1 mrad. Each of the three angles that specify the orientation of the sensing element relative to the desired orientation may be less than the specified tolerance orientation.

[0020] The complementary alignment features may be arranged such that when the magnetic field sensor engages with the undulator module the sensing element of the magnetic field sensor is in one of a finite number of fixed orientations. The alignment features may provide any number of fixed orientations.

[0021] For example, in some embodiments the alignment features may provide a single fixed orientation. This can prevent, for example, the magnetic field sensor from engaging with the undulator module with the sensing element in two different orientations for two different measurements thus ensuring that the measurements are consistent.

[0022] Alternatively, the alignment features may provide two or more fixed orientations. This can allow the magnetic field sensor to engage with the undulator module with the sensing element in two or more different orientations, which may for example allow two or more components of the magnetic field to be determined. This may improve the accuracy with which the magnetic field on the central axis can be determined. Allowing the magnetic field sensor to engage with the undulator module with the sensing element in two different orientations may provide a significant improvement over embodiments wherein the magnetic field sensor can only engage with the undulator module with the sensing element in a single orientation. Allowing the magnetic field sensor to engage with the undulator module with the sensing element in three or more different orientations may provide a smaller improvement over embodiments wherein the magnetic field sensor can only engage with the undulator module with the sensing element two different orientations.

[0023] The undulator module may be provided with a plurality of openings for receiving the sensing element of a magnetic field sensor.

[0024] This allows the magnetic field to be sampled in a plurality of different positions within the undulator module.

[0025] The apparatus may comprise a plurality of magnetic field sensors.

[0026] For example, for embodiments comprising a plurality of different openings, a different magnetic field sensor may be used for each of the plurality of openings. Alternatively, a single

magnetic field sensor may be used for more than one of the plurality of openings. For example, a single magnetic field sensor may be used for all of the plurality of openings. Alternatively, the plurality of openings may comprise a plurality of sets of openings and a different single magnetic field sensor may be used for each different set of openings. Each different set of openings may have different alignment features. The central axis may form a reference axis for a cylindrical coordinate system of the undulator module. Accordingly, a point within the undulator module may be specified by an axial position, a radial position and an azimuthal position. The axial position of a point may be the (signed) perpendicular distance between that point and a chosen reference plane that is perpendicular to the central axis. The radial position of a point may be the perpendicular distance between that point and the central axis. The azimuthal position of a point may be the angle between a plane passing through the central axis and that point and the plane passing through the central axis and a reference line.

[0027] At least one of the openings for receiving the sensing element of a magnetic field sensor may be provided in the support structure and may extend radially at an azimuthal position between that of two of the periodic magnetic structures.

[0028] This allows the sensing element of a magnetic field sensor to extend through the opening and in between two adjacent periodic magnetic structures. Advantageously, this allows the sensing element to be positioned close to the central axis of the undulator module (e.g. adjacent to an evacuated beam pipe).

[0029] Each of the periodic magnetic structures may comprise a plurality of magnets, each of the plurality of magnets being operable to produce a magnetic field, wherein at least one of the openings for receiving the sensing element of a magnetic field sensor extends radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures and at an axial position that is substantially the same as that of one of the magnets of that periodic magnetic structure.

[0030] This allows the sensing element of a magnetic field sensor to be placed adjacent to one of the magnets of one of the periodic magnetic structures, where the magnetic field is dominated by that of that magnet. Therefore, this allows the magnetic field of an individual magnet to be monitored.

[0031] The plurality of magnets of a given periodic structure may extend axially such that along a length of the periodic magnetic structure the polarization directions of the plurality of magnets form a repeating pattern in an axial direction. For example, in one embodiment in the axial direction the polarization directions of the plurality of magnets alternate between a positive

axial direction and a negative axial direction. In another embodiment, the plurality of magnets are arranged so as to form a Halbach array.

[0032] Each of the periodic magnetic structures may further comprise a plurality of ferromagnetic elements, which are arranged to direct the magnetic field generated by the plurality of magnets towards the central axis of the undulator module. For example, the plurality of ferromagnetic elements may be arranged alternately with the plurality of magnets in an axial direction.

[0033] At least one of the openings for receiving the sensing element of a magnetic field sensor may comprise a bore that extends into one of the ferromagnetic elements of one of the periodic magnetic structures. For example, the at least one of the openings for receiving the sensing element of a magnetic field sensor may extend radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures and at an axial position that is substantially the same as that of one of the ferromagnetic elements of that periodic magnetic structure. The magnetic field is stronger inside the ferromagnetic elements and therefore the accuracy of the measurement may be increased (with the same sensing element).

[0034] The opening may comprise an aperture in the support structure of the undulator module.

[0035] The undulator module may be a planar undulator module comprising two periodic magnetic structures. Alternatively, the undulator module may be a helical undulator module comprising four periodic magnetic structures.

[0036] According to a second aspect of the present invention there is provided a magnetic field sensor comprising: a body; and a sensing element operable to measure a magnetic field; wherein the magnetic field sensor comprises an alignment feature that provides releasable engagement between the magnetic field sensor and an undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

[0037] According to a third aspect of the present invention there is provided an undulator module comprising: a support structure; and a plurality of periodic magnetic structures, the periodic structures being supported by the support structure and being arranged around and extending parallel to a central axis; wherein the undulator module is provided with at least one opening for receiving a sensing element of a magnetic field sensor; wherein the undulator module comprises an alignment feature that provides releasable engagement between the magnetic field sensor and the undulator module such that the sensing element of the magnetic

field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

[0038] According to a fourth aspect of the present invention there is provided an undulator module, the undulator module comprising a plurality of periodic magnetic structures, the periodic structures being arranged around and extending parallel to a central axis and being operable to produce a periodic magnetic field for guiding an electron beam along a periodic path such that electrons within the electron beam interact with radiation in the undulator module to stimulate emission of coherent radiation to provide a radiation beam; wherein each of the periodic magnetic structures comprises a plurality of magnets and a plurality of ferromagnetic elements, each of the plurality of magnets being operable to produce a magnetic field and each of the plurality of ferromagnetic elements being arranged to direct the magnetic field generated by the plurality of magnets towards the central axis; wherein at least one of the ferromagnetic elements of at least one of the periodic magnetic structures is provided with an apparatus for determining the magnetic permeability of that ferromagnetic element.

[0039] The magnetic permeability of the ferromagnetic elements is dependent upon the magnetic field applied by the plurality of magnets. Therefore the apparatus for determining the magnetic permeability of the ferromagnetic elements of the second aspect of the invention provides an indirect measurement of the magnetic field provided by the magnets.

[0040] The undulator module may form part of a free electron laser. The plurality of periodic magnetic structures are operable to produce a periodic magnetic field for guiding an electron beam along a periodic path such that electrons within the electron beam interact with radiation in the undulator module to stimulate emission of coherent radiation to provide a radiation beam. A region around the central axis of an undulator module may be considered to be a "good field region". The good field region may be a volume around the central axis wherein, for a given position along the central axis of the undulator module, the magnitude and direction of the magnetic field within the volume are substantially constant. The electron beam propagates close to the central axis of the undulator module (i.e. in the good field region) in a region which is maintained at high vacuum (e.g. within an evacuated beam pipe).

[0041] High energy electrons from the electron beam may be scattered by residual gas molecules within this region, for example via Rutherford scattering. Such scattered electrons may be incident upon the periodic magnetic structures of the undulator module, producing an electromagnetic shower or cascade of lower energy electrons and photons. In turn, this may cause the magnetic structures to at least partially demagnetize and/or may alter one or more properties of ferromagnetic materials within the magnetic structures (e.g. the magnets and the

ferromagnetic elements) and thus change the magnetic field on the central axis of the undulator module. Over time, these effects lead to a distortion of the trajectory followed by electrons through the undulator module, resulting in a loss of conversion efficiency. It is therefore desirable to periodically monitor the magnetic field strength along the central axis of an undulator module. Once the conversion efficiency of the free electron laser falls below an acceptable level the periodic magnetic structures may be re-tuned (re-magnetised) or replaced.

[0042] From one or more measurements of the magnetic permeability of the ferromagnetic elements, the magnetic field strength on the central axis of the undulator module can be determined, for example by modelling or extrapolation.

[0043] The apparatus for determining the magnetic permeability of the ferromagnetic element may comprise: a coil assembly comprising one or more coils of wire wrapped around the ferromagnetic element; a power supply operable to apply an alternating current to a coil of the coil assembly; and an apparatus arranged to determine an inductance of, or a voltage induced in, a coil of the coil assembly.

[0044] When the power supply applies an alternating current to a coil of the coil assembly, an alternating magnetic field is generated within the ferromagnetic element. In turn, this will induce a voltage in any coils wrapped around the ferromagnetic element. The inductance, and the induced voltage, is dependent upon the magnetic permeability of the ferromagnetic element. Therefore by determining the inductance of, or a voltage induced in, a coil from the coil assembly, the magnetic permeability of the ferromagnetic element can be determined.

[0045] The coil of the coil assembly whose inductance is determined may be the same coil as that to which the alternating current is applied by the power supply. Alternatively, the alternating current may be applied by the power supply to a first coil and the inductance of, or induced voltage in, a second coil may be determined.

[0046] According to a fifth aspect of the present invention there is provided a free electron laser, comprising: an electron source for producing an electron beam comprising a plurality of bunches of relativistic electrons; and an undulator arranged to receive the electron beam and guide it along a periodic path so that the electron beam interacts with radiation within the undulator, stimulating emission of radiation and providing a radiation beam, wherein the undulator comprises the apparatus according to the first aspect of the invention or the undulator module according to the fourth aspect of the invention.

[0047] According to a sixth aspect of the present invention there is provided a lithographic system comprising: a free electron laser according to the fifth aspect of the invention; and at

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

[0048] According to a seventh aspect of the present invention there is provided a method for determining a magnetic field strength of an undulator module, the method comprising: inserting a magnetic field sensor comprising a sensing element into an opening in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with a complementary alignment feature on the undulator module such that the sensing element is accurately located at a measurement position relative to a central axis of the undulator module; measuring a magnetic field at the measurement position using the sensing element; and removing the magnetic field sensor from the opening in the undulator module.

[0049] The method may comprise: inserting a magnetic field sensor comprising a sensing element into each of a plurality of openings in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with a complementary alignment feature on the undulator module such that the sensing element is accurately located at one of a plurality of measurement positions relative to a central axis of the undulator module; measuring a magnetic field at that measurement position using the sensing element; and removing the a magnetic field sensor from each of the plurality of openings in the undulator module.

[0050] A different magnetic field sensor may be used for each of the plurality of openings. Alternatively, a single magnetic field sensor may be used for more than one of the plurality of openings. For example, a single magnetic field sensor may be used for all of the plurality of openings. Alternatively, the plurality of openings may comprise a plurality of sets of openings and different single magnetic field sensor may be used for each different set of openings. Each different set of openings may have different alignment features.

[0051] For embodiments wherein the method used a plurality of magnetic field sensors, the different magnetic field sensors may be inserted substantially simultaneously. Alternatively, the different magnetic field sensors may be inserted sequentially.

[0052] The method may further comprise: determining a magnetic field at a central axis of the undulator module from the measured magnetic field at the or each measurement position.

[0053] The magnetic field strength on the central axis may, for example, be determined by modelling or extrapolation.

[0054] According to an eighth aspect of the present invention there is provided a method for determining a magnetic field strength of an undulator module comprising a plurality of periodic magnetic structures, the periodic structures being arranged around and extending parallel to a central axis, each of the periodic magnetic structures comprising a plurality of magnets arranged

alternately with a plurality of ferromagnetic elements, the method comprising: determining the magnetic permeability of at least one of the ferromagnetic elements of at least one of the periodic magnetic structures.

[0055] The magnetic permeability of the ferromagnetic elements is dependent upon the magnetic field applied by the plurality of magnets and the properties of the material from which the ferromagnetic elements are formed. Therefore determining the magnetic permeability of the ferromagnetic elements provides an indirect measurement of the magnetic field provided by the magnets. Additionally or alternatively, a change in the magnetic permeability of the ferromagnetic elements while the magnetic field provided by the magnets remains constant may indicate a change in one or more of the properties of the ferromagnetic elements.

[0056] The method may comprise: determining the magnetic permeability of a plurality of the ferromagnetic elements of a plurality of the periodic magnetic structures.

[0057] The method may comprise: determining the magnetic field at a central axis of the undulator module from the measured magnetic permeability of the plurality of the ferromagnetic elements of the plurality of the periodic magnetic structures.

[0058] The magnetic field strength on the central axis may, for example, be determined by modelling or extrapolation.

[0059] 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

[0060] 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;
- 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 cross sectional view of a portion of an undulator module that forms part of the free electron laser of Figure 3 in a plane parallel to an axis of the undulator module;

- Figure 5 is a schematic illustration of a cross sectional view of a portion of the undulator module of Figure 4 in a plane perpendicular to an axis of the undulator module;
- Figure 6A shows a magnetic field sensor adjacent to an enlarged portion of the cross sectional view of a portion of the undulator module shown in Figure 5;
- 5 - Figure 6B shows another magnetic field sensor adjacent to an enlarged portion of the cross sectional view of a portion of the undulator module similar to that shown in Figure 5;
- Figure 7 shows a magnetic field sensor adjacent to an enlarged portion of the cross sectional view of a portion of the undulator module shown in Figure 5;
- Figure 8A shows a ferromagnetic element which may form part of an undulator module;
- 10 and
- Figure 8B shows the ferromagnetic element of Figure 8A which is provided with an apparatus for determining its magnetic permeability.

DETAILED DESCRIPTION

- 15 **[0061]** Figure 1 shows a lithographic system LS according to one embodiment of the invention. The lithographic system LS comprises a radiation source SO, a beam delivery system BDS 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).
- 20 **[0062]** 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.
- 25 **[0063]** 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
- 30 normal incidence. For example, the beam expanding optics may be operable to expand the main beam B from approximately 100 μm to more than 10 cm before the main beam B is split by the beam splitting optics.
- [0064]** 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 .

[0065] 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 minimise the absorption of EUV radiation. Different parts of the lithographic system LS may be provided with vacuums at different pressures (i.e. held at different pressures which are below atmospheric pressure).

[0066] 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.

[0067] 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.

[0068] 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 1mm across. The independently moveable mirrors may for example be microelectromechanical systems (MEMS) devices.

[0069] 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
5 projection system PS has two mirrors in Figure 2, the projection system may include any number of mirrors (e.g. six mirrors).

[0070] 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
10 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.

[0071] 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.

[0072] 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
20 and a beam dump 100.

[0073] 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
25 cavities, which are axially spaced along a common axis, and one or more radio frequency power sources, which are operable to control the electromagnetic fields along the common axis as bunches of electrons pass between them so as to accelerate each bunch of electrons. The cavities may be superconducting radio frequency cavities. Advantageously, this allows: relatively large electromagnetic fields to be applied at high duty cycles; larger beam apertures,
30 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.

[0074] 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.

[0075] The electron beam E then passes through the undulator 24. Generally, the undulator 24 comprises a plurality of modules. Each module comprises a periodic magnet structure, which is operable to produce a periodic magnetic field and is arranged so as to guide the 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.

[0076] 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.

[0077] 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.

[0078] 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 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.

[0079] Electrons moving through the undulator 24 may cause the amplitude of radiation to increase, i.e. the free electron laser FEL may have a non-zero gain. Maximum gain may be achieved when the resonance condition is met or when conditions are close to but slightly off resonance.

[0080] An electron which meets the resonance condition as it enters the undulator 24 will lose (or gain) energy as it emits (or absorbs) radiation, so that the resonance condition is no longer satisfied. Therefore, in some embodiments the undulator 24 may be tapered. That is, the amplitude of the periodic magnetic field and/or the undulator period λ_u may vary along the length of the undulator 24 in order to keep bunches of electrons at or close to resonance as they are guided through the undulator 24. 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 of the undulator 24 (by varying the parameter A) within each undulator module and/or from module to module.

[0081] A region around the central axis of each undulator module may be considered to be a “good field region”. The good field region may be a volume around the central axis wherein, for a given position along the central axis of the undulator module, the magnitude and direction of the magnetic field within the volume are substantially constant. An electron bunch propagating within the good field region may satisfy the resonant condition of Eq. (1) and will therefore amplify radiation. Further, an electron beam E propagating within the good field region should not experience significant unexpected disruption due to uncompensated magnetic fields. That is, an electron propagating through the good field region should remain within the good field region.

[0082] Each undulator module may have a range of acceptable initial trajectories. Electrons entering an undulator module with an initial trajectory within this range of acceptable initial trajectories may satisfy the resonant condition of Eq. (1) and interact with radiation in that undulator module to stimulate emission of coherent radiation. In contrast, electrons entering an undulator module with other trajectories may not stimulate significant emission of coherent radiation.

[0083] For example, generally, for helical undulator modules the electron beam E should be substantially aligned with the central axis of the undulator module. A tilt or angle between the electron beam E and the central axis of the undulator module (in radians) should generally not exceed $\rho/10$, where ρ is the FEL Pierce parameter. Otherwise the conversion efficiency of the undulator module (i.e. the portion of the energy of the electron beam E which is converted to radiation in that module) may drop below a desired amount (or may drop almost to zero). In an embodiment, the FEL Pierce parameter of an EUV helical undulator module may be of the order of 0.001, indicating that the tilt of the electron beam E with respect to the central axis of the undulator module should be less than 100 μ rad.

[0084] For a planar undulator module, a greater range of initial trajectories may be acceptable. Provided the electron beam E remains substantially perpendicular to the magnetic field of a planar undulator module and remains within the good field region of the planar undulator module, coherent emission of radiation may be stimulated.

[0085] As electrons of the electron beam E move through a drift space between each undulator module, the electrons do not follow a periodic path. Therefore, in this drift space, although the electrons overlap spatially with the radiation, they do not exchange any significant energy with the radiation and are therefore effectively decoupled from the radiation. The

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

[0086] The undulator 24 may further comprise an electron beam steering unit in between each adjacent pair of undulator modules which is arranged to provide fine adjustment of the electron beam E as it passes through the undulator 24. For example, each beam steering unit may be arranged to ensure that the electron beam remains within the good field region and enters the next undulator module with a trajectory from the range of acceptable initial trajectories for that undulator module.

[0087] 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 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 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.

[0088] 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.

[0089] 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. 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 recovering linear accelerator (ERL).

[0090] Two different cross sectional views of a portion of an undulator module 200 (which may form part of undulator 24) according to an embodiment of the present invention are illustrated in Figures 4 and 5. The undulator module 200 comprises a pipe 40 for the electron beam E, a support structure 50 and four periodic magnetic structures 42a-42d (Figure 5). The periodic structures 42a-42d are supported by the support structure 50 and are arranged around, and extend parallel to, a central axis 41 of the undulator module 200. Together, the four periodic magnetic structures 42a-42d are operable to produce a periodic magnetic field for guiding an electron beam along a periodic path such that electrons within the electron beam interact with radiation in the undulator module 200 to stimulate emission of coherent radiation to provide a radiation beam.

[0091] The undulator module 200 is an elongate structure, extending along its axis 41, which runs through the center of the pipe 40. The central axis 41 may form a reference axis for a cylindrical co-ordinate system of the undulator module 200. Accordingly, a point within the undulator module 200 may be specified by an axial position, a radial position and an azimuthal position. The axial position of a point may be the (signed) perpendicular distance between that point and a chosen reference plane that is perpendicular to the central axis. The radial position of a point may be the perpendicular distance between that point and the central axis. The azimuthal position of a point may be the angle between a plane passing through the central axis and that point and the plane passing through the central axis and a reference line.

[0092] The pipe 40 is arranged such that, in use, the electron beam E enters one end of the pipe 40, passes through it, substantially along central axis 41 of the undulator module 200, and exits an opposite end of the pipe 40. In use, the pipe 40 is held under vacuum conditions. As such, the pipe 40 may be formed from a material which does not suffer from outgassing. For example, the pipe 40 may be formed from stainless steel. Alternatively, the pipe 40 may be formed from an aluminium alloy. For embodiments wherein the pipe 40 is formed from an aluminium alloy the pipe 40 may be manufactured by extrusion. The pipe 40 may be generally circular in cross section, in a plane perpendicular to the axis 41 of the undulator 24. Two cooling channels 62, 64 extend parallel to the pipe 40 and are connected to the pipe 40 by radially extending connectors 62a, 64a. The connectors 62a, 64a form a thermal link between cooling channels 62, 64 and pipe 40. In use, a flow of coolant is provided through cooling channels 62, 64, which serves to cool the pipe 40 via connectors 62a, 64a.

[0093] An interior of the pipe 40 provides a suitable environment for the electron beam E to propagate through. In particular, it is held under vacuum conditions. In an alternative embodiment, the undulator module 200 does not comprise a pipe 40 but rather the electron beam propagates through a channel defined by the magnetic structures 42a-42d. In such an embodiment, the entire undulator module 200 may maintain a suitable environment for the electron beam E to propagate through (for example a vacuum).

[0094] The pipe 40 may extend through a plurality of undulator modules. Alternatively, each undulator module may be provided with a corresponding pipe and the pipes of two adjacent undulator modules may be connected in any suitable way.

[0095] All of the periodic magnetic structures 42a-42d are substantially similar in structure. In particular, each of the periodic magnetic structures 42a-42d has substantially the same period, i.e. the (axial) distance after which the magnetic field of the periodic magnetic structure 42a-42d repeats. The undulator period λ_u of undulator module 200 (i.e. the axial distance after which the magnetic field of the undulator module 200 repeats) is equal to the period of each of the periodic magnetic structures 42a-42d. Each of the periodic structures 42a-42d is separated from the axis 41 in a direction substantially perpendicular to the axis 41 of the undulator 24, which may be referred to as a radial direction.

[0096] Each of the periodic structures 42a-42d comprises a plurality of magnets 44, a plurality of ferromagnetic elements 48 and a plurality of spacer elements 46. In an alternative embodiment, each periodic structure 42a-42d may be generally of the form of a Halbach array. That is, each periodic structure may comprise a linear array of permanent dipole magnets, arranged such that the magnetic fields of the permanent dipole magnets interfere constructively on one side of the periodic array and destructively on an opposite side of the array.

[0097] Each of the plurality of magnets 44 is operable to produce a magnetic field. Each of the plurality of magnets 44 is a dipole magnet and has a substantially constant polarization direction. The polarization of each of the plurality of magnets 44 is generally in either the positive or negative axial direction. In Figure 4, the north pole N and south pole S of each of the magnets 44 are shown. It will be appreciated that the polarisation direction of each magnet 44 may by convention be a direction extending from the south pole S of the magnet 44 to the north pole N of the magnet 44. As can be seen from Figure 4, the plurality of magnets 44 of a given periodic structure are arranged such that along a length of the periodic magnetic structure 42a-42d the polarizations of the magnets 44 alternate between the positive and negative axial directions.

[0098] Each of the plurality of magnets 44 is formed from a relatively hard ferromagnetic material, which is relatively difficult to demagnetize. Hard ferromagnetic materials are those with a relatively large remanence and a relatively broad hysteresis curve. For example, the magnets 44 may be rare earth magnets, which are relatively strong permanent magnets. The magnets may be samarium-cobalt (SmCo) magnets, which are formed from an alloy of samarium and cobalt. These include the SmCo 1:5 series (SmCo₅) and the SmCo 2:17 series (Sm₂Co₁₇). Alternatively, the magnets 44 may be neodymium magnets (FeNdB), which are formed from an alloy of iron, neodymium and boron.

[0099] The plurality of ferromagnetic elements 48 are arranged to direct the magnetic field generated by the plurality of magnets 44 towards the central axis 41 of the undulator module 200. In particular, the ferromagnetic elements 48 are arranged alternately with the magnets 44 in an axial direction. Each of the plurality of ferromagnetic elements 48 is formed from a relatively soft ferromagnetic material. Soft ferromagnetic materials are easily magnetized and demagnetized, with a relatively small remanence, a narrow hysteresis loop (i.e. a low coercive field strength), a high magnetic permeability, and a high magnetic saturation induction. Each of the plurality of ferromagnetic elements 48 may be formed from a soft ferromagnetic material with coercive field strength less than 500 A/m and maximum relative permeability of more than 1000. In some embodiments, the ferromagnetic elements 48 are formed from soft iron or iron-cobalt.

[00100] Each periodic magnetic structure 42a-42d produces a periodic magnetic field, with the period λ_u being the length of two magnets 44 and two ferromagnetic elements 48.

[00101] Each of the plurality of magnets 44 is separated from the pipe 40 by a spacer element 46. That is, the spacer elements 46 are provided radially inside the magnets 44. Each spacer element 46 has substantially the same axial extent as its corresponding magnet 44. In cross section (in a plane perpendicular to the central axis 41) the spacer elements 46 may have any convenient shape. The spacer elements 46 may be formed from a non-magnetic material.

[00102] Each ferromagnetic element 48 separates an adjacent pair of magnets 44 and extends farther towards the pipe 40 than each of the magnets 44.

[00103] Although the pipe 40 is maintained at high vacuum, high energy electrons from the electron beam E may be scattered by residual gas molecules within the pipe 40, for example via Rutherford scattering. Such scattered electrons may be incident upon the periodic magnetic structures 42a-42d of the undulator module 200, producing an electromagnetic shower or cascade of lower energy electrons and photons, which may cause the magnets 44 to partially demagnetize. Over time, such demagnetization of the magnets 44 leads to a distortion of the

trajectory followed by electrons through the undulator module 200, resulting in a loss of conversion efficiency of the free electron laser. It is therefore desirable to periodically monitor the magnetic field strength along the central axis 41 of an undulator module 200. Once the conversion efficiency of a free electron laser falls below an acceptable level the periodic magnetic structures 42a-42d may be re-tuned (for example by re-magnetising magnets 44).

[00104] The use of ferromagnetic elements 48 allows the magnets 44 to be located away from the pipe 40 without significant loss of magnetic field strength at the central axis 41, since the ferromagnetic elements 48 are magnetized by the magnets 44 and guide the magnetic field exerted by the magnets 44 towards the axis 41. In fact, the geometry of the undulator module 200 may be selected so that the ferromagnetic elements 48 provide sufficient focusing to provide a magnetic field along the axis 41 with a larger amplitude B_0 than in conventional undulators with the same strength of magnets. This spatial separation of the permanent magnets 44 from the pipe 40 allows the spacer elements 46 to be placed between the magnets 44 and the pipe 40. The spacer elements 46 can be formed from a material that will absorb a large fraction of high energy electrons and photons that originate from the beam pipe 40. In this way, the permanent magnets 44 can be shielded from this electromagnetic radiation and the lifetime of the undulator module 200 can be extended. The sensitivity of the magnetization of the ferromagnetic elements 48 to radiation damage is significantly lower than that of the magnetization of the magnets 44. For example, for embodiments wherein the ferromagnetic elements 48 are formed from soft iron-cobalt, sensitivity of the magnetization of the ferromagnetic elements 48 to radiation damage is at least 100 times lower than that of the magnets 44. Therefore the magnetization of the ferromagnetic elements 48 is not significantly affected by high energy electrons or photons.

[00105] Electromagnetic showers that result from high energy electrons entering the spacer elements 46 will produce a significant number of photons. In turn, this increases the number of photonuclear reactions within the spacer elements 46, which can result in the emission of neutrons from nuclei. Therefore, in embodiments of the present invention, the magnets 44 are preferably formed from a magnetic material that is less likely to be demagnetized by high energy neutrons. For this reason samarium-cobalt (SmCo) magnets may be preferred to neodymium magnets (FeNdB) since the demagnetizing effect of neutrons is five orders of magnitude smaller for SmCo magnets than for FeNdB magnets.

[00106] In some embodiments, the undulator module 200 may be provided with a neutron absorbing material on, for example, an outer radial surface. This may protect the magnets from neutrons produced, for example, by other parts of the free electron laser.

[00107] The spacer elements 46 may be provided with cooling channels (not shown) through which a coolant may be circulated. In some embodiments of the present invention, a small gap (not shown) may be provided between the spacer elements 46 and the pipe 40 on the one side and the magnets 44 and the ferromagnetic elements 48 on the other side. Advantageously, such a gap may at least partially thermally insulate (against conduction) the magnets 44 from the spacer elements 46 and the pipe 40. This can help to stabilize the temperature of the magnets 44 and, in turn, stabilize the magnetic field produced along the central axis 41. The gap may be held under vacuum conditions, which may improve the level of thermal insulation. This may be achieved, for example, by placing the entire undulator module 200 within a chamber which can be held at low pressures. Further, one or more surfaces of the spacer elements 46, the pipe 40, the magnets 44 and the ferromagnetic elements 48 which define the gap may be coated with a low emissivity film. The low emissivity film may comprise, for example, gold. Advantageously, such a low emissivity film may at least partially thermally insulate (against infrared radiation) the magnets 44 from the spacer elements 46 and the pipe 40. This may provide further stability to the temperature of the magnets 44 and, in turn, the magnetic field produced along the central axis 41.

[00108] Each of the periodic magnetic structures 42a-42d extends axially alongside the pipe 40 (i.e. parallel to central axis 41). In a plane perpendicular to the axis 41 of the undulator module 200, the four periodic magnetic structures are distributed substantially evenly about the pipe 40. A first pair of the magnetic structures 42a, 42b are arranged symmetrically, on opposite sides of the pipe 40. Each magnet 44 of periodic magnetic structure 42a is opposed to one of the magnets 44 of periodic magnetic structure 42b and each ferromagnetic element 48 of periodic magnetic structure 42a is opposed to one of the ferromagnetic elements 48 of periodic magnetic structure 42b. The polarization direction of each magnet 44 of periodic magnetic structure 42a is in an opposite direction to that of the opposite magnet 44 of periodic magnetic structure 42b. That is, the first pair of the magnetic structures 42a, 42b are arranged out of phase by half of the undulator period λ_u .

[00109] A second pair of magnetic structures 42c, 42d are arranged out of phase by half of the undulator period λ_u and are arranged symmetrically, on opposite sides of the pipe 40. The second pair of magnetic structures 42c, 42d is rotated relative to the first pair 42a, 42b about the central axis 41 by 90° . The first pair 42a, 42b may be shifted axially relative to the second pair 42c, 42d such that the first 42a, 42b and second 42c, 42d pairs are out of phase. The amount of the shift may determine the polarization of radiation produced by the undulator module 200. For example, in the embodiment shown in Figures 4 and 5, the first pair 42a, 42b is shifted

axially relative to the second pair 42c, 42d by a quarter of the undulator period λ_u . That is, the magnets 44 of the first pair periodic magnetic structures 42a, 42b are disposed at substantially the same axial position as the ferromagnetic elements 48 of the second pair of magnetic structures 42c, 42d. That is, moving azimuthally around the central axis 41 of the undulator module 200 each periodic magnetic structure (i.e. in the sequence 42a, 42d, 42b, 42c) is shifted axially relative to the previous periodic magnetic structure by the same amount of either $+\lambda_u/4$ or $-\lambda_u/4$. Such an arrangement may produce circularly polarized radiation as the electron beam E propagates through it and may be referred to as a helical undulator module 200. The polarization state of the circularly polarized radiation is dependent on whether each periodic magnetic structure (in the sequence 42a, 42d, 42b, 42c) is shifted axially relative to the previous periodic magnetic structure by $+\lambda_u/4$ or by $-\lambda_u/4$.

[00110] In an alternative embodiment, moving azimuthally around the central axis 41 of the undulator module 200 the axial shift between each magnetic structure and the previous periodic magnetic structure (in the sequence 42a, 42d, 42b, 42c) alternates between $+\lambda_u/4$ and $-\lambda_u/4$. Such an arrangement may produce linearly polarized radiation as the electron beam E propagates through it and may be referred to as a planar undulator module 200. Other axial shifts between the four periodic magnetic structures 42a, 42b, 42c, 42d may produce elliptically polarized radiation.

[00111] In an alternative embodiment, the undulator module 200 may only comprise a first pair of the magnetic structures 42a, 42b, i.e. the second pair of magnetic structures 42c, 42d may not be present. Such an arrangement may produce linearly polarized radiation as the electron beam E propagates through it and may be referred to as a planar undulator module 200.

[00112] Some embodiments of the present invention are concerned with apparatus and methods for determining a magnetic field strength of an undulator module.

[00113] One embodiment relates to an apparatus comprising undulator module 200 and a magnetic field sensor. The undulator module 200 and the magnetic field sensor are arranged for releasable mutual engagement such that a magnetic field strength of the undulator module 200 can be measured.

[00114] The apparatus may comprise a plurality of magnetic field sensors. Three different magnetic field sensors 300, 310, 320 are shown in Figures 6A, 6B and 7 respectively. Each of the magnetic field sensors 300, 310, 320 comprises: a body 302, 312, 322; and a sensing element 304, 314, 324 which is operable to measure a magnetic field. For example, the sensing elements 304, 314, 324 may each comprise a Hall probe.

[00115] The undulator module 200 is provided with a plurality of openings 210, 220, 230 for receiving the sensing element 304, 314, 324 of a magnetic field sensor 300, 310, 320. Each of the openings 210, 220, 230 comprises an aperture in the support structure 50 of the undulator module 200. Each of the openings 210, 220, 230 extends along an opening axis 211, 221, 231.

5 **[00116]** The body 302, 312, 322 of each of the magnetic field sensors 300, 310, 320 comprises an engagement portion 302a, 312a, 322a, which is arranged to engage with the undulator module 200, and a projecting portion 302b, 312b, 322b, which extends away from the engagement portion 302a, 312a, 322a and to which the sensing element is attached. A surface of the engagement portion 302a, 312a, 322a is provided with projections 306, 316, 326.

10 **[00117]** A surface of the support structure 50 of the undulator module 200 is provided with recesses 52, 53, 54 in the vicinity of each of the openings 210, 220, 230. Recesses 52, 53, 54 and the projections 306, 316, 326 are complementary and allow the body 302, 312, 322 of each of the magnetic field sensors 300, 310, 320 to releasably engage with the support structure 50 of the undulator module 200.

15 **[00118]** In particular, recesses 52, 53, 54 and projections 306, 316, 326 are complementary alignment features that provide releasable engagement between each magnetic field sensor 300, 310, 320 and the undulator module 200 such that the sensing element 304, 314, 324 of the magnetic field sensor 310, 320, 330 can be repeatably positioned within the undulator module 200 in substantially the same position relative to the central axis 41. These alignment features
20 may be arranged to allow the sensing element 304, 314, 324 of each magnetic field sensor 300, 310, 320 to be positioned within one of the openings 210, 220, 230, removed from the opening 210, 220, 230 and subsequently re-positioned within the opening 210, 220, 230 in substantially the same fixed position relative to the undulator module 200. For example, the alignment features may be arranged to allow the sensing element 304, 314, 324 of each magnetic field
25 sensor 300, 310, 320 to be repeatably positioned within one of the openings 210, 220, 230 to within a specified tolerance distance of the fixed position relative to the undulator module 200. In some embodiments, the specified tolerance distance may be 10 μm or less, for example 2 μm or less.

30 **[00119]** The apparatus allows the sensing element 304, 314, 324 of each magnetic field sensor 310, 320, 330 to be moved between: (a) an accurate position within the undulator module 200 that is in the vicinity of the central axis 41 of the undulator module 200 so that the magnetic field strength and/or direction at that position may be determined; and (b) a location outside of the undulator module 200, where it is not subject to significant levels of radiation or radioactivity. It will be appreciated that a position within the undulator module 200 that is in the

vicinity of the central axis 41 of the undulator module 200 may be any position which is sufficiently close to the central axis 41 to allow a useful determination of the magnetic field (strength and/or direction) on the central axis 41 from a measurement of the magnetic field at that position. The sensing element 304, 314, 324 of the magnetic field sensor 300, 310, 320 may for example be periodically and accurately positioned in the vicinity of the central axis 41 of the undulator module 200 while no electron beam E is passing through the undulator module 200. Further, it may be positioned in the vicinity of the central axis 41 of the undulator module 200 for a relatively short time period, for example just long enough to take a measurement. This allows periodic measurements of the magnetic field in the vicinity of the central axis 41 of the undulator module 200 to be made whilst limiting the level of radioactivity that the sensing elements 304, 314, 324 are subject to. Allowing the magnetic field sensor 300, 310, 320 to be removed from the openings 210, 220, 230 defined by the undulator module 200 allows it to be recalibrated in between measurements. It also limits the amount of damage that the magnetic field sensor 300, 310, 320 sustains due to radioactivity.

[00120] From one or more measurements of the magnetic field strength in the vicinity of the central axis 41 of the undulator module 200, the magnetic field strength on the central axis 41 can be determined, for example by modelling or extrapolation. In order to determine the magnetic field strength at the central axis 41 of the undulator module 200 accurately, it is important that the sensing element 304, 314, 324 of the magnetic sensor 300, 310, 320 can be located in substantially the same position relative to the undulator module 200 for each measurement. This is achieved by the alignment features (i.e. recesses 52, 53, 54 and projections 306, 316, 326).

[00121] This apparatus allows the magnetic field within the undulator module 200 to be sampled without disassembling the undulator module 200 because the openings 210, 220, 230 allows the sensing elements 204, 214, 224 of the magnetic field sensors 200, 210, 220 to be positioned within the undulator 200. This may be advantageous since disassembly of the undulator module 200 may be time consuming. Furthermore, parts of the undulator module 200 which are closer to the central axis 41 may be radioactive for a time after the electron beam E has been switched off. Since disassembly of the undulator module 200 may expose such parts of the undulator module 200, either the resultant radiation must be contained or the undulator module 200 should be allowed to cool down for a time period before disassembly. This increases the complexity of disassembly of undulator modules 200 and/or increases the down time of the free electron laser FEL.

[00122] The provision of a plurality of openings 210, 220, 230 allows the magnetic field to be sampled in a plurality of different positions within the undulator module 200. Measurement of the magnetic field at greater number of different positions within the undulator module 200 may increase the accuracy with which the magnetic field on the central axis 41 can be determined.

5 **[00123]** The releasable engagement between the magnetic field sensor 300, 310, 320 and the undulator module 200 provided by the complementary alignment features (i.e. recesses 52, 53, 54 and projections 306, 316, 326) may be such that the sensing element 304, 314, 324 can be repeatably positioned within the undulator module 200 with substantially the same orientation.

10 **[00124]** This may be advantageous if, for example, the sensing element 304, 314, 324 is operable to determine a component of the magnetic field in a single sensing direction (relative to the magnetic field sensor 300, 310, 320). For example, for embodiments wherein the sensing element 304, 314, 324 comprises a Hall probe. With such embodiments, in order to determine the magnetic field strength at the central axis 41 of the undulator module 200 accurately, it may
15 be important that the sensing element 304, 314, 324 of the magnetic sensor 300, 310, 320 can be positioned with substantially the same orientation for each measurement of the magnetic field (so that the sensing element 304, 314, 324 determines the same component of the magnetic field for each measurement).

[00125] The alignment features (i.e. recesses 52, 53, 54 and projections 306, 316, 326) may
20 be arranged to allow the sensing element 304, 314, 324 of the magnetic field sensor 300, 310, 320 to be positioned within the opening 210, 220, 230 to within a specified tolerance orientation of a desired orientation. The specified tolerance orientation may be 1 mrad or less, for example 0.1 mrad.

[00126] The complementary alignment features (i.e. recesses 52, 53, 54 and projections 306,
25 316, 326) may be arranged such that when each magnetic field sensor 300, 310, 320 engages with the undulator module 200 the sensing element 304, 314, 324 of the magnetic field sensor 300, 310, 320 is in one of a finite number of fixed orientations. The alignment features may provide any number of fixed orientations. For example, in some embodiments the alignment features may provide a single fixed orientation. This can prevent, for example, the magnetic
30 sensor 300, 310, 320 from engaging with the undulator module 200 with the sensing element 304, 314, 324 in two different orientations for two different measurements and thus ensures that the measurements are consistent. Alternatively, the complementary alignment features may provide two or more fixed orientations. That is, the complimentary alignment features may provide a plurality of discrete fixed orientations for the magnetic sensor 300, 310, 320. This can

allow the magnetic field sensor 300, 310, 320 to engage with the undulator module 200 with the sensing element 204, 214, 224 in one of two or more different orientations, which may for example allow two or more components of the magnetic field to be determined.

[00127] The complementary alignment features (i.e. recesses 52, 53, 54 and projections 306, 316, 326) may be arranged such that when each magnetic field sensor 300, 310, 320 engages with the undulator module 200 it makes contact with the undulator module 200 at three or more contact points. That is each magnetic field sensor 300, 310, 320 may be provided with three or more projections 306, 316, 326 and the undulator module 200 may be provided with three or more recesses 52, 53, 54. This may improve the accuracy with which the position and orientation of the sensing element 304, 314, 324 can be controlled.

[00128] The openings 210, 220, 230 may be located at a range of different (axial and azimuthal) positions within the undulator module 200.

[00129] In some embodiments, at least one of the openings 220 (Figures 5 and 7) is provided in the support structure 50 extending radially at an azimuthal position between that of two of the periodic magnetic structures 42a-42d. This allows the sensing element 324 of a magnetic field sensor 320 to extend through the opening 220 and in between two adjacent periodic magnetic structures 42a-42d. Advantageously, this allows the sensing element 324 to be positioned in the vicinity of the central axis 41 of the undulator module 200 (e.g. adjacent to pipe 40).

[00130] In some embodiments, at least one of the openings 230 extends radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures 42a-42d and at an axial position that is substantially the same as that of one of the magnets 44 of that periodic magnetic structure 42a-42d. This allows the sensing element of a magnetic field sensor to be placed adjacent to one of the magnets 44 of one of the periodic magnetic structures 42a-42d, where the magnetic field is dominated by that of that magnet 44. Therefore, this allows the magnetic field of an individual magnet 44 to be monitored.

[00131] In some embodiments, at least one of the openings 210 extends radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures 42a-42d and at an axial position that is substantially the same as that of one of the ferromagnetic elements 48 of that periodic magnetic structure 42a-42d. At such a position, radially above one of the ferromagnetic elements 48, the magnetic field is generally aligned with the radial direction, i.e. the projecting portion 302b, 312b, 322b of the body of magnetic field sensor. This may be advantageous since it may be easier to attach a sensing element, such as a Hall probe, to the projecting portion 302b, 312b, 322b of the body of magnetic field sensor such that it is sensitive to magnetic fields along the projecting portion 302b, 312b, 322b.

[00132] In some embodiments, at least one of the openings may comprise a bore 48a that extends into one of the ferromagnetic elements 48 of one of the periodic magnetic structures 42a-42d. For example, as shown in Figure 6B, opening 210 may extend through the support structure and into one of the ferromagnetic elements 48. That is, the opening 210 may extend
5 radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures 42a-42d and at an axial position that is substantially the same as that of one of the ferromagnetic elements 48 of that periodic magnetic structure 42a-42d. Due to the relatively high magnetic permeability of the ferromagnetic elements 48, the magnetic field is stronger inside the ferromagnetic elements 48. Therefore by measuring the magnetic field
10 inside the ferromagnetic elements 48 the accuracy of the measurement may be increased (with the same sensing element).

[00133] An apparatus according to the present invention may comprise an undulator module 200 that is provided with at least one opening. For embodiments comprising a plurality of different openings, a different magnetic field sensor may be used for each of the plurality of
15 openings. Alternatively, a single magnetic field sensor may be used for more than one of the plurality of openings. For example, a single magnetic field sensor may be used for all of the plurality of openings. Alternatively, the plurality of openings may comprise a plurality of sets of openings (e.g. of different types, i.e. radially above a magnet 44, within a ferromagnetic element 48 or azimuthally between two periodic magnetic structures 42a-42d) and a different single
20 magnetic field sensor may be used for each different set of openings. Each different set of openings may have different alignment features (i.e. recesses 52, 53, 54).

[00134] Another embodiment of the invention which allows a magnetic field strength of the undulator module 200 to be measured relates to an undulator module 200 wherein at least one of the ferromagnetic elements 48 of at least one of the periodic magnetic structures 42a-42d is
25 provided with an apparatus for determining the magnetic permeability of that ferromagnetic element 48.

[00135] The magnetic permeability of the ferromagnetic elements 48 is dependent upon the magnetic field applied by the plurality of magnets 44. Therefore the apparatus for determining the magnetic permeability of the ferromagnetic elements 48 of this embodiment of the invention
30 provides an indirect measurement of the magnetic field provided by the magnets 44. From one or more measurements of the magnetic permeability of the ferromagnetic elements 48, the magnetic field strength on the central axis 41 of the undulator module 200 can be determined, for example by modelling or extrapolation.

[00136] An apparatus for determining the magnetic permeability of one of the ferromagnetic elements 48 is now described with reference to Figures 8A and 8B. The apparatus for determining the magnetic permeability of a ferromagnetic element 48 comprises: a coil assembly comprising one or more coils of wire 400 wrapped around the ferromagnetic element 48; a power supply (not shown) operable to apply an alternating current to a coil 400 of the coil assembly; and an apparatus (not shown) arranged to determine an inductance of a coil 400 of the coil assembly.

[00137] When the power supply applies an alternating current to a coil 400 of the coil assembly, an alternating magnetic field is generated within the ferromagnetic element 48. In turn, this will induce a voltage in any coils 400 wrapped around the ferromagnetic element 48. The inductance, and the induced voltage, is dependent upon the magnetic permeability of the ferromagnetic element 48. Therefore by determining the inductance of a coil 400 from the coil assembly, the magnetic permeability of the ferromagnetic element 48 can be determined.

[00138] In this embodiment, the coil 400 of the coil assembly whose inductance is determined is the same coil 400 as that to which the alternating current is applied by the power supply. Alternatively, in another embodiment, two coils may be provided. For such embodiments the alternating current may be applied by the power supply to a first coil and the inductance of a second coil may be determined.

[00139] Optionally, grooves 410 may be provided on an outer surface of the ferromagnetic element 48 and one or more of the coils 400 of the coil assembly may be received within said grooves 410. This may facilitate easy mounting and alignment of the coils 400 with the ferromagnetic element 48.

[00140] Any of the embodiments of the present invention described above may be provided in combination or alone.

[00141] For example some embodiments of the invention may comprise one or more openings in an undulator module and one or more magnetic field sensors, the undulator module and the magnetic field sensor comprising complementary alignment features that provide releasable engagement between the magnetic field sensor and the undulator module. Such embodiments may or may not further comprise an apparatus for determining the magnetic permeability of at least one of the ferromagnetic elements of at least one of the periodic magnetic structures.

[00142] Furthermore, some embodiments of the invention may comprise an apparatus for determining the magnetic permeability of at least one of the ferromagnetic elements of at least one of the periodic magnetic structures of an undulator module. Such embodiments may or

may not further comprise one or more openings in an undulator module and one or more magnetic field sensors, the undulator module and the magnetic field sensor comprising complementary alignment features that provide releasable engagement between the magnetic field sensor and the undulator module.

5 **[00143]** Embodiments of the invention have been described wherein the undulator module and the magnetic field sensor comprise complementary alignment features that provide releasable engagement between the magnetic field sensor and the undulator module. It will be appreciated in this context releasable engagement means that the magnetic field sensor and the undulator module can engage and disengage. It does not mean that the magnetic field
10 sensor and the undulator module are provided with a locking mechanism that prevents or limits disengagement. In some embodiments the magnetic field sensor and the undulator module may be provided with such a locking mechanism. In contrast, in some embodiments the magnetic field sensor may be manually held in engagement with the undulator module.

[00144] Embodiments of the invention have been described wherein a surface of a magnetic
15 field sensor is provided with projections and a surface of an undulator module is provided with recesses, the recesses and the projections being complementary and allowing the magnetic field sensor to releasably engage with the undulator module. It will be appreciated that in alternative embodiments the undulator module and the magnetic field sensor comprise different complementary alignment features that provide releasable engagement between the magnetic
20 field sensor and the undulator module. For example, a surface of the magnetic field sensor may be provided with recesses and a surface of an undulator module may be provided with projections. Alternatively a surface of the magnetic field sensor may be provided with a combination of projections and recesses and a surface of an undulator module may be provided with complementary recesses and projections.

25 **[00145]** Whilst embodiments of a radiation source SO have been described and depicted as comprising a free electron laser FEL, it should be appreciated that a radiation source may comprise any number of free electron lasers FEL. For example, a radiation source may comprise more than one free electron laser FEL. For example, two free electron lasers may be arranged to provide EUV radiation to a plurality of lithographic apparatus. This is to allow for
30 some redundancy. This may allow one free electron laser to be used when the other free electron laser is being repaired or undergoing maintenance.

[00146] Although the described embodiment of a lithographic system LS comprises eight lithographic apparatuses LA_a - LA_n , a lithographic system LS may comprise any number of lithographic apparatus. The number of lithographic apparatus which form a lithographic system

LS may, for example, depend on the amount of radiation which is output from a radiation source 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.

[00147] Embodiments of a lithographic system LS may also include one or more mask inspection apparatus MIA and/or one or more Aerial Inspection Measurement Systems (AIMS). In some embodiments, the lithographic system LS may comprise a plurality of mask inspection apparatuses to allow for some redundancy. This may allow one mask inspection apparatus to be used when another mask inspection apparatus is being repaired or undergoing maintenance. Thus, one mask inspection apparatus is always available for use. A mask inspection apparatus 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.

[00148] 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.

[00149] The term “relativistic electrons” should be interpreted to mean electrons which have relativistic energies. An electron may be considered to have a relativistic energy when its kinetic energy is comparable to or greater than its rest mass energy (511 keV in natural units). In practice a particle accelerator which forms part of a free electron laser may accelerate electrons to energies which are much greater than its rest mass energy. For example a particle accelerator may accelerate electrons to energies of >10 MeV, >100 MeV, >1GeV or more.

[00150] 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.

[00151] 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.

[00152] 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.

[00153] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

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. An apparatus comprising an undulator module and a magnetic field sensor, the magnetic field sensor comprising:

a body; and

a sensing element operable to measure a magnetic field;

the undulator module comprising:

a support structure; and

a plurality of periodic magnetic structures, the periodic structures being supported by the support structure and being arranged around and extending parallel to a central axis;

wherein the undulator module is provided with at least one opening for receiving the sensing element of the magnetic field sensor;

wherein the undulator module and the magnetic field sensor comprise complementary alignment features that provide releasable engagement between the magnetic field sensor and the undulator module such that the sensing element of the magnetic field sensor can be repeatedly positioned within the undulator module in substantially the same position relative to the central axis.

2. The apparatus of clause 1, wherein the complementary alignment features comprise one or more projections on one of the magnetic field sensor and the undulator module and one or more complementary recesses on the other of the magnetic field sensor and the undulator module.

3. The apparatus of clause 1 or clause 2, wherein the releasable engagement between the magnetic field sensor and the undulator module provided by the complementary alignment features is such that the sensing element of the magnetic field sensor can be repeatedly positioned within the undulator module with substantially the same orientation.

4. The apparatus of any preceding clause, wherein the complementary alignment features are arranged such that when the magnetic field sensor engages with the undulator module the sensing element of the magnetic field sensor is in one of a finite number of fixed orientations.
5. The apparatus of any preceding clause, wherein the undulator module is provided with a plurality of openings for receiving the sensing element of a magnetic field sensor.
6. The apparatus of any preceding clause, comprising a plurality of magnetic field sensors.
7. The apparatus of any preceding clause, wherein at least one of the openings for receiving the sensing element of a magnetic field sensor is provided in the support structure and extends radially at an azimuthal position between that of two of the periodic magnetic structures.
- 10 8. The apparatus of any preceding clause, wherein each of the periodic magnetic structures comprises a plurality of magnets, each of the plurality of magnets being operable to produce a magnetic field, wherein at least one of the openings for receiving the sensing element of a magnetic field sensor extends radially at an azimuthal position that is substantially the same as that of one of the periodic magnetic structures and at an axial position that is substantially the same as that of one of the magnets of that periodic magnetic structure.
- 15 9. The apparatus of clause 8, wherein the plurality of magnets of a given periodic structure extend axially such that along a length of the periodic magnetic structure the polarization directions of the plurality of magnets form a repeating pattern in an axial direction.
10. The apparatus of clause 8 or clause 9, wherein each of the periodic magnetic structures
- 20 further comprises a plurality of ferromagnetic elements, which are arranged to direct the magnetic field generated by the plurality of magnets towards the central axis of the undulator module.
11. The apparatus of clause 10, wherein at least one of the openings for receiving the sensing element of a magnetic field sensor comprises a bore that extends into one of the
- 25 ferromagnetic elements of one of the periodic magnetic structures.
12. The apparatus of any preceding clause, wherein the opening comprises an aperture in the support structure of the undulator module.
13. The apparatus of any preceding clause, wherein the undulator module is a planar undulator module comprising two periodic magnetic structures.
- 30 14. The apparatus of any preceding clause, wherein the undulator module is a helical undulator module comprising four periodic magnetic structures.
15. A magnetic field sensor comprising:
 - a body; and
 - a sensing element operable to measure a magnetic field;

wherein the magnetic field sensor comprises an alignment feature that provides releasable engagement between the magnetic field sensor and an undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

- 5 16. An undulator module comprising:
a support structure; and
a plurality of periodic magnetic structures, the periodic structures being supported by the support structure and being arranged around and extending parallel to a central axis;
wherein the undulator module is provided with at least one opening for receiving a
10 sensing element of a magnetic field sensor;

wherein the undulator module comprises an alignment feature that provides releasable engagement between the magnetic field sensor and the undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

- 15 17. An undulator module, the undulator module comprising a plurality of periodic magnetic structures, the periodic structures being arranged around and extending parallel to a central axis and being operable to produce a periodic magnetic field for guiding an electron beam along a periodic path such that electrons within the electron beam interact with radiation in the undulator module to stimulate emission of coherent radiation to provide a radiation beam;

20 wherein each of the periodic magnetic structures comprises a plurality of magnets and a plurality of ferromagnetic elements, each of the plurality of magnets being operable to produce a magnetic field and each of the plurality of ferromagnetic elements being arranged to direct the magnetic field generated by the plurality of magnets towards the central axis;

wherein at least one of the ferromagnetic elements of at least one of the periodic
25 magnetic structures is provided with an apparatus for determining the magnetic permeability of that ferromagnetic element.

18. The undulator module of clause 17, wherein the apparatus for determining the magnetic permeability of the ferromagnetic element comprises:

30 a coil assembly comprising one or more coils of wire wrapped around the ferromagnetic element;

a power supply operable to apply an alternating current to a coil of the coil assembly;
and

an apparatus arranged to determine an inductance of, or a voltage induced in, a coil of the coil assembly.

19. A free electron laser, comprising:

an electron source for producing an electron beam comprising a plurality of bunches of relativistic electrons; and

an undulator arranged to receive the electron beam and guide it along a periodic path so that the electron beam interacts with radiation within the undulator, stimulating emission of radiation and providing a radiation beam,

wherein the undulator comprises the apparatus of any one of clauses 1 to 14 or the undulator module of any one of clauses 17 to 18.

20. A lithographic system comprising:

a free electron laser according to clause 19; and

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

21. A method for determining a magnetic field strength of an undulator module, the method comprising:

inserting a magnetic field sensor comprising a sensing element into an opening in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with a complementary alignment feature on the undulator module such that the sensing element is accurately located at a measurement position relative to a central axis of the undulator module;

measuring a magnetic field at the measurement position using the sensing element; and removing the magnetic field sensor from the opening in the undulator module.

22. The method of clause 21 comprising:

inserting a magnetic field sensor comprising a sensing element into each of a plurality of openings in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with a complementary alignment feature on the undulator module such that the sensing element is accurately located at one of a plurality of measurement positions relative to a central axis of the undulator module;

measuring a magnetic field at that measurement position using the sensing element; and removing the a magnetic field sensor from each of the plurality of openings in the

undulator module.

23. The method of clause 21 or clause 22 further comprising: determining a magnetic field at a central axis of the undulator module from the measured magnetic field at the or each measurement position.

24. A method for determining a magnetic field strength of an undulator module comprising a plurality of periodic magnetic structures, the periodic structures being arranged around and extending parallel to a central axis, each of the periodic magnetic structures comprising a plurality of magnets arranged alternately with a plurality of ferromagnetic elements, the method comprising: determining the magnetic permeability of at least one of the ferromagnetic elements of at least one of the periodic magnetic structures.

25. The method of clause 24 comprising: determining the magnetic permeability of a plurality of the ferromagnetic elements of a plurality of the periodic magnetic structures.

26. The method of clause 24 or clause 25 comprising: determining the magnetic field at a central axis of the undulator module from the measured magnetic permeability of the plurality of the ferromagnetic elements of the plurality of the periodic magnetic structures.

CLAIMS

1. An apparatus comprising an undulator module and a magnetic field sensor,
the magnetic field sensor comprising:
5 a body; and
a sensing element operable to measure a magnetic field;
the undulator module comprising:
a support structure; and
a plurality of periodic magnetic structures, the periodic structures being supported by the
10 support structure and being arranged around and extending parallel to a central axis;
wherein the undulator module is provided with at least one opening for receiving the
sensing element of the magnetic field sensor;
wherein the undulator module and the magnetic field sensor comprise complementary
alignment features that provide releasable engagement between the magnetic field sensor and
15 the undulator module such that the sensing element of the magnetic field sensor can be
repeatedly positioned within the undulator module in substantially the same position relative to
the central axis.
2. The apparatus of claim 1, wherein the complementary alignment features comprise one
20 or more projections on one of the magnetic field sensor and the undulator module and one or
more complementary recesses on the other of the magnetic field sensor and the undulator
module.
3. The apparatus of claim 1 or claim 2, wherein the releasable engagement between the
25 magnetic field sensor and the undulator module provided by the complementary alignment
features is such that the sensing element of the magnetic field sensor can be repeatedly
positioned within the undulator module with substantially the same orientation.
4. The apparatus of any preceding claim, wherein the complementary alignment features
30 are arranged such that when the magnetic field sensor engages with the undulator module the
sensing element of the magnetic field sensor is in one of a finite number of fixed orientations.
5. The apparatus of any preceding claim, wherein the undulator module is provided with a
plurality of openings for receiving the sensing element of a magnetic field sensor.

6. A magnetic field sensor comprising:

a body; and

a sensing element operable to measure a magnetic field;

5 wherein the magnetic field sensor comprises an alignment feature that provides releasable engagement between the magnetic field sensor and an undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

10 7. An undulator module comprising:

a support structure; and

a plurality of periodic magnetic structures, the periodic structures being supported by the support structure and being arranged around and extending parallel to a central axis;

15 wherein the undulator module is provided with at least one opening for receiving a sensing element of a magnetic field sensor;

wherein the undulator module comprises an alignment feature that provides releasable engagement between the magnetic field sensor and the undulator module such that the sensing element of the magnetic field sensor can be repeatably positioned within the undulator module in substantially the same position relative to the central axis.

20 8. A free electron laser, comprising:

an electron source for producing an electron beam comprising a plurality of bunches of relativistic electrons; and

25 an undulator arranged to receive the electron beam and guide it along a periodic path so that the electron beam interacts with radiation within the undulator, stimulating emission of radiation and providing a radiation beam,

wherein the undulator comprises the apparatus of any one of claims 1 to 5.

9. A lithographic system comprising:

30 a free electron laser according to claim 8; and

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

10. A method for determining a magnetic field strength of an undulator module, the method comprising:

inserting a magnetic field sensor comprising a sensing element into an opening in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with
5 a complementary alignment feature on the undulator module such that the sensing element is accurately located at a measurement position relative to a central axis of the undulator module;

measuring a magnetic field at the measurement position using the sensing element; and
removing the magnetic field sensor from the opening in the undulator module.

10 11. The method of claim 10 comprising:

inserting a magnetic field sensor comprising a sensing element into each of a plurality of openings in the undulator module, such that an alignment feature on the magnetic field sensor cooperates with a complementary alignment feature on the undulator module such that the sensing element is accurately located at one of a plurality of measurement positions relative to a
15 central axis of the undulator module;

measuring a magnetic field at that measurement position using the sensing element; and

removing the a magnetic field sensor from each of the plurality of openings in the undulator module.

20 12. The method of claim 10 or claim 11 further comprising: determining a magnetic field at a central axis of the undulator module from the measured magnetic field at the or each measurement position.

13. A method for determining a magnetic field strength of an undulator module comprising a
25 plurality of periodic magnetic structures, the periodic structures being arranged around and extending parallel to a central axis, each of the periodic magnetic structures comprising a plurality of magnets arranged alternately with a plurality of ferromagnetic elements, the method comprising: determining the magnetic permeability of at least one of the ferromagnetic elements of at least one of the periodic magnetic structures.

30

14. The method of claim 13 comprising: determining the magnetic permeability of a plurality of the ferromagnetic elements of a plurality of the periodic magnetic structures.

15. The method of claim 13 or claim 14 comprising: determining the magnetic field at a central axis of the undulator module from the measured magnetic permeability of the plurality of the ferromagnetic elements of the plurality of the periodic magnetic structures.

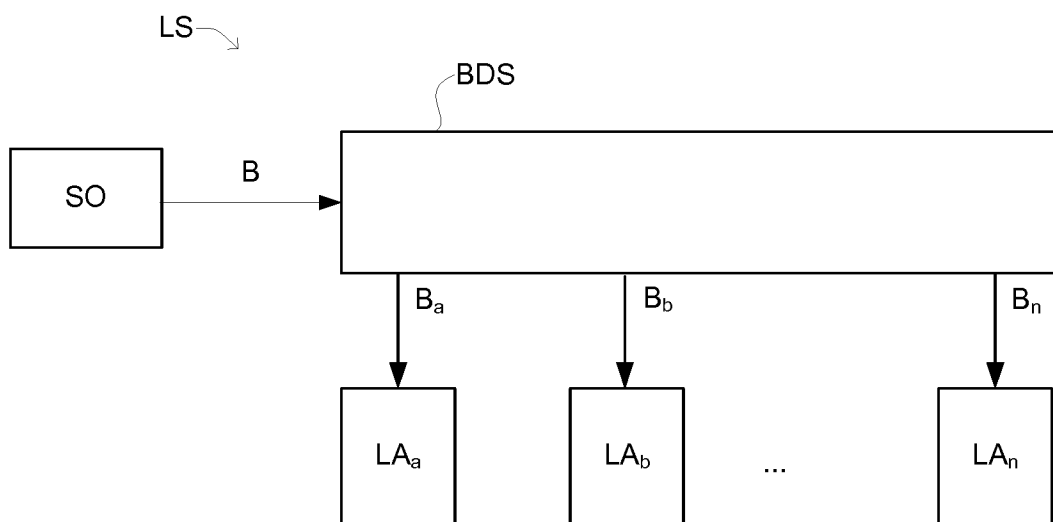


Fig. 1

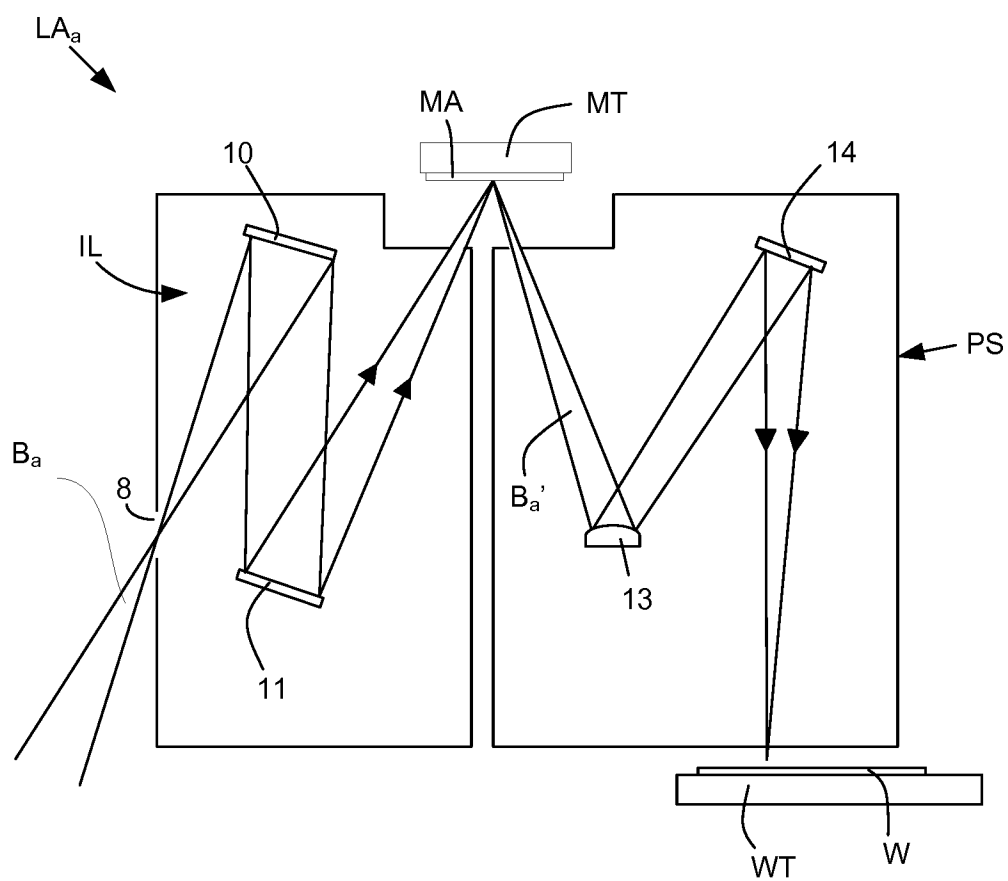


Fig. 2

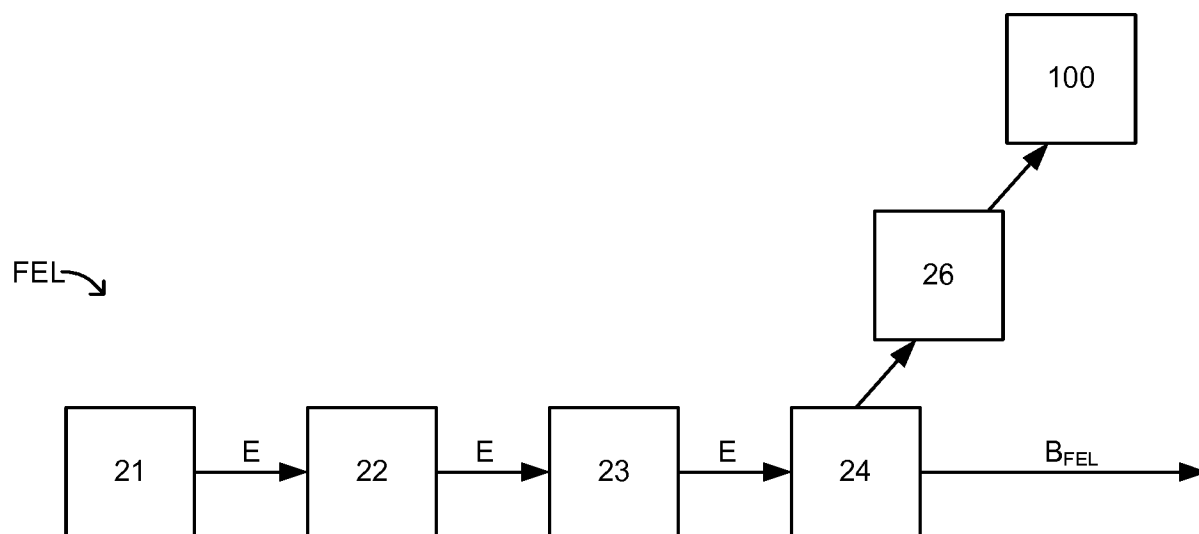


Fig. 3

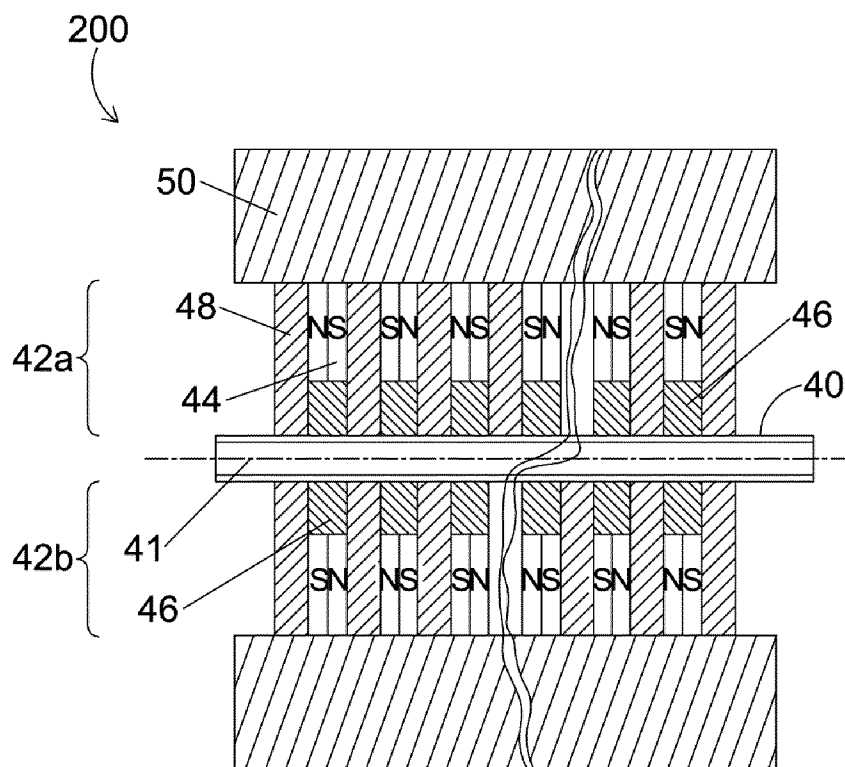


Fig. 4

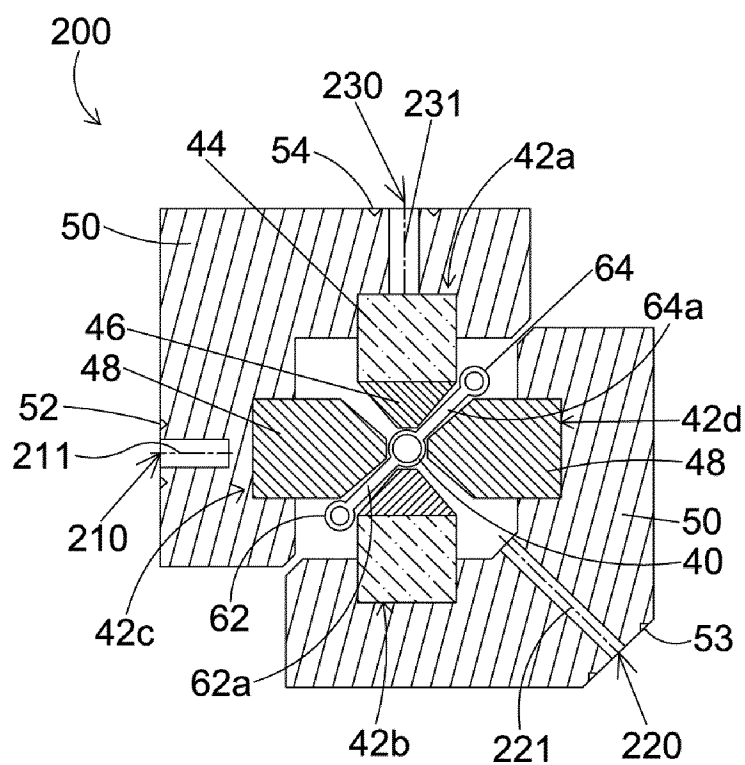


Fig. 5

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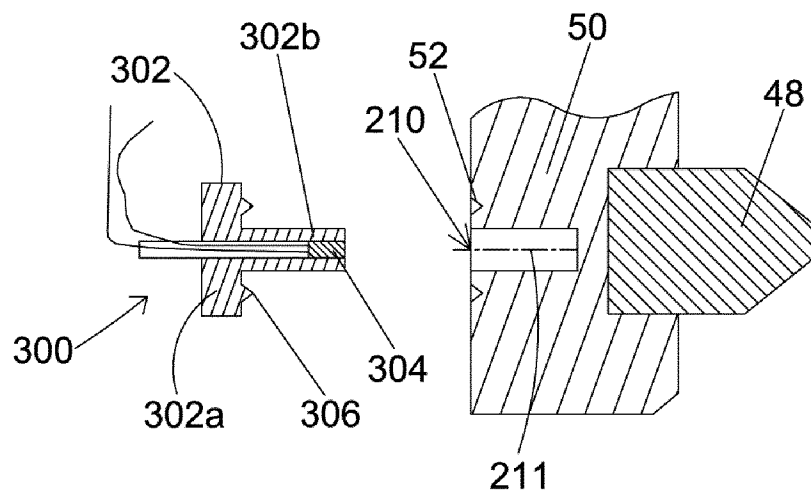


Fig. 6A

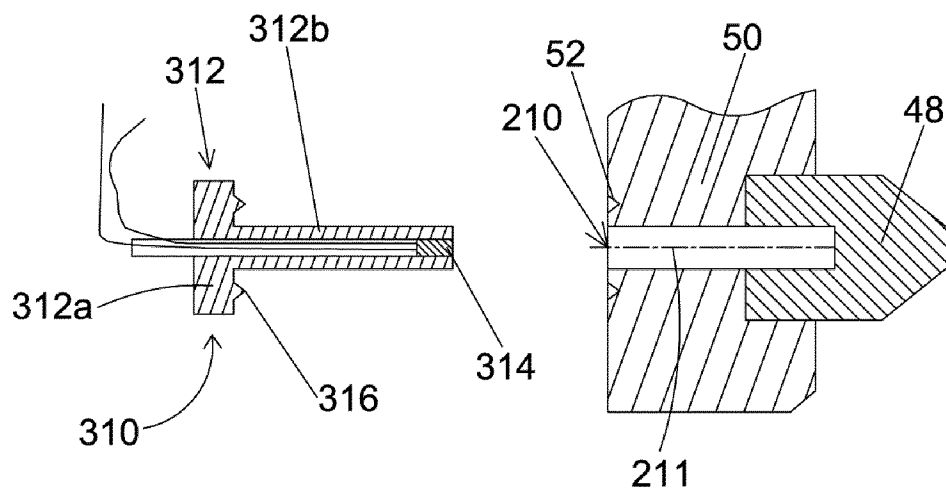


Fig. 6B

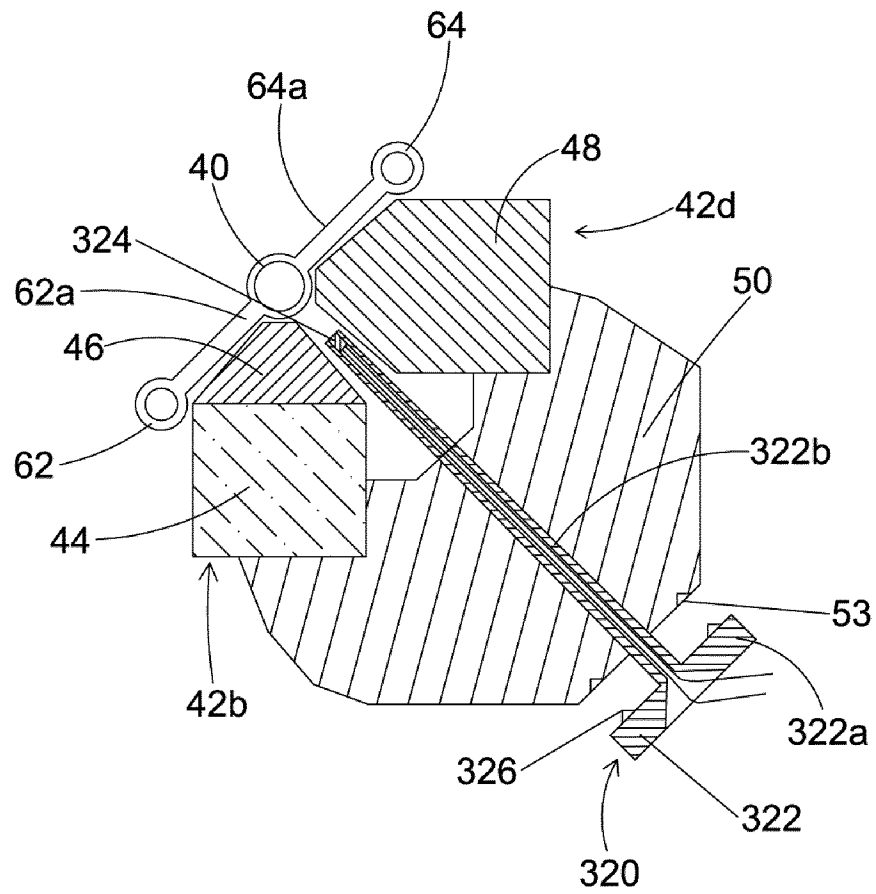


Fig. 7

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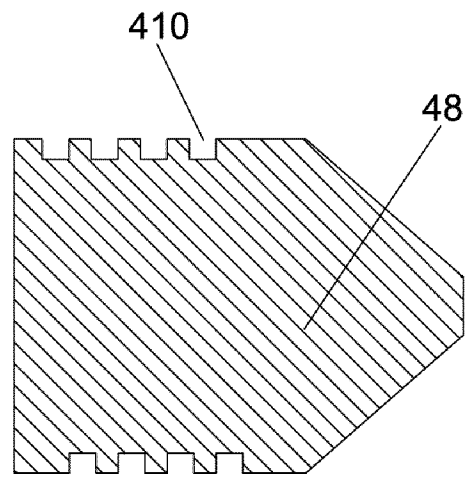


Fig. 8A

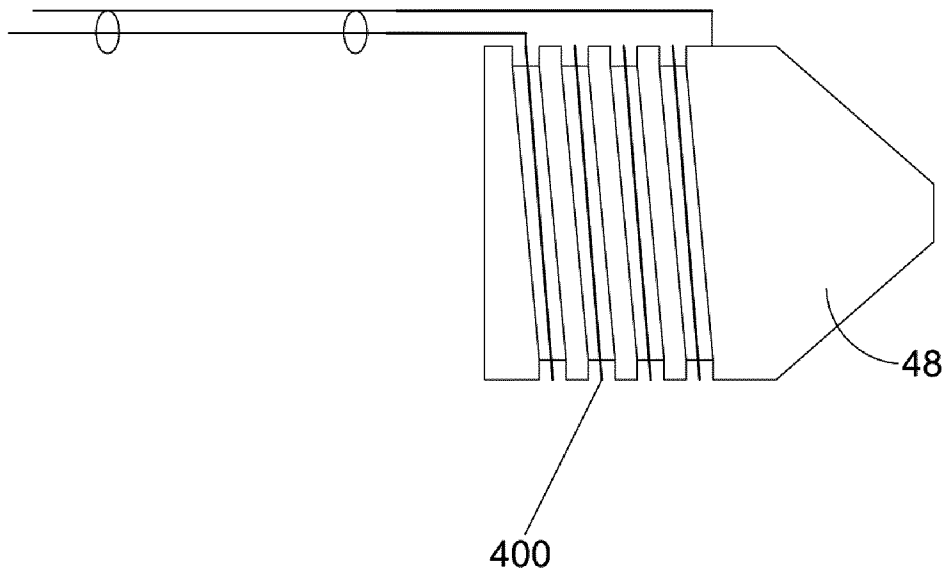


Fig. 8B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/076962

A. CLASSIFICATION OF SUBJECT MATTER
INV. H05H7/04
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H05H

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GRAU A ET AL: "Instrumentation for Local and Integral Field Measurements of Superconducting Undulator Coils", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, IEEE SERVICE CENTER, LOS ALAMITOS, CA, US, vol. 21, no. 3, 1 June 2011 (2011-06-01), pages 2312-2315, XP011325070, ISSN: 1051-8223, DOI: 10.1109/TASC.2010.2092748 abstract; figures 1-4 paragraph [III.A]	1-12
A	DE 10 2013 211830 A1 (ZEISS CARL SMT GMBH [DE]) 12 June 2014 (2014-06-12) abstract Figure ----- -/--	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

14 January 2016

Date of mailing of the international search report

25/01/2016

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INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2015/076962

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	F.H.O'SHEA ET AL: "Status of Praesodymium Undulator with Textured Dysprosium Poles for compact X-Ray FEL Applications", PROCEEDINGS OF IPAC2013, June 2013 (2013-06), pages 2298-2300, XP002752949, ISBN: 978-3-95450-122-9 abstract; figures 2,4 -----	13-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2015/076962

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102013211830 A1	12-06-2014	NONE	