Radiation Source, Radiography Device, and a Method for Analyzing Objects by the Radiography Device

The present invention relates to a radiation source, a radiography device and a method for a (non-destructive) analysis of objects (samples) using the radiography device and, in particular, to a generation of combined neutrons and x-rays for radiography using a laser-based source.

BACKGROUND

In many applications X-ray radiographs and neutron radiographs are utilized for non-destructive analyses. Conventional systems rely either on neutron sources or on X-ray sources to provide the appropriate radiation source. Similarly, different detectors are likewise used to detect either the neutron radiation or the X-radiation.

However, there is a demand of having X-radiation as well as neutron radiation available at the same time when analyzing objects or probes, in particular, when the objects should not be destroyed during the analysis and when the object is very large or very massive.

Therefore, there is a demand for radiation sources that can provide simultaneously neutron radiation and X-radiation.

SUMMARY OF THE INVENTION

At least some of the above-mentioned problems are solved by a radiation source according to claim 1, a radiography device according to claim 5, and a method for analyzing objects according to claim 10. The dependent claims refer to further advantageous realizations for the subject matters of the independent claims.

The present invention relates to a radiation source for a radiation beam of

combined neutrons and X-rays. The radiation source comprises a particle source adapted to generate a particle beam, and a converter adapted to utilize the particle beam to generate the radiation beam that includes simultaneously neutrons and X-rays, and to emit the radiation beam in a forward direction.

The term radiation beam shall indicate that it includes X-radiation and neutrons combined in a beam. The forward direction can be defined as direction in an angular range of +/-30° measured relative to a main direction of the incoming particle beam.

Optionally, the particle source includes a laser source configured to irradiate a laser beam. The particle source may further include a laser target configured to receive the laser beam and to release the particle beam. The laser target may include a deuterated material to provide as particles deuterium nuclei and/or protons and/or electrons simultaneously or separately.

The generation of the particles may be a multi-stage process, where, at first, the laser may generate hot electrons at the rear surface of the target and the target surface may be ionized. Subsequently, the electrons may drag protons, deuterium nuclei, or other ions resulting in an ion beam which is emitted normal to the target surface. The electrons may remain in the particle beams.

Optionally, if only electrons are accelerated, the laser can accelerate electrons via the process of laser wakefield acceleration or direct laser acceleration by being directed onto a underdense target or a target that has been made underdense by previous laser pulse irradiation. The wakefield acceleration is an acceleration produced by a plasma wake which may be excited by appropriately shaped laser pulses.

Optionally, high energy x-rays can also be produced directly from the laser target interaction.

Optionally, the laser target includes a deuterated target material to provide

deuterium nuclei and/or protons as ions. The laser target may have a thickness of less than 1 μm or less than 2 μm and may comprise heavy water or deuterated glycol. Optionally, the laser can be shot on a less dense material such as a gas to accelerate electrons which will be directed onto a converter to produce bremsstrahlung, which then will be used to generate neutrons via so-called gamma-to-neutron nuclear reactions inside the converter.

Optionally, the radiation source includes a converter with a conversion material adapted to trigger a reaction that releases, upon a particle absorption, neutrons. The conversion material may include at least one of the following: tungsten, lithium or lithium fluoride, beryllium, vanadium, molybdenum, copper, lead, uranium or a combination thereof. Optionally, moderator material may be provided to lower the energy of the neutrons, wherein the moderator material may include hydrogen, polyethylene, graphite, heavy water, or other suitable materials.

Further Embodiments relate to a radiography device for a non-destructive analysis of an object (e.g. a sample). The radiography device includes: a radiation source as described before and a detector. The radiation source is adapted to irradiate the radiation beam onto the object. The detector is adapted to receive the radiation beam after penetrating the object and to detect the neutrons and the X-rays in the received radiation beam. The detecting may include an analyzing and/or imaging of the radiographed object.

According to further embodiments, if a neutron radiography and an x-ray radiography are taken of the same sample in the same angle and position, then the difference in neutron attenuation and x-ray attenuation can be used to define an absorption ratio called R-value. This R-value differs for most materials and can be used to identify the investigated material and its spatial distribution.

Optionally, multiple radiographies can be recorded and combined to a tomography. This can then be used to attribute a material to every voxel inside the sample.

Optionally, the detector includes a scintillator device for converting the radiation beam after passing through the object into visible light or an ultraviolet spectrum. The detector may further include a camera device adapted to capture images emitted from the scintillator device.

Optionally, the radiography device comprises at least one of the following components:

- a mirror adapted to reflect an output of the scintillator device;
- at least one lens adapted to focus the output of the scintillator device;
- at least one image intensifier adapted to amplify the received output from the scintillator device to increase an optical visibility for the camera device.

Optionally, the radiography device further comprises a control unit configured to control the detector to provide a time-gate to separate detection events caused by the received neutrons from the received X-rays and/or to provide an energy resolution for detection events caused by the neutrons. The control unit may further synchronize the laser device of the particle source with camera device or the timing of capturing images. Besides a camera, it is also possible to either directly or via a light guiding medium couple the scintillator to a CCD, CMOS or an amorphous silicon detector array (or any other photon detecting device).

Optionally, separate neutron detectors and x-ray detectors can be used as long as they aligned in the same angle. This can be helpful if the x-ray and neutron radiography should be recorded in parallel and not subsequently.

Optionally, the control unit is configured to select the time-gate in the range from 100 nanoseconds to 1 microsecond.

Optionally, time gating up to 10 ms (or between 10 ns up to 1 ms) is possible to investigate thermal neutrons, which have a longer time of flight.

Optionally, the control unit or the detection device is configured to take a neutron radiography and an X-ray radiography on a same sample in a same angle and position and to determine an absorption ratio, R-value, based on a difference in neutron attenuation and x-ray attenuation. The control unit may also be configured to combine multiple radiographies to a tomography. The R-value may be used to identify the various materials in the sample and the tomography can visualize the 3d or spatial distribution of the materials.

It is understood that the control unit can comprise one or more data processing systems with installed software that enable the control unit to perform the described functions. Likewise, the control unit can be a single unit but may also include multiple components, e.g. one entity for controlling the devices and another entity for processing and/or visualizing the data (e.g. from the detector). Thus, the control unit shall be construed broadly to cover all entities that are able to provide the defined functions and may include also a screen for visualizing.

Embodiments relate also to any radiography device as described before, wherein the control unit is configured to control the detector and/or the radiation source to cause at least one of the following:

- to perform a combined X-ray and neutron radiographies and tomographies;
- to assign absorption ratios, R-values, to pixels or to voxels or to areas;
- to assign a material to a region in the object based on the R-value alone or based on shape, density or documentation;
- to evaluate different regions inside the object;
- to summarize the content of the investigated object.

Further embodiments relate to a method for analyzing an object. The method comprising:

- generating, by a particle source or a laser source, a particle beam;

- converting, by a converter, the particle beam into a radiation beam that includes simultaneously neutrons and X-rays;
- emitting the radiation beam in a forward direction onto the object;
- receiving the radiation beam after penetrating the object; and
- detecting the neutrons and the X-rays in the received radiation beam.

According to embodiments, a laser can likewise generate the particle beam. Existing technologies can already produce x-ray and neutron beams, but the pulse length of the particle beam is longer than the time of flight, so x-ray beams and neutron beams cannot be separated via time of flight (ToF). For example, a Laser Neutron source has an initial x-ray pulse width of ~1 ps and a neutron pulse width of 1 ns. This makes it possible to separate them via ToF even after 2-3 meters of flight path. This holds especially for fast neutrons > 200 keV as their ToF is less than 1 µs within a 5 m flight path.

The step of detecting may include an imaging and/or recording and/or analysis and of captured images (e.g. identification of structures or materials)

Embodiments overcome at least some of the above-mentioned problems of conventional devices by making it possible to record both hard X-ray radiography as well as neutron radiography with the same source and with the same detector. Embodiments provide the advantage that the different attenuation of different types of radiation can be utilized at the same time or with negligible time in between. Thus, various materials can be identified in the object to be analyzed without the need to apply different sources or to use different detectors.

An additional benefit is that the sample can be analyzed simultaneously in time and space. If two sources are used, then they will be always slightly shifted in space, relative to the sample and the detectors. This smears out the image and makes reconstruction more difficult and less accurate. While having the same source and the same detector and the same sample position makes the measurement more accurate. Also, the time difference between x-rays and neutrons can

be up to only 1 μs in time difference, making it possible to image fast moving objects.

An additional benefit is that the source size of laser driven particle sources (down to 50 μm) is significantly smaller than with conventional x-ray or neutron sources (cm sized), significantly increasing the spatial resolution of the measurement.

An additional benefit is that the neutron energies that can be reached with laser neutron sources is significantly higher than with DT generators which are limited to 14 MeV neutrons while laser neutrons can reach up to 83 MeV or higher, which significantly increases the size of samples that can be analyzed.

Brief Description of the Drawings

Various embodiments of the present invention will be described in the following by way of examples only, and with respect to the accompanying drawings, in which:

Fig. 1 depicts a source for a radiation beam according to an embodiment of the present invention.

Fig. 2 depicts a combined detector for neutrons and X-radiation according to embodiments.

Fig. 3 shows a schematic flow chart for a method for detecting fissile material in a nuclear reactor according to embodiments.

Detailed Description

Various examples will now be described more fully with reference to the accompanying drawings in which some examples are illustrated.

Accordingly, while examples are capable of various modifications and alternative forms, the illustrative examples in the figures will herein be described in detail.

It should be understood, however, that there is no intent to limit examples to the particular forms disclosed, but on the contrary, examples are to cover all modifications, equivalents, and alternatives falling within the scope of the disclosure. Like numbers refer to like or similar elements throughout the description of the figures.

It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present. Other words used to describe the relationship between elements should be interpreted in a like fashion (e.g., "between" versus "directly between," "adjacent" versus "directly adjacent," etc.).

The terminology used herein is for the purpose of describing illustrative examples only and is not intended to be limiting. As used herein, the singular forms "a," "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes" and/or "including," when used herein, specify the presence of stated features, steps, operations, elements and/or components, but do not preclude the presence or addition of one or more other features, steps, operations, elements, components and/or groups thereof.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which examples belong. It will be further understood that terms, e.g., those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Fig. 1 depicts a radiation source 100 for a radiation beam 125 according to an

embodiment of the present invention, wherein the radiation beam 125 includes a combination of neutrons as well as X-rays. The radiation source 100 includes a particle source 110 adapted to generate a particle beam 115 and a converter 120 for receiving the generated particle beam 115 and converting it into the radiation beam 125. In the conversion process in the converter 120 neutron are simultaneously generated with X-rays which are both emitted in a forward direction. The forward direction may be defined as the direction of a main direction of the incoming particle beam 115, wherein a spread of ± 30° may occur. In other words, an outlet of the converter 120 for the radiation beam 125 may be opposite to an inlet of the converter 120 for the particle beam 115. The particles constituting the particle beams 115 may include ions (e.g. deuterium nuclei or protons) and/or electrons.

The converter 120 may include or may be surrounded by a moderator (not shown in the Fig. 1) to slow down neutrons and to emit a beam of neutrons at a moderator surface. The moderator and thus the energy of the radiation beam (e.g. the neutrons) may be adjusted or selected dependent on the object to be analyzed. Some objects need higher energies others need lower energies to detect the desired features in the object (e.g. certain materials or structural deficits).

Optionally, a reflector can be used to direct neutrons that are emitted in other directions also into the direction of the sample to increase the neutron flux. Such a reflector could be made out of beryllium, graphite, steel, lead or other materials. Inside the reflector there could be inlets to breed radioactive medical isotopes during normal radiography operation.

According to the depicted embodiment, the particle source 110 includes a laser source 112 and a target 114. The laser source 112 irradiates a laser beam 113 on the target 114. A generation of ions can be achieved as follows. A direct acceleration of ions in a laser field would need intensities in the range of 10^{24} W/cm^2 which is still out of reach for modern laser systems. Laser intensities of current system are about 10^{22} W/cm^2. Therefore, the laser energy is first transferred to hot electrons, e.g. (J x B) heating (of a plasma current J in a magnetic field B) or

pondermotive heating or via direct laser acceleration followed by a subsequent laser-driven acceleration. The electrons are capable to accelerate ions via the generation of quasi-static electric fields. If only the acceleration of electrons is desired, then a less dense target material in a plasma state can be chosen to drive laser electron acceleration by the formation of density bubbles inside the plasma which follow the propagating laser beam and trap electrons and accelerate them to an energy of tens MeV to hundreds of MeV (e.g. between 1 MeV and 1 GeV or between 10 MeV and 500 MeV).

The ions released from the target 114 are, for example, protons and/or deuterium nuclei. In addition, at least some of the generated electrons are released, too. According to embodiments, the target 114 may include liquid water jets, wherein hydrogen atoms are replaced by deuterium which may provide the neutrons. The laser driven neutron source, LDNS, according to embodiments operate through the acceleration of protons and deuterium nuclei via the interaction of high-intensity laser irradiation (>10^{18} W/cm2) of the target 114, which may have a thickness in the sub-μm range.

If the particle beam 115 utilizes electrons, these electrons generate gamma-radiation as bremsstrahlung which in turn generates the neutrons.

The particle beam 115 is then directed to the converter 120 with a material that catches the ions (or electrons) and emits through nuclear processes the neutron beam 125. The conversion material may include: tungsten, lithium or lithium fluoride, beryllium, vanadium, molybdenum, copper, lead, uranium or a combination thereof that produce neutrons upon exposure to the ion or electron beam 115. Exemplary nuclear reactions are:

$$^{2}d + {}^{7}Li \rightarrow {}^{8}Be + n + 15.03\ \text{MeV}, \quad (1)$$

$$^{1}p + {}^{7}Li \rightarrow {}^{7}Be + n - 1.64\text{MeV}\ , \quad (2)$$

$$\gamma + {}^{208}Pb \rightarrow {}^{207}Pb + n + 100\ \text{keV}, \quad (3)$$

wherein the superscript is the mass number for the deuterium (d), the proton (p), lithium (Li), Lead (Pb) and of beryllium (Be). The sign of the energy indicates whether there is surplus of energy or energy is needed to trigger the reaction. The energy of neutron will depend on the (kinetic) energy of the ions which in turn depend on the intensity of the laser beam 113. In general, this technique allows to generate neutrons with initial energies between 100 keV and up to 100 MeV.

However, these neutron energies may be too high for the analysing the object. Therefore, the converter 120 may be coupled to a moderator which is adapted to lower the energy of the generated neutrons to a predetermined energy range. The moderator comprises specific materials such as water, beryllium, graphite, polyethylene which achieve different power energy reduction. The amount of energy reduction depends on the number of collisions and thus on the available volume through which the high energy neutrons have to travel before they leave the moderator surface. According to embodiments, the energy of the neutrons is adjusted to the desired range by selecting the materials of the conversion material and/or of the moderator material, or by using an appropriate form for the moderator (e.g. its size, the length and/or the height may be adjusted accordingly, e.g. between the 1 cm and 20 cm or up to 50 cm). Likewise, the power of the laser source can be adjusted to generate ions with higher/lower energy. Embodiments may utilize different neutron energy ranges for different applications: thick samples from 30 cm up to 1 meter in thickness of solid material may use neutron energy of more than 20 MeV; intermediate samples from 10 cm to 30 cm may use neutron energies of 7-20 MeV; smaller samples 5-10 cm may use neutron energy of 1-7 MeV; below 1-5 cm may use epi-thermal neutrons with 0,3 eV- 100 keV, and for samples below 1 cm, thermal neutrons of 25 meV -0.3 eV may be used. Energies of up to of up to 14 MeV can be achieved with DT neutron generators (without ToF). For higher energies one may need a conventional large scale particle accelerator if no laser is used. Currently, no compact or transportable technology

is available to produce neutrons of more than 20 MeV and X-rays of more than 20 MeV, especially not with a 50 µm source size.

The usage of an electron beam instead of an ion beam produces lower neutron energies from 100 keV up to around 6 MeV. This increases the moderation efficiency of the produced neutrons and more of the initially produced neutrons can be slowed down to the relevant energies.

According to embodiments, the radiation beam 125 is irradiated from the converter 120 in a forward direction of the incoming ion (or electron) beam 115. It is understood that neutrons may be emitted in all direction, but embodiments use the forward scattered neutrons, because it turned out that these neutrons are particularly suited for the analysis and are accompanied with X-rays to result in the desired combination of neutrons and X-rays.

Fig. 2 depicts an embodiment for a radiography device for analyzing an object 50 (sample), wherein the radiography device includes a radiation source 100 as described with Fig. 1, which irradiates the radiation beam 125 onto the object 50. The radiography device further includes a combined detector 200 to detect neutrons as well as the incoming X-radiation after penetrating the object 50.

The detector 200 may include a scintillator device 220 for converting the radiation beam 125 after passing the object 50 into visible light or an ultraviolet spectrum, and a camera device 230 adapted to capture images emitted from the scintillator device 220. The scintillator device 220 may be made of organic scintillator fibers which is sensitive to both neutrons and hard X-rays.

There are various known scintillator materials. For example, fast organic scintillators may us EJ-228 and EJ 230 of Eljen Technology, or a high light output can be achieved by EJ-200, EJ-204, EJ-208, EJ-212 of Eljen Technology, or liquid scintillators may use EJ-301, EJ-309 of Eljen Technology. There are also gel scintillators based on a hydrocarbon base with scintillation attributes.

The detector 200 may also include a mirror 240 adapted to reflect an output of the scintillator device 220 and/or at least one lens 250 (or a more complex optics) adapted to focus the output of the scintillator device 220. Optionally, the detector 200 includes at least one image intensifier 260 adapted to amplify the received output from the scintillator device 220 to increase an optical visibility for the images to be captured by the camera device 230.

Optionally, the detector 200 might also use light guides to transfer the light from the scintillator device 220 to the photon detecting device (not shown in Fig. 2). Optionally, a photon detecting device such as a camera or a CCD device can also be directly coupled to the scintillator device 220 (not shown in Fig. 2).

The radiography device and/or the detector 200 may be controlled by a control unit 210 (or a processing unit), which may also analyze the detection results of the camera 230. The control unit 210 may be configured to control the detector 200 to provide a gating for the received radiation beam 125 to separate the neutron-beam portion from the received X-ray-portion. Because the neutrons are massive particle, they will arrive later at the scintillator 220 and thus the images caused by the neutrons will be generated after the images caused by the X-rays (which are massless and thus propagate with speed of light). A time threshold can be used to separate both portions depend on the geometry and, in particular, on the length of the path for the radiation beam 125. In addition, further time slices (gating) can be defined to separate images associated with different neutron energies, because neutrons with higher energies will arrive earlier at the scintillator and will thus generate images prior to neutrons with less energies.

According to embodiments, the neutron pulse width is significantly smaller than the ToF time. This is an advantageous feature of embodiments compared to conventional neutron sources which have pulse lengths of 5 μs or longer. A 1 MeV neutron will arrive namely at 5 meters distance after 360 ns which is not distinguishable from a gamma or x-ray or a neutron with another energy if the energy uncertainty from time of flight uncertainty is not small.

Therefore, according to embodiments, the control unit 210 may be configured to capture images with predetermined periodicity (gating), which may be in the range of 30 ns to 2 μs (or of about 100 ns). The smaller the gating the better the time resolution and thus energy resolution. However, the smaller the gating the less photons are available for a given image. Therefore, there is tradeoff to be made to obtain optimal results – even though the image intensifier 260 may improve the visibility also for very short exposure times.

Advantageously, the control unit 210 may control or may be synchronized with the laser source 112 of the radiation source 100. For example, the laser device 112 may be driven in a pulsed operation with a predetermined pulse repetition frequency. Then, according to embodiment, the first images for each laser pulse of the laser source 112 can be captured as the X-ray image, whereas the subsequent images can be associated with images caused by neutron with increasingly less energy.

Thus, embodiments achieve the energy resolution by operating the laser source 112 in a pulsed mode (or intermittent operation) with a predetermined frequency. Each burst of laser irradiation 113 will generate a bunch of neutrons with energies in an adjustable energy range. When the next laser pulse is generated, a new bunch of neutrons is generated and can again be used for the next images. Optionally, neutrons from the previous pulse with very low energies (< < 1 eV) can be removed with a Cadmium plate between the detector 200 and the object 50 to prevent pulses from temporally overlapping.

In summary, embodiments overcome the problems of conventional systems by equipping a laser-driven radiation source 100 with a converter material, which at the same time has a high neutron production and a high conversion efficiency into X-rays. This is combined with a detector 200 made of organic scintillator fibers which is sensitive to both neutrons and hard X-rays. The emitted light is then picked up by an image intensifier 260, which can be time-gated.

According to further embodiments, the combined x-ray and neutron detection

technique is utilized to identify materials inside a sample, for which conventional systems with a single source are unable.

Due to the short pulse duration (e.g. 1 ns), the radiation to be detected can be selected by selecting the recording period. If an early point in time is selected, X-rays will be recorded, since this will arrive first. If the recording time is set to approx. 100 nanoseconds later, a neutron radiograph can be recorded with the same setup, since neutrons, due to their mass, arrive at the detector well after the X-ray signal. The recording time for the neutron radiographs may be in the range from 100 ns to 1 µs. Due to the high repetition rate, radiographs can be taken at intervals of 1 ms. After this, a new laser pulse of 1 ns length may be triggered to initiate a new measurement. Therefore, the frequency of the pulsed laser of the laser source 112 may be adjusted accordingly (e.g. up to 1 kHz).

Fig. 3 shows a schematic flow chart for a method for analyzing an object. The method comprises:

- generating S110 a particle beam 115;
- converting S120 the particle beam 115 into a radiation beam 125 that includes simultaneously neutrons and X-rays by utilizing the particle beam 115;
- emitting S130 the radiation beam 125 in a forward direction onto the object 50;
- receiving S140 the radiation beam 125 after penetrating the object 50; and
- detecting S150 the neutrons and the X-rays in the received radiation beam 125.

According to further embodiments, the step of detecting S150 includes data processing, e.g., to analyze an interior of the object 50.

Various embodiments provide at least some of the following advantages:

- There is no need to utilize two different neutron and X-ray sources.
- The relative position between source 100, sample (object 50) and detector 200 can be chosen freely.
- Differences between neutron and X-ray absorption are enabled based on the detector pixels instead of subsequent assignment using separate software (as in conventional systems).
- The energy of the X-ray radiation for non-destructive analysis is higher than that of conventional X-ray sources.
- Larger objects can be examined (because of the higher energies).
- The neutron energies are higher than with conventional deuterium-deuterium and deuterium tritium neutron sources, which, likewise, means that larger objects can be scanned.
- The short pulse duration of the laser neutrons allows energy-resolved measurements of neutron attenuation.
- The short pulse durations and the high repetition rates enable very short snapshots to be taken.
- The recording time for X-ray radiographs is in the range of 1 nanosecond and the recording time for neutron radiographs is in the range from 100 ns to 1 μs. Due to the high repetition rate, radiographs can be taken at intervals of 1 ms.
- The technique enables the capability to identify materials based on the combined neutron and x-ray source. It can be used to allocate pixels to materials in a radiography and materials to voxels in a tomography.
- Having only one source, one detector and neutron and x-ray imaging at the same time enables less spatial shift between the taken images, which increases the spatial resolution and enhances the material identification possibilities.
- Using a laser source allows a much better spatial resolution for x-ray images than existing solutions.

Therefore, in contrast to conventional systems, these sources do not relate to separate configurations to generate, for example, neutrons by a lithium fluoride

or beryllium converter, or to generate X-rays by the so-called Bremsstrahlung when applying a particle radiation on a high mass number (Z) material. Moreover, there is no need to use different detectors as in conventional systems to detect the radiation. Furthermore, these different detectors do not need to be equipped with different scintillators.

Conventional neutron sources that are not based on laser devices allow only much longer pulse durations, during which the neutrons are generated, than the time-of-flight of the neutrons from the generation to the detector. In such systems, no energy resolution based on the time-of-flight would be possible. Embodiments overcome these disadvantages by the laser-driven neutron generation.

The description and drawings merely illustrate the principles of the disclosure. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the disclosure and are included within its scope.

Furthermore, while each embodiment may stand on its own as a separate example, it is to be noted that in other embodiments the defined features can be combined differently, i.e. a particular feature descripted in one embodiment may also be realized in other embodiments. Such combinations are covered by the disclosure herein unless it is stated that a specific combination is not intended.

Although the invention has been illustrated and described in detail by way of preferred embodiments, the invention is not limited by the examples disclosed, and other variations can be derived from these by the person skilled in the art without leaving the scope of the invention. It is therefore clear that there is a plurality of possible variations. It is also clear that embodiments stated by way of example are only really examples that are not to be seen as limiting the scope, application possibilities or configuration of the invention in any way. In fact, the preceding description and the description of the figures enable the person skilled in the art to implement the exemplary embodiments in concrete manner, wherein, with the knowledge of the disclosed inventive concept, the person

skilled in the art is able to undertake various changes, for example, with regard to the functioning or arrangement of individual elements stated in an exemplary embodiment without leaving the scope of the invention, which is defined by the claims and their legal equivalents, such as further explanations in the description.

List of reference signs

50	object/sample to be analyzed
100	radiation source
110	particle source (ions, electrons)
112	laser source
113	laser beam
114	laser target
115	particle beam (ions, electrons)
120	converter
125	neutron beam and X-rays
200	detector
210	control unit
220	scintillator
230	camera
240	mirror
250	lens (or an optic)
260	intensifier

CLAIMS

1. A radiation source (100) for a radiation beam (125) of combined neutrons and X-rays, the radiation source (100) comprising:

a particle source (110) adapted to generate a particle beam (115);

a converter (120) adapted to utilize the particle beam (115) to generate the radiation beam (125) that includes simultaneously neutrons and X-rays, and to emit the radiation beam (125) in a forward direction.

2. The radiation source (100) according to claim 1, wherein the particle source (110) includes:

- a laser source (112) configured to irradiate a laser beam (113); and
- a laser target (114) configured to receive the laser beam (113) and to release the particle beam (115).

3. The radiation source (100) according to claim 1 or claim 2, wherein the laser target (114) includes a deuterated material to provide as particles one or more of the following: deuterium nuclei, protons, electrons.

4. The radiation source (100) according to any one of claims 1 to 3, wherein:

the converter (120) comprises a conversion material adapted to trigger a reaction that releases, upon a particle absorption, neutrons,

wherein the conversion material includes at least one of the following: tungsten, lithium or lithium fluoride, beryllium, vanadium, molybdenum, copper, lead, uranium or a combination thereof, or a combination thereof.

5. A radiography device for a non-destructive analysis of an object (50), the radiography device includes:

a radiation source (100) according to any one of claims 1 to 4; and

a detector (200) adapted to receive the radiation beam (125) after penetrating the object (50) and to detect the neutrons and the X-rays in the received radiation beam (125).

6. The radiography device according to claim 5, wherein the detector (200) includes:

a scintillator device (220) for converting the radiation beam (125) after passing the object (50) into visible light or an ultraviolet spectrum;

a camera or imaging device (230) adapted to capture images emitted from the scintillator device (220).

7. The radiography device according to claim 6, wherein the camera or imaging device (230) includes a charged coupled device, CCD, or a complementary metal-oxide semiconductor, CMOS, or an amorphous silicon detector array, or another photon detecting device.

8. The radiography device according to claim 6 or claim 7, further comprising at least one of the following components:

a mirror (240) adapted to reflect an output of the scintillator device (220);

at least one lens (250) adapted to focus the output of the scintillator device (220);

at least one image intensifier (260) adapted to amplify the received output from the scintillator device (220) to increase an optical visibility for the camera device (230);

a light guiding medium coupled between the scintillator device (220) and the camera or imaging device (230).

9. The radiography device according to any one of claims 6 to 8, wherein the camera or imaging device (230) is directly coupled to an output surface of the scintillator device (220).

10. The radiography device according to any of claims 5 to 9, further comprising:

a control unit (210) configured to control the detector (200) to provide a time-gate to separate detection events caused by the received neutrons from the received X-rays and/or to provide an energy resolution for detection events caused by the neutrons.

11. The radiography device according to claim 10, wherein the control unit (210) is configured to select the time-gate in the range from 10 nanoseconds to 1 microsecond.

12. The radiography device according to claim 10 or claim 11, wherein the control unit (210) is configured to take a neutron radiography and an X-ray radiography on a same sample in a same angle and position and to determine an absorption ratio, R-value, based on a difference in neutron attenuation and x-ray attenuation.

13. The radiography device according to any of claims 10 to 12, wherein the control unit (210) is configured to combine multiple radiographies to a tomography.

14. The radiography device according to any of claims 10 to 13, wherein the control unit (210) is configured to also control the radiation source (100) to cause at least one of the following:

- to perform a combined X-ray and neutron radiographies and tomographies;
- to assign absorption ratios, R-values, to pixels or to voxels or to areas;
- to assign a material to a region in the object (50) based on the R-value alone or based on shape, density or documentation;
- to evaluate different regions inside the object (50);
- to summarize the content of the investigated object (50).

15. A method for analyzing an object, the method comprising:

generating (S110), by a particle source (110), a particle beam (115);

converting (S120), by a converter (120), the particle beam (115) into a radiation beam (125) that includes simultaneously neutrons and X-rays;

emitting (S130) the radiation beam (125) in a forward direction onto the object (50);

receiving (S140) the radiation beam (125) after penetrating the object (50); and

detecting (S150) the neutrons and the X-rays in the received radiation beam (125).