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(71) Applicant: **European XFEL GmbH**
22869 Schenefeld (DE)

(72) Inventor: **Shayduk, Roman**
22869 Schenefeld (DE)

(74) Representative: **RGTH**
Patentanwälte PartGmbB
Neuer Wall 10
20354 Hamburg (DE)

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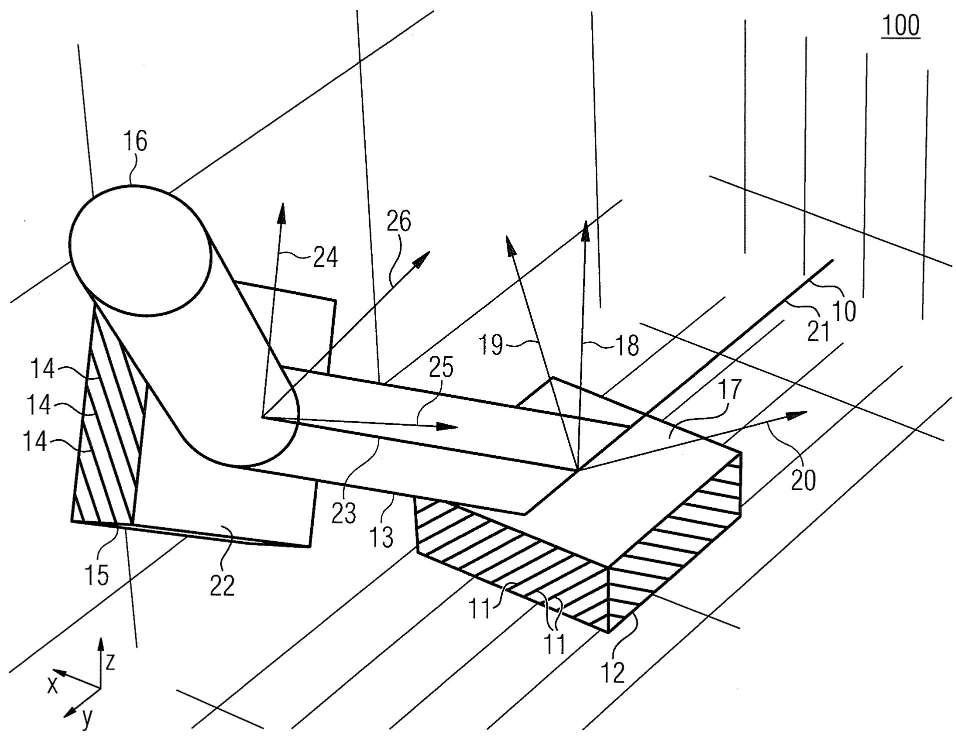
(54) METHOD AND APPARATUS FOR X-RAY SHAFT EXPANSION AND/OR COMPRESSION AND/OR COLLIMATION AND/OR FOCUSING AND/OR X-RAY MAGNIFICATION

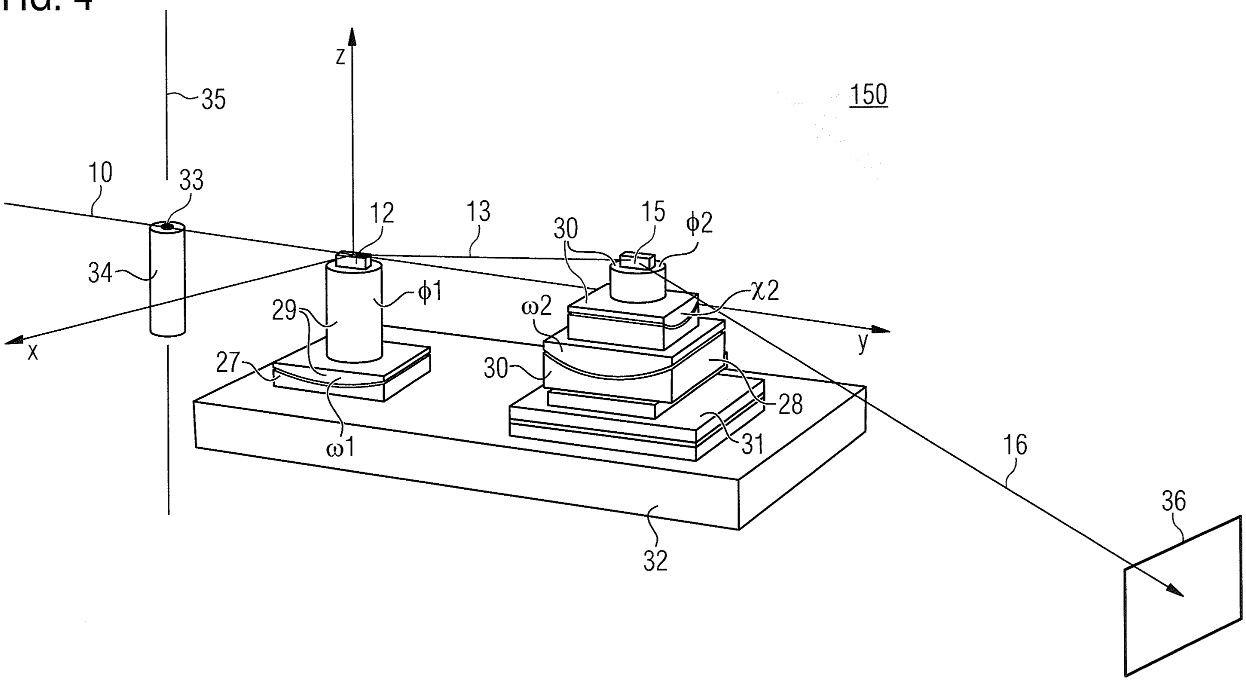
(57) A Method (100) for X-ray beam expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification is provided, wherein a first shaft of X-ray radiation (10) is scattered in a first scattering process at a first plurality of parallel lattice planes (11) of a first crystal (12) to generate a scattered second beam of X-ray radiation (13), wherein the scattered second shaft of X-ray radiation (13) is scattered in a second scattering process at a second plurality of parallel lattice planes (14) of a second crystal (15) to generate a scattered third beam of X-ray radiation (16), and wherein the first scattering process and the second scattering process are non-coplanar Bragg-scattering processes.

FIG. 3



EP 3 723 103 A1

FIG. 4



Description

[0001] The present invention relates to a method and apparatus for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray magnification.

Technological background

[0002] Modern radiography and computer tomography has reached sub-micrometer resolution [P.J. Withers, Materials Today 10, 12, 26-34, (2007)]. Besides various scanning methods, a parallel projection of a collimated beam or a cone projection of a divergent beam are widely employed [U. Bonse, F. Busch, Progress in Biophysics and Molecular Biology, 56, 1/2, 133-169, 1996]. Whilst different methods of obtaining real space image contrasts are employed, it is always mandatory to have 2d X-ray detectors with best possible spatial resolution. For state of the art X-ray detectors the resolution is limited to few tens of micrometers. To improve the radiographic/tomographic resolution beyond the detector limit in parallel projection various X-ray shaft magnification devices and methods are known.

[0003] One of the technics that improves the tomographic/radiographic resolution by a factor of up to 100 in projection-based imaging uses Bragg magnifiers [P.J. Withers, Materials Today 10, 12, 26-34, (2007); SPIE Proceedings 2516, 1995]. In such systems a single Bragg-diffracted X-ray beam from an asymmetrically cut crystal results in an increase of the beam cross-section in one dimension. A second scattering from an asymmetrically cut crystal rotated by 90° stretches the beam in another dimension.

[0004] In recent years X-ray free electron lasers (FELs) such as the one currently in operation in Hamburg, Germany are used for research in many disciplines. For example, by using X-ray FELs it is possible to determine the structure of molecules critical to biology, to determine ultrafast energy transfers within molecules and the structure of nanocrystals.

[0005] US 5,259,013 A discloses a hard X-ray magnification apparatus and method with submicrometer spatial resolution of images in more than one dimension. A monochromatic hard X-ray beam is applied to a specimen and thereafter is directed to arrive at a small angle of incidence at a flat, optically polished surface of a nearly perfect crystal, to be diffracted at the surface thereof. The diffracted X-ray beam is directed at a small angle of incidence to the surface of a second nearly perfect crystal, the receiving surface being oriented orthogonal to the surface of the first nearly perfect crystal.

[0006] Prior art document JP H06-235704 A relates to a method for monochromatizing and enlarging X-rays, for example synchrotron radiation by using a single crystal.

[0007] The magnification factor of Bragg-magnifiers with asymmetric cut crystals in coplanar Bragg-scattering is determined by the ratio of exit and incidence angles. Thus, in coplanar Bragg scattering the magnification factor drops rapidly with the decrease of X-ray beam energy [M. Stamponini, Nuclear Instruments and Methods in Physics research A 551, 119-124, (2005)]. Importantly, in coplanar Bragg-scattering it is not possible to control or stabilize the magnification factor over a larger energy or wavelength range. To stabilize the magnification factor over a larger energy range, a new asymmetric crystal with a different miss cut angle is required for each new X-ray energy or wavelength of interest.

Disclosure of the invention: problem, solution, advantages

[0008] It is an object of the present invention to provide a method and an apparatus for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray magnification in a broad energy or wavelength range with a single Bragg-scattering setup and without the requirement to exchange the scattering crystals for each new X-ray energy or wavelength of interest.

[0009] The problem is solved by the provision of a method for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, wherein a first shaft of X-ray radiation is scattered in a first scattering process at a first plurality of parallel lattice planes of a first crystal to generate a scattered second shaft of X-ray radiation, wherein the scattered second shaft of X-ray radiation is scattered in a second scattering process at a second plurality of parallel lattice planes of a second crystal to generate a scattered third shaft of X-ray radiation, wherein the first scattering process and the second scattering process are non-coplanar Bragg scattering processes.

[0010] The first shaft of X-ray radiation and/or the scattered second shaft of X-ray radiation and/or the scattered third shaft of X-ray radiation can be collimated or directional shafts of radiation with a finite divergence. Furthermore, in particular when the first, second or third shaft of X-ray radiation is a collimated or directional shaft of radiation with a small divergence, the first shaft of X-ray radiation, the second shaft of X-ray radiation or the third shaft of X-ray radiation can be configured as X-ray beams.

[0011] The first shaft of X-ray radiation and/or the scattered second shaft of X-ray radiation and/or the scattered third shaft of X-ray radiation can have a respective first, second or third beam axis.

[0012] Bragg scattering occurs, when radiation with a wavelength comparable to atomic spacings is scattered in a specular fashion by atoms of a crystalline system and undergoes constructive interference. For a crystalline solid, the waves are scattered from lattice planes separated by an inter-planar distance d. Scattered waves interfere constructively when the difference between the path lengths of waves scattered at different parallel lattice planes is equal to an integer multiple of the wavelength.

Thus, constructive Bragg scattering occurs when the Bragg condition $2d \sin(\theta) = n\lambda$ is satisfied, where d is the inter-planar distance, n is a positive integer, λ is the wavelength of the incident waves and θ is the incidence angle with the scattering lattice planes.

[0013] The non-coplanar Bragg scattering processes are preferably asymmetric Bragg scattering processes.

[0014] In asymmetric Bragg scattering the lattice planes of the crystals off of which the respective shaft of X-ray radiation is scattered are not parallel to the incidence surface of the scattering crystal, the incidence surface being the crystal surface onto which the shaft of X-ray radiation impinges. Since for the Bragg scattering process the incidence and exit angle with the scattering lattice planes are equal, the incidence and exit angle of the radiation with the incidence surface of the crystal are not equal, resulting in an expansion or compression of the shaft of X-ray radiation.

[0015] The first crystal has an incidence surface onto which the first shaft of X-ray radiation impinges at an incidence angle. The scattered second shaft of X-ray radiation leaves the incidence surface at an exit angle. A surface normal of the incidence surface and the beam axis of the incident first shaft of X-ray radiation define an incidence plane. Similarly, the surface normal of the incidence surface and the beam axis of the scattered second shaft of X-ray radiation define a scattering plane.

[0016] In coplanar Bragg scattering the incidence plane coincides with scattering plane. In contrast, in non-coplanar Bragg scattering the incidence plane does not coincide with scattering plane, i.e. these planes are not parallel. In non-coplanar Bragg scattering the surface normal of the incidence surface is not parallel to the normal vector of the scattering lattice planes.

[0017] In asymmetric coplanar Bragg scattering processes the magnification factor drops rapidly with a decrease of X-ray radiation energy or increase in wavelength, respectively. The reason for this drop of the magnification factor is that because of the coplanarity condition the incidence angle of the first shaft of X-ray radiation with the scattering lattice plane cannot be chosen independently of the incidence angle of the first shaft of X-ray radiation with the incidence surface of the crystal.

[0018] The present invention is based on the insight that in non-coplanar Bragg scattering the angle between the first and/or second shaft of X-ray radiation and the scattering lattice plane and the incidence angle of the first and/or second shaft of X-ray radiation with the incidence surface of the first or second crystal can be adjusted at least over a certain range mostly independently from each other.

[0019] For example, when the Bragg condition is satisfied for asymmetric Bragg scattering, i.e. when the surface normal of the incidence surface is not parallel to the normal vector of the scattering lattice planes, the incidence angle of the incident X-ray radiation with the incidence surface can be adjusted by rotating the scattering crystal about the normal vector of the scattering lattice planes, all the while satisfying the Bragg condition.

[0020] The applicant has found that in non-coplanar Bragg scattering processes an additional degree of freedom for the orientation of the scattering crystal can be exploited to adjust the incidence and/or exit angles of the X-ray radiation with the incidence surface and, thus, the magnification factor for X-ray radiation of a certain wavelength can be fixed or stabilized over a certain large energy or wavelength range.

[0021] By employing two successive non-coplanar Bragg scattering processes, an X-ray image can be magnified or compressed in two dimensions.

[0022] Preferably, in contrast to prior art the incidence surface of the first crystal and the incidence surface of the second crystal are not restricted to be orthogonal to each other.

[0023] The inventive method can also be used for monochromatization of X-ray radiation, for polarisation experiments, for tomography, radiography or for tweaking of coherence properties of radiation, in particular of X-ray radiation.

[0024] Due to the non-coplanar Bragg scattering processes the cross section of the first, second or third shaft of X-ray radiation can be subjected to an isomorphic distortion. For example if a cross section of the first shaft of X-ray radiation is rectangular, the cross section of the scattered third shaft of X-ray radiation can have the shape of a parallelogram. If the first shaft of X-ray radiation has a circular cross section, the scattered third shaft of X-ray radiation can have an elliptical cross section.

[0025] Similarly, a magnified or compressed X-ray image can be isomorphically distorted.

[0026] Preferably, a sample is disposed in the first shaft of X-ray radiation or in the scattered second shaft of X-ray radiation or in the scattered third shaft of X-ray radiation for imaging, and/or the scattered third shaft of X-ray radiation is detected with an X-ray detector.

[0027] Further preferably, the scattered third shaft of X-ray radiation detected with the X-ray detector, in particular an X-ray image detected with the X-ray detector, is corrected for the distortion using image processing methods.

[0028] Furthermore, the method can be used to determine lattice constants and/or unit cell angles of the first crystal and/or the second crystal.

[0029] Still further, more than two non-coplanar Bragg scattering processes can be employed in the method.

[0030] The first crystal and/or the second crystal can be a symmetric cut or an asymmetric cut crystal and/or an elastically bent crystal.

[0031] In crystallography, lattice planes of a crystal are usually described using Miller indices (hkl) with h, k, l being integer. A family of lattice planes is defined by vector $hb_1+kb_2+hb_3$ where b_1, b_2 and b_3 are the basis vectors of the reciprocal crystal lattice.

[0032] In the context of the present invention a symmetric cut crystal is a crystal whose incidence surface is parallel to a lattice plane defined by three integer Miller indices. Accordingly, an asymmetric cut crystal is a crystal having an incidence surface not parallel to such a lattice plane. In analogy to the Miller indices, the surfaces of asymmetric cut crystals could be specified using a vector (mno) where the indices m, n, o are real numbers excluding integers.

[0033] Furthermore, in a more restricted sense, a symmetric cut crystal can be understood as a crystal having a surface parallel to an (hkl) lattice plane with h, k, l integer and with a maximum difference between h, k and l of less than 3, preferably less than 2, more preferably less than 1. Thus, using this definition a symmetric cut crystal can have an incidence surface parallel to, for example the (100) or (020) or (113) lattice planes, etc.

[0034] While the method works with both asymmetric cut and symmetric cut crystals it is preferred that the crystals are symmetric cut crystals.

[0035] An advantage of using symmetric cut crystals is that symmetric cut crystals possess lower surface energy compared to crystals with asymmetric cut surfaces. Therefore, even naturally grown crystals of many minerals in ores are found in the so called "equilibrium crystal shape" that has faces that would correspond to a symmetrically cut crystal. Symmetrically cut crystals, therefore, are closer to their equilibrium shape and therefore are generally more stable.

[0036] For symmetric cut crystals smoothening processes other than polishing, such as UHV-based ion sputtering and/or annealing and the like can be used to achieve atomic scale smoothness. When working at angles of total X-ray reflection and below, which is covered by this invention, the surface quality is relevant.

[0037] The symmetric cut crystal may be cut with tolerances of less than 2°, preferably less than 1°, more preferably less than 0.5°.

[0038] An elastically bent crystal has a crystal surface, in particular an incidence surface for the first shaft of X-ray radiation or the scattered second shaft of X-ray radiation, which is not planar but has a curvature. By using an elastically bent crystal focusing and/or defocusing characteristics of the method can be manipulated or improved and/or strain fields due to crystal lattice imperfections can be compensated for. For providing an elastically bent crystal a mechanical crystal bending mechanism may be employed to introduce the desired crystal lattice elastic deformation fields.

[0039] Preferably a wavelength for the first shaft of X-ray radiation is chosen, and an incidence angle for the first shaft of X-ray radiation with an incidence surface of the first crystal and/or an incidence angle for the scattered second shaft of X-ray radiation with an incidence surface of the second crystal is chosen, and/or an exit angle for the scattered second shaft of X-ray radiation with the incidence surface of the first crystal and/or an exit angle for the scattered third shaft of X-ray radiation with the incidence surface of the second crystal is chosen, and/or a magnification factor is chosen, and the first and/or the second crystal are positioned and/or oriented so that the Bragg condition for the first non-coplanar Bragg scattering process and the second non-coplanar Bragg scattering process are fulfilled for the chosen wavelength and the chosen incidence angle and/or exit angle and/or magnification factor.

[0040] By employing double non-coplanar Bragg scattering processes the additional degree of freedom available for orienting the first and/or the second crystal can beneficially be used to set or fix incidence and/or exit angles and/or magnification factors over a large range of wavelengths, i.e. energies, of the X-ray radiation. Thus, in contrast to the prior art it is possible to choose a wavelength and/or energy of the first shaft of X-ray radiation and, in addition, to choose an incidence angle or exit angle or magnification factor comparatively independently from the wavelength or the energy of the X-ray radiation. In other words, because of the additional degree of freedom accessible in non-coplanar Bragg scattering the first and/or the second crystal can be positioned and/or oriented so that the Bragg condition for the first non-coplanar Bragg scattering and the second non-coplanar Bragg scattering process are fulfilled for the chosen wavelength and incidence angle, exit angle or magnification factor.

[0041] Preferably the energy of the first X-ray radiation is between 1 keV and 500 keV, more preferably between 4 keV and 100 keV, further preferably between 4 keV and 50 keV, still further preferably between 5 keV to 30 keV.

[0042] It is furthermore preferred, that the wavelength of the first shaft of X-ray radiation is changed and that the first crystal and/or the second crystal are repositioned and/or reoriented so that the Bragg condition for the first non-coplanar Bragg scattering process and the second non-coplanar Bragg scattering process are fulfilled for the changed wavelength and the chosen incidence angle and/or exit angle and/or magnification factor, and that further preferably the first crystal and/or the second crystal are not exchanged or substituted for the changed wavelength of the first shaft of X-ray radiation.

[0043] Thus, during conducting the method the wavelength of the first shaft of X-ray radiation can be changed in a comparatively broad range. Due to the additional degree of freedom accessible in non-coplanar Bragg scattering the first and second crystal can be reoriented such that the Bragg condition for the first non-coplanar Bragg scattering and the second non-coplanar Bragg scattering processes are fulfilled while simultaneously the exit angle, incidence angle or magnification factor are kept relatively constant.

[0044] Preferably the first crystal is oriented or reoriented by applying a first rotation to the first crystal, which includes at least one of

- a rotation about an axis not parallel to a normal vector of the first plurality of parallel lattice planes to fulfill the Bragg condition for the first shaft of X-ray radiation and the first plurality of parallel lattice planes, and/or

- a rotation about a normal vector of the first plurality of parallel lattice planes to adjust the incidence angle of the first shaft of X-ray radiation with the incidence surface of the first crystal.

[0045] In case both rotations are conducted the rotations must not necessarily be conducted sequentially, but can be conducted in a combined rotation. It is also possible that more than two rotations of the first crystal are conducted.

[0046] Still further preferably, the second crystal is oriented or reoriented by applying a second rotation to the second crystal, which includes at least one of

- a rotation about a beam axis of the scattered second shaft of X-ray radiation, and/or
- a rotation about an axis to adjust the incidence angle of the scattered second shaft of X-ray radiation with the incidence surface of second crystal, and/or
- a rotation about a surface normal of the incidence surface of the second crystal until Bragg condition is satisfied for the scattered second shaft of X-ray radiation and the second plurality of parallel lattice planes.

[0047] The rotation about an axis to adjust the incidence angle of the scattered second shaft of X-ray radiation with the incidence surface of the second crystal is preferably about an axis normal to the beam axis of the scattered second shaft of X-ray radiation and parallel to a plane tangent to the incidence surface at a point of incidence. The rotations can be either sequential rotations or they can be conducted in one combined rotation.

[0048] The rotations of the first and/or second crystal can be rotations about Euler angles of the first and/or second crystal.

[0049] For rotating the first and/or the second crystal manipulation stages comprising rotator elements can be used.

[0050] For determining the individual rotations or the combined rotations a dedicated algorithm, formula or computer program can be used.

[0051] An advantage of rotating the second crystal about the beam axis of the scattered second shaft of X-ray radiation is that skew and/or distortions of the shaft of X-ray radiation or of a magnified or compressed image can be reduced.

[0052] Furthermore, by rotating the first crystal and/or the second crystal about at least one angle, the shape of the cross section of the scattered second shaft of X-ray radiation and/or of the third scattered shaft of X-ray radiation can be adjusted or modified.

[0053] It is furthermore preferred that the first and/or the second crystal are repositioned by a translation in the X-, Y- or Z direction.

[0054] Still further, since the first and the second crystal can be rotated and/or oriented and/or positioned and/or repositioned in the X-, Y- and/or Z direction it is possible to use different crystal surfaces as incidence surfaces.

[0055] By positioning, orienting, repositioning or reorienting the first and/or the second crystal the divergence of the shafts of X-ray radiation can be adjusted or modified.

[0056] For example, by expanding a shaft of X-ray radiation in one dimension the divergence of the shaft of X-ray radiation in said dimension will be decreased and vice versa.

[0057] It may furthermore be preferred that the second crystal is translated in at least one direction.

[0058] For translating the second crystal a translation stage, preferably an XYZ-translation stage may be used.

[0059] A further solution to the problem is the provision of an apparatus for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, in particular for conducting a method as described above, comprising a first crystal mounted on a first manipulation stage and a second crystal mounted on a second manipulation stage, wherein the first manipulation stage is configured for rotating the first crystal about at least two angles, in particular about at least two Euler angles, wherein the second manipulation stages is configured for rotating the second crystal about at least three angles, in particular at least three Euler angles.

[0060] It is particularly preferred, that the first manipulation stage and/or the second manipulation stage are configured so that the first and second crystal can be oriented such that the orientation of the incidence surfaces or the first and second crystal is not restricted to an orthogonal orientation.

[0061] Preferably the first manipulation stage is configured for rotating the first crystal about at least three angles, in particular Euler angles.

[0062] The first manipulation stage and/or the second manipulation stage may comprise rotator elements for conducting the rotations about the at least two angles for the first crystal and about the at least three angles for the second crystal. The manipulation stages may be configured as hexapods or the like.

[0063] The rotations conductible by the first manipulation stage may be rotations about Euler angles denoted with ω_1 and ϕ_1. The second manipulation stage may be configured to rotate the second crystal about Euler angles ω_2 and ϕ_2 and χ_2.

[0064] Furthermore, it may be preferred that the first manipulation stage provides an additional rotation axis about Euler angle.

[0065] The first and second manipulation stage may comprise additional rotator elements for rotating the first and/or second crystal about more than three angles.

[0066] By allowing additional rotation axes for the first and/or the second manipulation stage, a more convenient and precise orientation of the first crystal and the second crystal can be achieved.

[0067] Preferably the first crystal and/or the second crystal are symmetric cut or asymmetric cut crystals.

[0068] Still further preferably, an incidence surface of the first crystal is located in a center of rotation of the first manipulation stage and/or an incidence surface of the second crystal is located in a center or rotation of the second manipulation stage.

[0069] The incidence surface of the first and/or of the second crystal is the respective surfaces of the crystal, onto which the first shaft of X-ray radiation and/or the scattered second shaft of X-ray radiation are impinging.

[0070] In particular by using XYZ-translation stages the first and/or the second crystal can be moved and positioned such that the respective shaft of incoming X-ray radiation hits the respective incidence surface.

[0071] Still further preferably the apparatus comprises a base on which the first and second manipulation stage are arranged. The base can be rotatable about an axis.

[0072] The axis about which the base is rotatable is preferably an axis in approximately the direction of the first second or third shaft of X-ray radiation. By providing an additional rotation of the base, the direction of the first shaft of X-ray radiation and/or of the scattered third shaft of X-ray radiation can be adjusted to lie in a desired laboratory plane.

[0073] Still further preferably the first manipulation stage and/or the second manipulation stage comprises a translation stage, preferably an XYZ-translation stage.

[0074] It may be preferred that the apparatus comprises X-ray optics, in particular collimators and/or X-ray mirrors, preferably Göbel mirrors, and/or Kirkpatrik-Baez optics or mirrors and/or X-ray lenses, preferably compound refractive lenses.

[0075] It may be preferred to introduce a mechanical crystal bending mechanism for each of the crystals to be able to introduce desired crystal lattice elastic deformation fields for each of the crystal to improve focusing/defocusing characteristics of the setup or to compensate for strain fields due to crystal lattice imperfections.

[0076] The X-ray optics are preferably positioned in the path of the first shaft of X-ray radiation. Additionally or alternatively it is also possible to provide X-ray optics in the scattered second shaft of X-ray radiation or the scattered third shaft of X-ray radiation.

[0077] It is a particular advantage of the apparatus that the direction of the X-ray radiation through the apparatus can be reversed.

[0078] Preferably, the apparatus comprises a sample stage, wherein the sample stage is further preferably configured to rotate the sample about at least one angle.

[0079] By allowing for rotations of the sample about at least one angle, the apparatus is particularly suited for use in three dimensional X-ray tomography.

Short description of the figures

[0080] The present invention is described with reference to the accompanying figures.

Fig. 1 shows a schematic of the basic concept of asymmetric Bragg scattering,

Fig. 2a shows a configuration of non-coplanar Bragg scattering,

Fig. 2bshows a configuration of asymmetric non-coplanar Bragg scattering using an elastically bent crystal,

Fig. 3 shows a configuration for conducting the method for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification,

Fig. 4 a first apparatus for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, and

Fig. 5 shows a second apparatus for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification.

Detailed description of the figures

[0081] Fig. 1 shows the basic concept of asymmetric Bragg scattering. A first shaft of X-ray radiation 200 is directed onto an incidence surface 201 of a crystal 202 at an incidence angle θ_{in} with the incidence surface 201. The first shaft of X-ray radiation 200 satisfies the Bragg condition with lattice planes 203 of crystal 202. Because lattice planes 203 are not parallel to the incidence surface 201 the scattered second shaft of X-ray radiation 204 is scattered off of incidence surface 201 at an exit angle θ_{out} which is larger than incidence angle θ_{in}, resulting in an expansion of the X-ray radiation in one dimension. The asymmetric Bragg scattering process shown in Fig. 1 is a coplanar Bragg scattering process, i.e., the incidence plane 205 of the incoming first shaft of X-ray radiation 200 defined by the beam axis 205 of the first shaft of X-ray radiation 200 and the surface normal 207 of the incidence surface 201 coincides with the scattering plane 208 defined by the beam axis 209 of the scattered second shaft of X-ray radiation 204 and the surface normal 207. Incidence plane 205 and scattering plane 208 lie in the drawing plane of Fig. 1. By rotating the crystal 202 about the normal vector 210 of the scattering lattice planes 203 non-coplanar Bragg scattering occurs. At each point during rotation of crystal 202 about normal vector 210 the incident first shaft of X-ray radiation 200 fulfills the Bragg condition with lattice planes 203, while the surface normal 207 rotates about normal vector 210.

[0082] A configuration for non-coplanar Bragg scattering is shown in Fig. 2a. In non-coplanar Bragg scattering, the incidence plane 205 of the incoming first shaft of X-ray radiation 200 defined by the beam axis 206 of the first shaft of X-ray radiation 200 and the surface normal 207 of the incidence surface 201 does not coincide with the scattering plane 208 defined by the beam axis 209 of the scattered second shaft of X-ray radiation 204 and the surface normal 207.

[0083] Fig. 2b shows a further configuration for asymmetric non-coplanar Bragg scattering. In the configuration of Fig. 2b crystal 202 is an elastically bent crystal, which has an incidence surface 201 for the first shaft of X-ray radiation 200, which is not planar but has a curvature. Because of the elastically bending of crystal 200 lattice planes 203 are subject to crystal lattice elastic deformation fields, which result in a deformation of lattice planes 203. The elastically bent crystal 202 can be used for Bragg scattering with a parallelized X-ray radiation as shown in Fig. 1 or, as shown in Fig. 2b, with divergent X-ray radiation. The divergent first shaft of X-ray radiation 200 is directed onto curved incidence surface 201 of a crystal 202 at an incidence angle θ_{in} with the incidence surface 201. First shaft of X-ray radiation 200 satisfies the Bragg condition with lattice planes 203 of crystal 202. Scattered second shaft of X-ray radiation 204 is scattered off of incidence surface 201 at an exit angle θ_{out}. The incidence plane 205 of the incoming first shaft of X-ray radiation 200 defined by the beam axis 206 of the first shaft of X-ray radiation 200 and the surface normal 207 of the incidence surface 201 does not coincide with the scattering plane 208 defined by the beam axis 209 of the scattered second shaft of X-ray radiation 204 and the surface normal 207. By using an elastically bent crystal 202 first shaft of X-ray radiation 200 can be focused or defocused.

[0084] Fig. 3 discloses a configuration for conducting the method 100 of the present invention. According to the method 100 a first shaft of X-ray radiation 10 is scattered in a first non-coplanar Bragg scattering process at a first plurality of parallel lattice planes 11 of a first crystal 12 to generate a scattered second shaft of X-ray radiation 13. The scattered second shaft X-ray radiation 13 is scattered in a second non-coplanar Bragg scattering process at a second plurality of parallel lattice plane 14 of a second crystal 15 to generate a scattered third shaft of X-ray radiation 16. In the first non-coplanar Bragg scattering process at the first crystal 12 the first shaft of X-ray radiation 10 is expanded in a first dimension to yield expanded second shaft of X-ray radiation 13. In the subsequent second non-coplanar Bragg scattering process the second shaft of X-ray radiation 13 is expanded in a second dimension to yield expanded third shaft of X-ray radiation 16. The magnification factor is roughly 100 in both dimensions. The first crystal 12 and/or the second crystal 15 can be unbent crystals such as crystal 202 of Figs. 1 and 2a, or the first crystal 12 and/or the second crystal 15 can be mechanically bent crystals such as crystal 202 of Fig. 2b. It is also possible that one of the crystals 12, 15 is an unbent crystal while the other crystal 12, 15 is a mechanically bent crystal.

The incidence surface 17 of the first crystal 12 is defined by surface normal 18. The scattering lattice planes 11 of first crystal 12 are defined by normal vector 19. When the energy or wavelength of the first shaft of X-ray radiation 10 is changed, the Bragg condition $2d \sin(\theta) = n\lambda$ for the first shaft of X-ray radiation 10 and the scattering lattice planes 11 is no longer fulfilled. Hence, the first crystal 12 has to be reoriented by applying a first rotation to the first crystal 12. The first rotation can include a rotation about an axis 20, which is not parallel to normal vector 19 of the first lattice planes 11. In the configuration shown in Fig. 3 axis 20 is perpendicular to normal vector 19 and beam axis 21 of the first shaft of X-ray radiation 10. When the Bragg condition is once again fulfilled, the first crystal 12 can be rotated about the normal vector 19 to reorient the incidence surface 17 of the first crystal 12 with respect to the beam axis 21 of the first shaft of X-ray radiation 10 to adjust the incidence angle $\theta_{1,in}$ of first shaft of X-ray radiation 10 with incidence surface 17 and/or the exit angle $\theta_{1,out}$ of the scattered second shaft of X-ray radiation 13 with incidence surface 17 and/or the magnification factor provided by the first non-coplanar Bragg scattering process. Since the first rotation may change the direction of the scattered second shaft of X-ray radiation 13 it might be necessary to move the second crystal 15 in X-, Y-, or Z-direction until the scattered second shaft of X-ray radiation 13 impinges on incidence surface 22 of the second crystal 15. A further reorientation of the second crystal 15 might then be necessary. The second crystal 15 can be rotated about the beam axis 23 of the scattered second shaft of X-ray radiation 13. With this rotation, skew or distortions of the third shaft of X-ray radiation 16 can be eliminated or manipulated. Furthermore a rotation about an axis 24, which is preferably perpendicular to the beam axis 23 and the surface normal 25 of the incidence surface 22 of the second crystal 15, is applied to adjust the incidence angle $\theta_{2,in}$ of second shaft of X-ray radiation 13 and/or the exit angle $\theta_{2,out}$ of the scattered third shaft of X-ray radiation 16 and/or the magnification factor provided by the second non-coplanar Bragg scattering process. Still further, a rotation about the surface normal 25 of the incidence surface 22 of the second crystal 15 is applied until Bragg condition of the second shaft of X-ray radiation 13 with lattice planes 14 is fulfilled. The rotations of the first crystal 12 and the second crystal 15 must not necessarily conducted sequentially, but can be conducted in a respective single combined rotation. For calculating the rotations or the combined rotations a dedicated formula, for example implemented with a software program executed on a computer, may be used. It is important to notice, that in most configurations incidence surface 17 of the first crystal 12 and incidence surface 22 of the second crystal 15 are not orthogonal to each other. Furthermore, second plurality of parallel lattice planes 14 is defined by normal vector 26.

[0085] Fig. 4 shows an apparatus 150 for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification. The apparatus comprises a first manipulation stage 27 and a second manipulation stage 28. A first crystal 12 is mounted on the first manipulation stage 27 and a second crystal 15 is mounted on the second manipulation stage 28. The first manipulation stage 27 comprises rotator elements 29 for rotating the first crystal 12 about Euler angles ω_1 and ϕ_1. The second manipulation stage 28 comprises rotator elements 30 for rotating the second crystal 15 about Euler angles ω_2, ϕ_2 and χ_2. In addition, the second manipulating stage 28 comprises an XYZ-translation stage 31 to move the second crystal 15 in the X-, Y- or Z-direction. The first manipulation stage 27 and the second manipulation stage 28 are mounted on a base 32. A sample 33 is mounted on a sample stage 34, by which the sample 33 can be rotated about rotation axis 35. For X-ray imaging of sample 33, sample 33 is positioned in the first shaft of X-ray radiation 10. The first shaft of X-ray radiation 10 carrying an X-ray image of sample 33 is scattered in a first scattering process at a first lattice plane 11 of first crystal 12 to generate a scattered second shaft of X-ray radiation 13 in a non-coplanar Bragg scattering process. The scattered second shaft X-ray radiation 13 is scattered in a subsequent second scattering process at a second lattice plane 14 of a second crystal 15 to generate a scattered third shaft of X-ray radiation 16 in a second non-coplanar Bragg scattering process. The magnified X-ray image of sample 33 is detected with X-ray detector 36.

[0086] Fig. 5 shows a variation of the apparatus 150 of Fig. 4. Apparatus 150 of Fig. 5 additionally comprises a rotating mechanism 37 to rotate base 32 about an additional angle χ_1.

List of reference numerals

[0087]

100 Method
150 Apparatus

10 First shaft of X-ray radiation
11 Lattice plane of first plurality
12 First crystal
13 Second shaft of X-ray radiation
14 Lattice plane of second plurality
15 Second crystal
16 Third shaft of X-ray radiation
17 Incidence surface of first crystal
18 Surface normal of incidence surface of first crystal
19 Normal vector of lattice planes of first plurality

20 Axis
21 Beam axis of first shaft of X-ray radiation
22 Incidence surface of second crystal
23 Beam axis of second shaft of X-ray radiation
24 Axis
25 Surface normal of incidence surface of second crystal
26 Normal vector of lattice planes of second plurality
27 First manipulation stage
28 Second manipulation stage
29 Rotator elements of first manipulation stage

30 Rotator elements of second manipulation stage
31 XYZ-translation stage
32 Base
33 Sample
34 Sample stage
35 Rotation axis
36 X-ray detector

200 First shaft of X-ray radiation
201 Incidence surface
202 Crystal
203 Lattice plane
204 Second shaft of X-ray radiation
205 Incidence plane
206 Beam axis
207 Surface normal
208 Scattering plane
209 Beam axis
210 Normal vector

Claims

1. Method (100) for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, wherein a first shaft of X-ray radiation (10) is scattered in a first scattering process at a first plurality of parallel lattice planes (11) of a first crystal (12) to generate a scattered second shaft of X-ray radiation (13), wherein the scattered second shaft of X-ray radiation (13) is scattered in a second scattering process at a second plurality of parallel lattice planes (14) of a second crystal (15) to generate a scattered third shaft of X-ray radiation (16), **characterized in that** the first scattering process and the second scattering process are non-coplanar Bragg-scattering processes.

2. Method (100) according to claim 1, **characterized in that** a sample (33) is disposed in the first shaft of X-ray radiation (10) or the scattered second shaft of X-ray radiation (13) or the scattered third shaft of X-ray radiation (16) for imaging, and/or that the scattered third shaft of X-ray radiation (16) is detected with an X-Ray detector (36).

3. Method (100) according to claim 1 or 2, **characterized in that** the first crystal (12) and/or the second crystal (15) is a symmetric cut or an asymmetric cut crystal and/or an elastically bent crystal.

4. Method (100) according to any one of the preceding claims, **characterized in that** a wavelength for the first shaft of X-ray radiation (10) is chosen, and that an incidence angle ($\theta_{1,in}$) for the first shaft of X-ray radiation (10) with an incidence surface (17) of the first crystal (12) and/or an incidence angle ($\theta_{2,in}$) for the scattered second shaft of X-ray radiation (13) with an incidence surface (22) of the second crystal (15) is chosen, and/or that an exit angle ($\theta_{1,out}$) for the scattered second shaft of X-ray radiation (13) with the incidence surface (17) of the first crystal (12) and/or an exit angle ($\theta_{2,out}$) for the scattered third shaft of X-ray radiation (16) with the incidence surface (22) of the second crystal (15) is chosen, and/or that a magnification factor is chosen, and that the first crystal (12) and/or the second crystal (15) are positioned and/or oriented so that the Bragg condition for the first non-coplanar Bragg scattering process and the second non-coplanar Bragg scattering process are fulfilled for the chosen wavelength and the chosen incidence angle ($\theta_{1,in}$, $\theta_{2,in}$) and/or exit angle ($\theta_{1,out}$, $\theta_{2,out}$) and/or magnification vector.

5. Method (100) according to any one of claim 4, **characterized in that** the wavelength of the first shaft of X-ray radiation (10) is changed and that the first crystal (12) and/or the second crystal (15) are repositioned and/or reoriented so that the Bragg condition for the first non-coplanar Bragg-scattering process and the second non-coplanar Bragg-scattering process are fulfilled for the changed wavelength and the chosen incidence angle ($\theta_{1,in}$, $\theta_{2,in}$) and/or exit angle ($\theta_{1,out}$, $\theta_{2,out}$) and/or magnification factor, and that preferably the first crystal (12) and/or the second crystal (15) are not exchanged for the changed wavelength of the first shaft of X-ray radiation (10).

6. Method (100) according to claim 4 or 5, **characterized in that** the first crystal (12) is oriented or reoriented by applying a first rotation to the first crystal (12), which includes at least one of

   - a rotation about an axis (20) not parallel to a normal vector (19) of the first plurality of parallel lattice planes (11) to fulfill the Bragg condition for the first shaft of X-ray radiation (10) and the first plurality of parallel lattice planes (11), and/or
   - a rotation about a normal vector (19) of the first plurality of parallel lattice planes (11) to adjust the incidence angle ($\theta_{1,in}$) of the first shaft of X-ray radiation (10) with the incidence surface (17) of the first crystal (12).

7. Method (100) according to any one of claims 4 to 6 **characterized in that** the second crystal (15) is oriented or reoriented by applying a second rotation to the second crystal (15), which includes at least one of

   - a rotation about a beam axis (23) of the scattered second shaft of X-ray radiation (13), and/or
   - a rotation about an axis (24) to adjust the incidence angle ($\theta_{2,in}$) of the scattered second shaft of X-ray radiation (13) with the incidence surface (22) of second crystal (15), said axis (24) being preferably normal to the beam axis (23) of the scattered second shaft of X-ray radiation (13) and parallel to a plane tangent to the incidence surface (22) at a point of incidence, and/or
   - a rotation about a surface normal (25) of the incidence surface (22) of the second crystal (15) until Bragg condition is satisfied for the scattered second shaft of X-ray radiation (13) and the second plurality of parallel lattice planes (14).

8. Method (100) according to any one of claims 4 to 7, **characterized in that** the second crystal (15) is translated in at least one direction.

9. Apparatus (150) for X-ray shaft expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, in particular for conducting a method (100) according to any one of claims 1 to 8, comprising a first crystal (12) mounted on a first manipulation stage (27) and a second crystal (15) mounted on a second manipulation stage (28), wherein the first manipulation stage (27) is configured for rotating the first crystal (12) about at least two angles, in particular about at least two Euler angles (ω_1, ϕ_1), **characterized in that** the second manipulation stage is configured for rotating the second crystal (15) about at least three angles, in particular at least three Euler angles (ω_2, ϕ_2, χ_2).

10. Apparatus (150) according to claim 9, **characterized in that** the first manipulation stage (27) is configured for rotating the first crystal (12) about at least three angles, in particular Euler angles (ω_1, ϕ_1, χ_1).

11. Apparatus (150) according to claim 9 or 10, **characterized in that** the first crystal (12) and/or the second crystal (15) are symmetric cut or asymmetric cut crystals.

12. Apparatus (150) according to any one of claims 9 to 11, **characterized in that** an incidence surface (17) of the first crystal (12) is located in the center of rotation of the first manipulation stage (27) and/or that an incidence surface (22) of the second crystal (15) is located in the center of rotation of the second manipulation stage (28).

13. Apparatus (150) according to any one of claims 9 to 12, **characterized in that** the apparatus comprises a base (32) on which the first manipulation stage (27) and the second manipulation stage (28) are arranged, and that the base (32) is rotatable about an axis.

14. Apparatus (150) according to any one of claims 9 to 13, **characterized in that** the first manipulation stage (27) and/or the second manipulation stage (28) comprises a translation stage, preferably a XYZ-translation stage (31).

15. Apparatus (150) according to any one of claims 9 to

14, **characterized in that** the apparatus comprises X-ray optics, in particular collimators and/or X-ray mirrors, preferably Göbel-Mirrors, and/or Kirkpatrik-Baez optics or mirrors and/or X-ray lenses, preferably compound refractive lenses.

Amended claims in accordance with Rule 137(2) EPC.

1. Method (100) for X-ray beam expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification, wherein a first beam of X-ray radiation (10) is scattered in a first scattering process at a first plurality of parallel lattice planes (11) of a first crystal (12) to generate a scattered second beam of X-ray radiation (13), wherein the scattered second beam of X-ray radiation (13) is scattered in a second scattering process at a second plurality of parallel lattice planes (14) of a second crystal (15) to generate a scattered third beam of X-ray radiation (16), wherein the first scattering process and the second scattering process are non-coplanar Bragg-scattering processes, wherein in the first non-coplanar Bragg-scattering process the incidence plane (205) of the first beam of X-ray radiation (10) does not coincide with the scattering plane (207) of the scattered second beam of X-ray radiation (13) and wherein in the second non-coplanar Bragg-scattering process the incidence plane (205) of the second beam of X-ray radiation (10) does not coincide with the scattering plane (207) of the third beam of X-ray radiation (13),
characterized in that

- a wavelength for the first beam of X-ray radiation (10) is chosen,
- and that an incidence angle ($\theta_{1,in}$) for the first beam of X-ray radiation (10) with an incidence surface (17) of the first crystal (12) or that an exit angle ($\theta_{1,out}$) for the scattered second beam of X-ray radiation (13) with the incidence surface (17) of the first crystal (12) is chosen,
- and that an incidence angle ($\theta_{2,in}$) for the scattered second beam of X-ray radiation (13) with an incidence surface (22) of the second crystal (15) or an exit angle ($\theta_{2,out}$) for the scattered third beam of X-ray radiation (16) with the incidence surface (22) of the second crystal (15) is chosen,
- and that a magnification factor is chosen,

and that the first crystal (12) and/or the second crystal (15) are positioned and/or oriented so that the Bragg condition for the first non-coplanar Bragg scattering process and the second non-coplanar Bragg scattering process are fulfilled for the chosen wavelength and the chosen incidence angle ($\theta_{1,in}$) or exit angle ($\theta_{1,out}$) with the incidence surface (17) of the first crystal (12) and the chosen incidence angle ($\theta_{2,in}$) or exit angle ($\theta_{2,out}$) with the incidence surface (22) of the second crystal (15) and the chosen magnification factor.

2. Method (100) according to claim 1, **characterized in that** a sample (33) is disposed in the first beam of X-ray radiation (10) or the scattered second beam of X-ray radiation (13) or the scattered third beam of X-ray radiation (16) for imaging, and/or that the scattered third beam of X-ray radiation (16) is detected with an X-Ray detector (36).

3. Method (100) according to claim 1 or 2, **characterized in that** the first crystal (12) and/or the second crystal (15) is a symmetric cut or an asymmetric cut crystal and/or an elastically bent crystal.

4. Method (100) according to any one of the preceding claims, **characterized in that** the wavelength of the first beam of X-ray radiation (10) is changed and that the first crystal (12) and/or the second crystal (15) are repositioned and/or reoriented so that the Bragg condition for the first non-coplanar Bragg-scattering process and the second non-coplanar Bragg-scattering process are fulfilled for the changed wavelength and the chosen incidence angle ($\theta_{1,in}$, $\theta_{2,in}$) and/or exit angle ($\theta_{1,out}$, $\theta_{2,out}$) and/or magnification factor, and that preferably the first crystal (12) and/or the second crystal (15) are not exchanged for the changed wavelength of the first beam of X-ray radiation (10).

5. Method (100) according to any one of the preceding claims, **characterized in that** the first crystal (12) is oriented or reoriented by applying a first rotation to the first crystal (12), which includes at least one of

- a rotation about an axis (20) not parallel to a normal vector (19) of the first plurality of parallel lattice planes (11) to fulfill the Bragg condition for the first beam of X-ray radiation (10) and the first plurality of parallel lattice planes (11), and/or
- a rotation about a normal vector (19) of the first plurality of parallel lattice planes (11) to adjust the incidence angle ($\theta_{1,in}$) of the first beam of X-ray radiation (10) with the incidence surface (17) of the first crystal (12).

6. Method (100) according to any one of the preceding claims, **characterized in that** the second crystal (15) is oriented or reoriented by applying a second rotation to the second crystal (15), which includes at least one of

- a rotation about a beam axis (23) of the scattered second beam of X-ray radiation (13), and/or

- a rotation about an axis (24) to adjust the incidence angle ($\theta_{2,in}$) of the scattered second beam of X-ray radiation (13) with the incidence surface (22) of second crystal (15), said axis (24) being preferably normal to the beam axis (23) of the scattered second beam of X-ray radiation (13) and parallel to a plane tangent to the incidence surface (22) at a point of incidence, and/or
- a rotation about a surface normal (25) of the incidence surface (22) of the second crystal (15) until Bragg condition is satisfied for the scattered second beam of X-ray radiation (13) and the second plurality of parallel lattice planes (14).

7. Method (100) according to any one of the preceding claims, **characterized in that** the second crystal (15) is translated in at least one direction.

8. Apparatus (150) for X-ray beam expansion and/or compression and/or collimation and/or focusing and/or X-ray image magnification for conducting a method (100) according to any one of claims 1 to 7, comprising a first crystal (12) mounted on a first manipulation stage (27) and a second crystal (15) mounted on a second manipulation stage (28), wherein the first manipulation stage (27) is configured for rotating the first crystal (12) about at least two angles, in particular about at least two Euler angles (ω_1, ϕ_1), **characterized in that** the second manipulation stage is configured for rotating the second crystal (15) about at least three angles, in particular at least three Euler angles (ω_2, ϕ_2, χ_2).

9. Apparatus (150) according to claim 8, **characterized in that** the first manipulation stage (27) is configured for rotating the first crystal (12) about at least three angles, in particular Euler angles (ω_1, ϕ_1, χ_1).

10. Apparatus (150) according to claim 8 or 9, **characterized in that** the first crystal (12) and/or the second crystal (15) are symmetric cut or asymmetric cut crystals.

11. Apparatus (150) according to any one of claims 8 to 10, **characterized in that** an incidence surface (17) of the first crystal (12) is located in the center of rotation of the first manipulation stage (27) and/or that an incidence surface (22) of the second crystal (15) is located in the center of rotation of the second manipulation stage (28).

12. Apparatus (150) according to any one of claims 8 to 11, **characterized in that** the apparatus comprises a base (32) on which the first manipulation stage (27) and the second manipulation stage (28) are arranged, and that the base (32) is rotatable about an axis.

13. Apparatus (150) according to any one of claims 8 to 12, **characterized in that** the first manipulation stage (27) and/or the second manipulation stage (28) comprises a translation stage, preferably a XYZ-translation stage (31).

14. Apparatus (150) according to any one of claims 8 to 13, **characterized in that** the apparatus comprises X-ray optics, in particular collimators and/or X-ray mirrors, preferably Gobel-Mirrors, and/or Kirkpatrik-Baez optics or mirrors and/or X-ray lenses, preferably compound refractive lenses.

FIG. 1

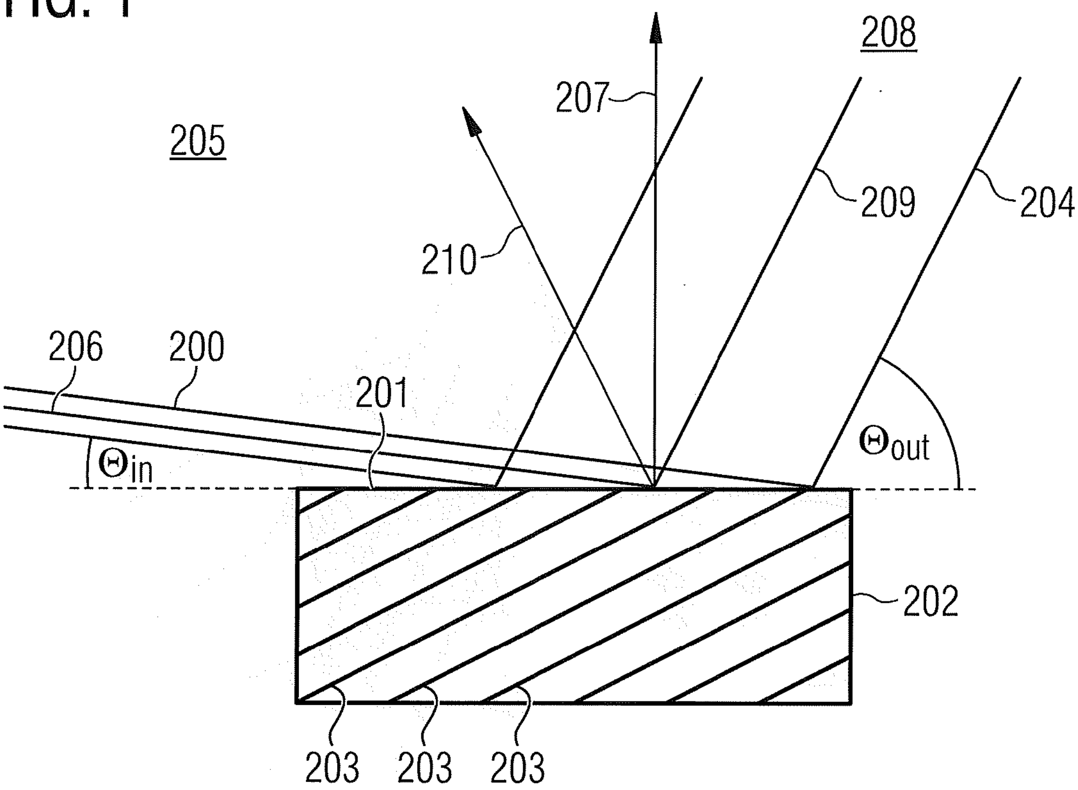

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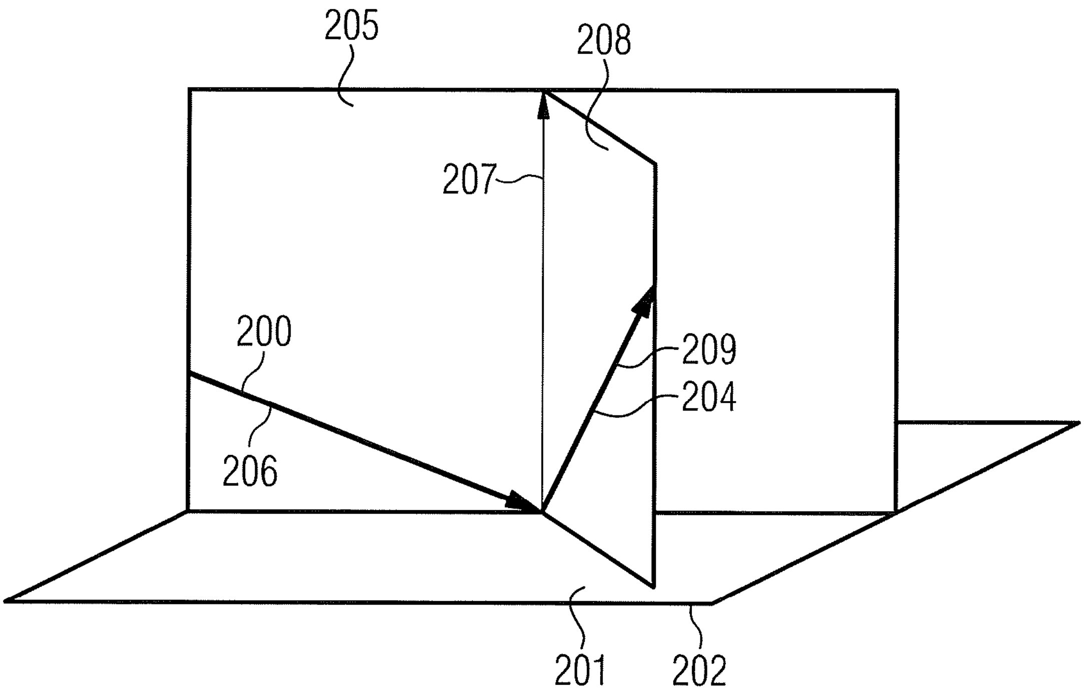
FIG. 2a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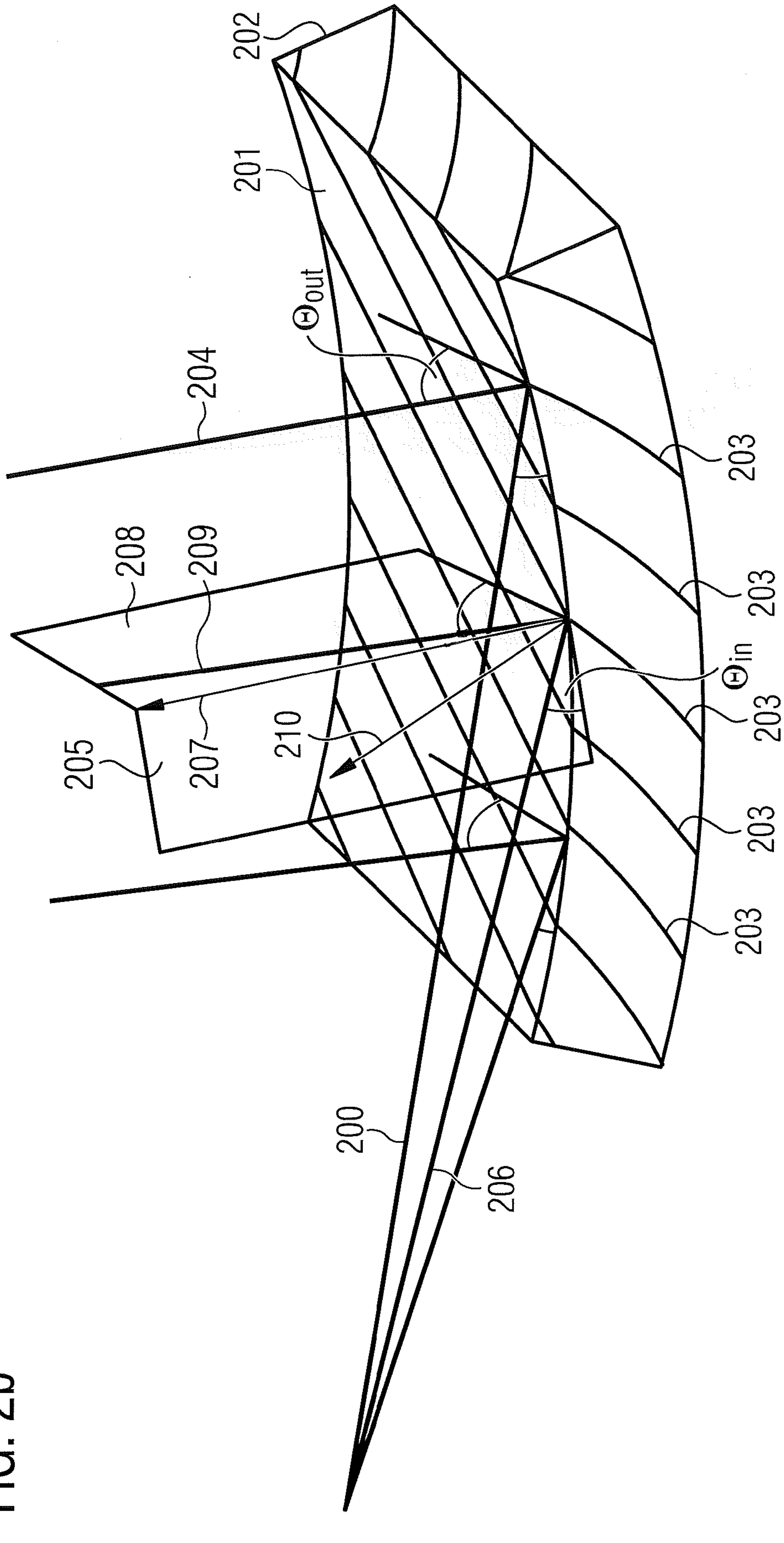
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FIG. 2b

FIG. 3

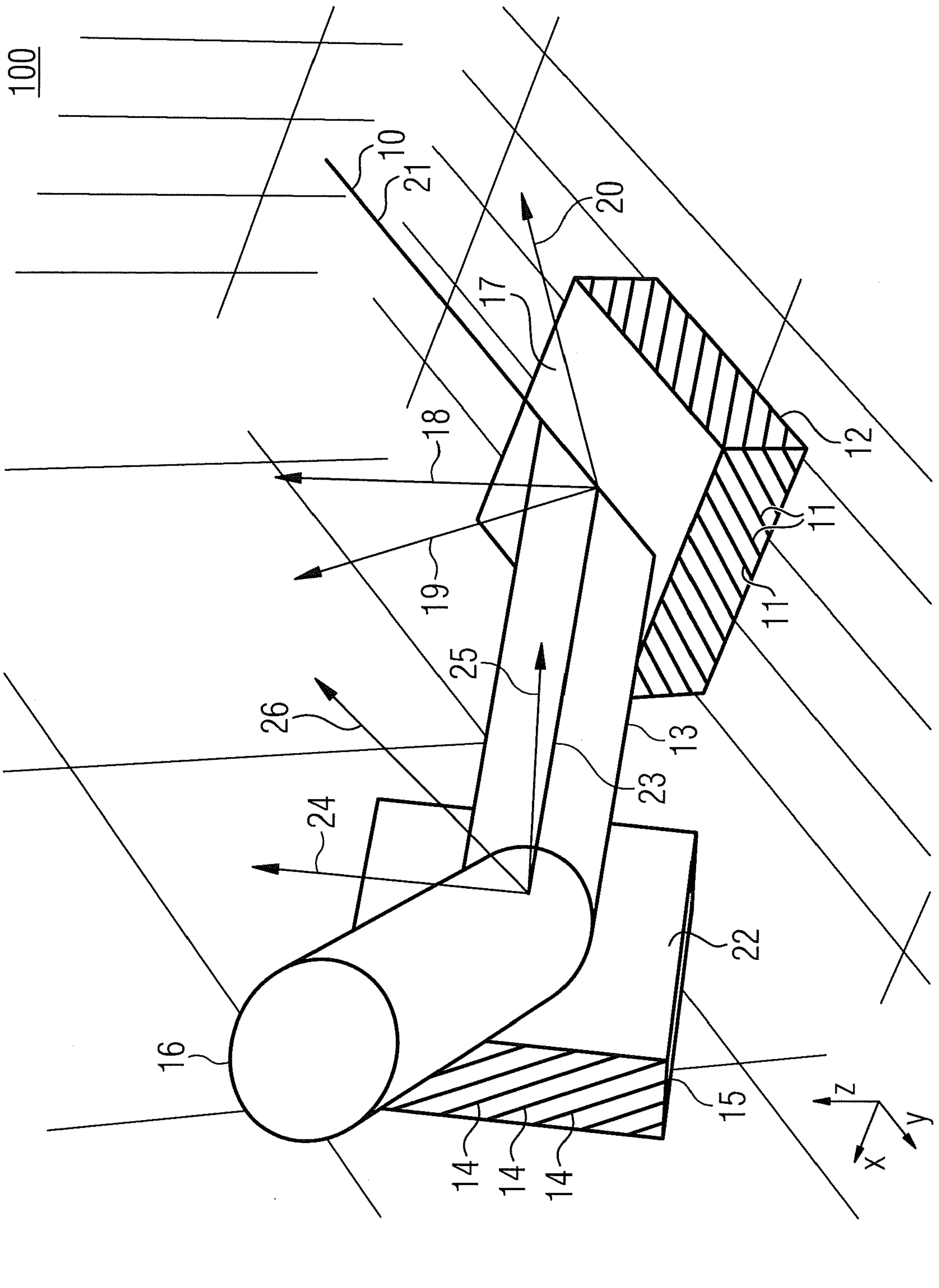

FIG. 4

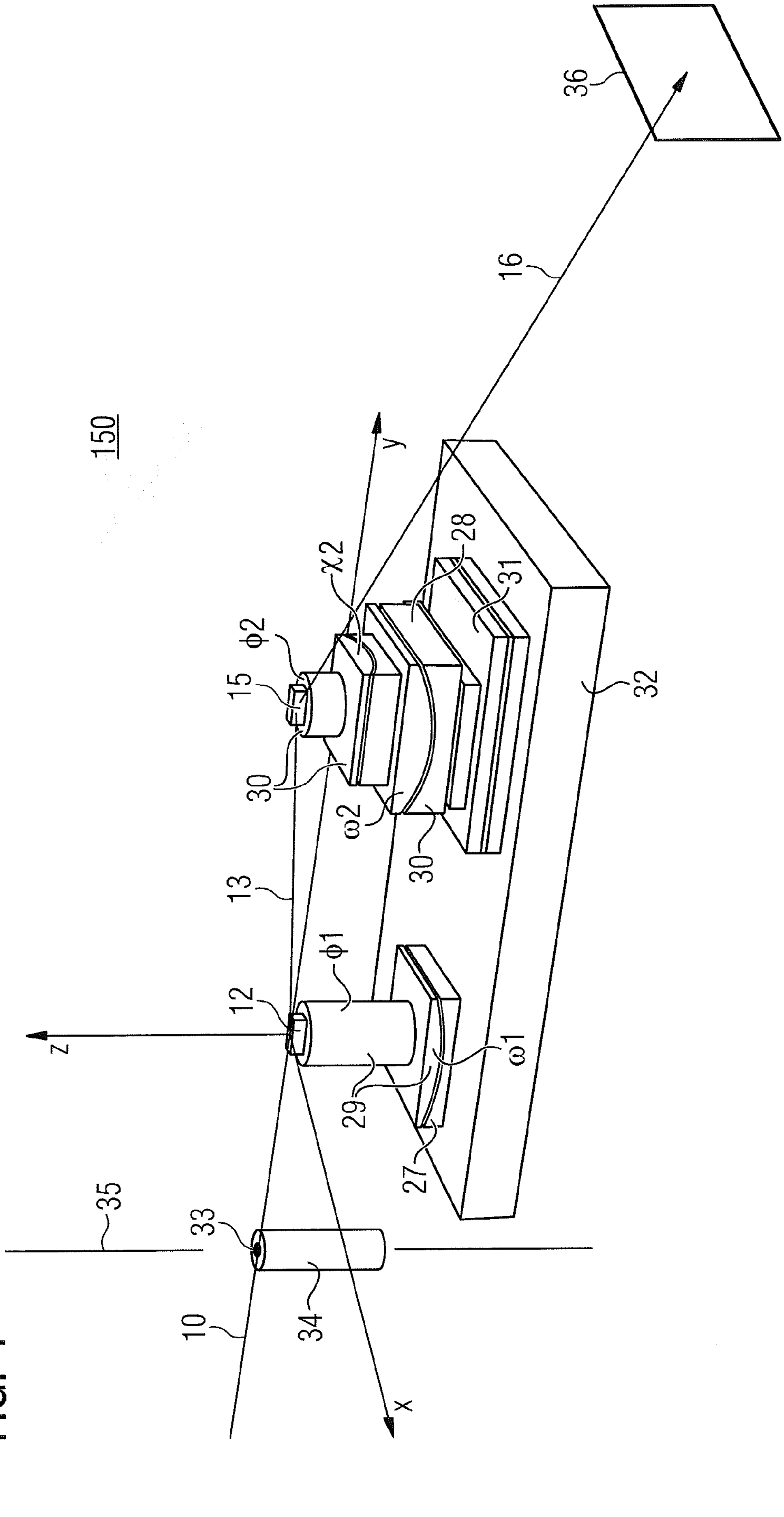
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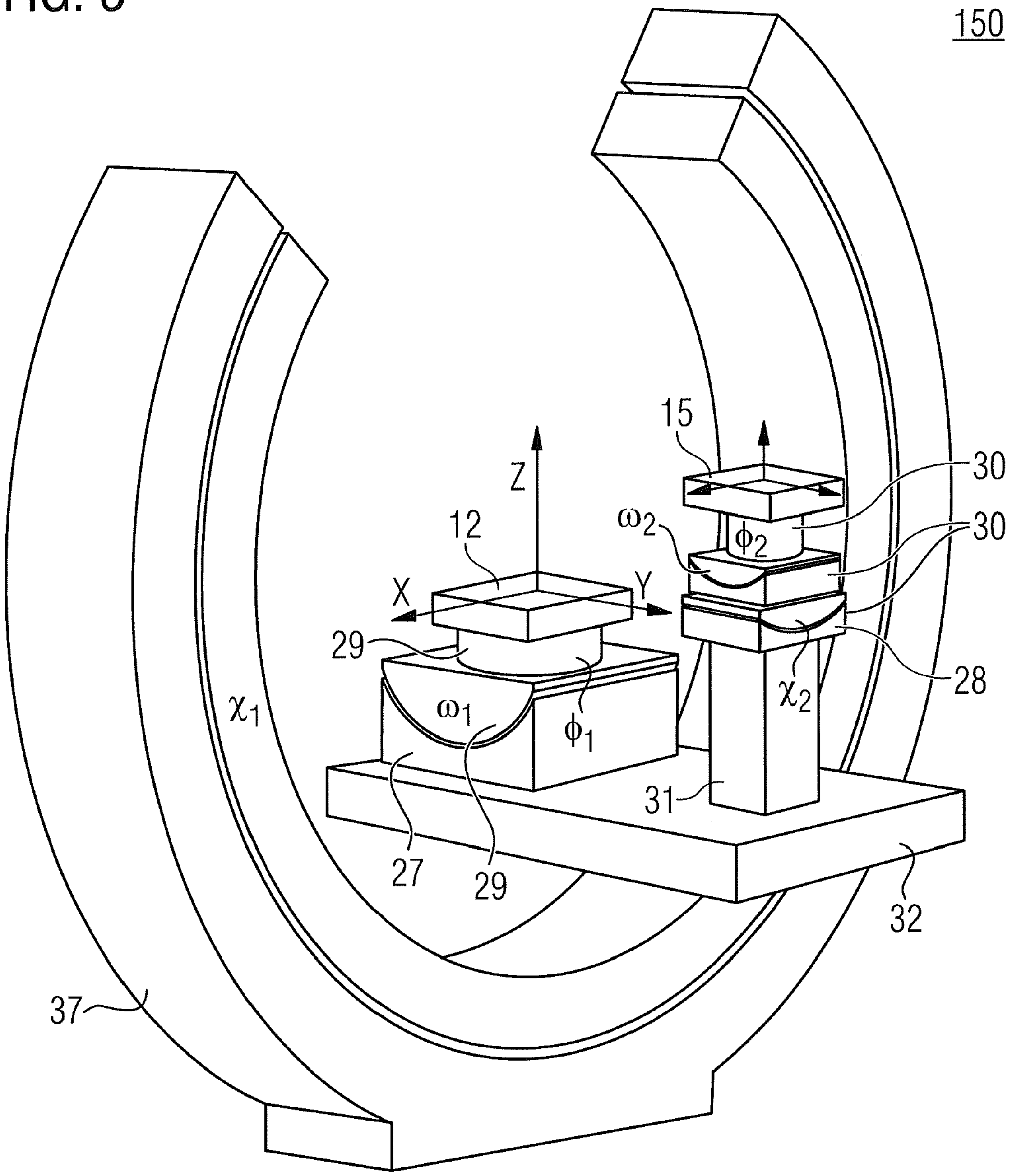
FIG. 5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EUROPEAN SEARCH REPORT

Application Number
EP 19 16 8109

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X	D KORYTAR: "Monolithic devices for high-resolution X-ray diffractometry and topography (*)", IL NOUVO CIMENTO D, vol. 19, no. 2-4, 1 January 1997 (1997-01-01), pages 481-487, XP055623796, * the whole document * -----	1-15	
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1 The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	19 September 2019	Krauss, Jan

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L : document cited for other reasons
& : member of the same patent family, corresponding document

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Application Number
EP 19 16 8109

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X	JAROMÍRA HRDÁ ET AL: "Self-filtering extremely inclined X-ray crystal monochromator", JOURNAL OF APPLIED CRYSTALLOGRAPHY., vol. 44, no. 6, 1 December 2011 (2011-12-01), pages 1169-1172, XP055624089, DK ISSN: 0021-8898, DOI: 10.1107/S0021889811040763 * the whole document * -----	1-15	

TECHNICAL FIELDS SEARCHED (IPC)

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The present search report has been drawn up for all claims

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L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

page 2 of 2

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