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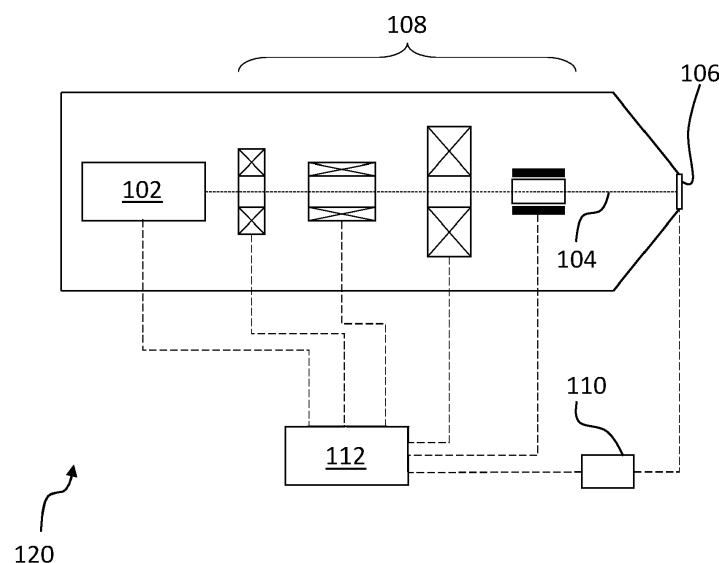
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(54) DISTURBANCE DETECTION

(57) An electron-impact X-ray source is disclosed, comprising an electron beam generator arranged to provide an electron beam; a target comprising a first edge between regions of different electron backscatter probabilities; an electron optic system arranged to focus and position the electron beam; and a controller configured to control the electron optic system to direct the electron beam towards and form a spot at an intended target position on the target; measure a first series of values

indicative of an electric current absorbed in the target as a function of time with the spot directed towards the intended target position and overlapping the first edge; and calculate a first quality measure indicative of a displacement between the intended target position and the actual target position based on the first series of values. A corresponding method for identifying disturbances in an X-ray source is also disclosed.

**Fig. 12**

DescriptionTechnical field

5 **[0001]** The present disclosure relates to X-ray sources. In particular, the disclosure relates to identification and estimation of disturbances in X-ray sources.

Background

10 **[0002]** In an electron-impact X-ray source, X-ray radiation is generated by letting an electron beam impact upon a solid target. Conventionally, the target may comprise a layer of tungsten (W) deposited on a diamond substrate. The quality of the generated X-ray radiation depends, *inter alia*, on the spot size of the electron beam on the target and on the stability of both the electron beam and the target. Any disturbance in the electron-impact X-ray source will adversely influence the quality of the generated X-ray radiation. Hence, there is a general desire to detect, categorize and/or characterize such disturbances.

15 **[0003]** WO 2019/154994 discloses a method for protecting a liquid-jet X-ray source. A monitoring arrangement is used for collecting data from various parts of the X-ray source in order to obtain a quality measure indicating a performance of the liquid jet. From the quality measure, any malperformance of the liquid jet is identified. The monitoring arrangement comprises an acoustic sensor, an accelerometer, an optic sensor, an electron detector, an X-ray detector and/or an inductive coil arrangement.

20 **[0004]** Solutions for identifying or estimating disturbances are sought also for solid-target X-ray sources, for example of the transmission type.

Summary

25 **[0005]** In brief, the present invention relates to detection of disturbances, such as variations caused by electrical noise and/or mechanical vibrations, that may be present in an electron-impact X-ray source. By sampling an electrical current absorbed in the target (or at least a quantity indicative of the absorbed target current) while directing the electron beam towards an edge between target regions with different electron absorption properties, variations caused by relative movement between the electron beam and the target can be detected by analyzing the sampled electrical current. A type of disturbance may be identified by analyzing, for example, a frequency content of the sampled electrical current. Other characteristics of the absorbed target current that can be analyzed to detect, categorize and/or characterize disturbances include a standard deviation, a peak-to-peak value, an average absolute deviation, or the like. Further, in case of a repeatable disturbance, the electron beam may be controlled to counteract the disturbance.

30 **[0006]** Several types of disturbances may contribute to X-ray spot instabilities. Two different main types of such disturbances are mechanically induced disturbances (e.g., vibrations of internal or external origin) and electrically induced disturbances (e.g., caused by electron-optical systems, variations in emission current, or acceleration voltage supply).

35 **[0007]** While an operator of the X-ray source may observe effects arising from such instabilities, e.g., increased noise levels in a captured X-ray image, the operator may not be able to determine which part of the system that is the source of the noise. Indeed, the operator may not even be able to notice the instability at all. For most practical applications the integration time for an X-ray image is long compared to the time scale of the disturbances, in which case the operator may notice this as an apparently larger X-ray spot size than expected according to system settings. In other words, the spot may be smeared by a disturbance of the electron beam spot position. It would therefore be advantageous to be able to monitor the stability of the electron beam spot and identify/characterize disturbances internally within the X-ray source.

40 **[0008]** When an electron-impact X-ray source is operated, the electron beam is typically controlled to be directed towards and form a spot at an intended target position, at which X-ray radiation is to be generated by interaction between the electron beam and the target. However, since disturbances such as mechanical vibrations may be present, the spot is not necessarily formed at the intended target position but at a slightly different actual target position. A mechanical disturbance such as vibrations will then manifest as deviations between the intended target position and the actual target position that may vary over time with the frequencies of the vibrations. It may be noted that the time scale of such vibrations is in many cases short on the time scale of X-ray imaging, i.e. in a resulting X-ray image the spot is perceived as stationary at the intended position and somewhat enlarged.

45 **[0009]** The present invention relies on measuring the absorbed target current (or a quantity indicative of the absorbed target current) with the electron beam directed at an edge separating two regions having different electron backscatter probabilities. As will be understood, different electron backscatter probabilities lead to a different number of electrons being absorbed in the regions, thereby causing different target currents. When a spot of the electron beam is located on the target such that it overlaps the edge separating the two regions, the absorbed target current will be highly sensitive to the position of the electron beam spot relative to the edge. Thus, sampling the target current while keeping the intended

electron beam spot position fixed (i.e., while not intentionally moving the intended target position) will yield a measure of any unintended relative movement between the actual electron beam spot and the edge. The signal generated in this way may be analyzed to determine its frequency spectrum which may provide guidance on what type of disturbance it is that causes the variation. Typically, mechanically induced disturbances will have a comparatively low frequency, e.g., about 100 Hz, whereas electrically induced disturbances may have a comparatively high frequency, e.g., in the range of tens of kHz. Some electrically induced disturbances, however, may also have a comparatively low frequency, e.g. as caused by the 50/60 Hz mains power.

[0010] Although the intended target position of the electron beam spot will, in general, not be identical to the actual target position, it is a straightforward task to ensure that the electron beam spot overlaps with the edge when impacting at the actual target position. Either the electron beam spot is sufficiently large, such that it can be reliably assumed that it will overlap the edge if the intended target position is centered at the edge. Alternatively, a scan of the electron beam across the target can be performed and the overlap of the electron beam spot with the edge can then be identified in any suitable manner, for example from changes in the amount of generated X-ray radiation, the amount of electron backscattering from the target and/or the electrical current absorbed by the target.

[0011] The term "quantity indicative of the absorbed target current" refers to any quantity that can be measured or determined, either directly or indirectly, and which comprises information that can be used for determining or characterizing the current absorbed by the target (also referred to as "target current" or "absorbed current"). Examples of such quantities may include an amount of generated X-ray radiation, a number of electrons passing through the target or being absorbed by the target, and a number of secondary electrons or electrons being backscattered from the target. Further examples include heat generated in the target, light emitted from the target, e.g., due to cathodoluminescence, and electric charging of the target. The quantity may also refer to brightness of the generated X-ray radiation. The brightness may for instance be measured as photons per steradian per square millimeter at a specific power or normalized per Watt. Alternatively, or additionally, the quantity may relate to the bandwidth of the X-ray radiation, i.e., the flux distribution over the wavelength spectrum.

Brief description of the drawings

[0012] In the following detailed description reference will be made to the accompanying drawings, on which:

Fig. 1 shows the absorbed target current relative to the electron beam current (i.e. normalized absorbed current) as a function of displacement of electron beam spot relative to an edge separating a target layer from a bare substrate. Fig. 2 shows the normalized absorbed current as a function of time in an idealized example where the disturbance consists of motion at only one frequency and an amplitude that is less than an electron beam spot radius. Fig. 3 shows the normalized absorbed current as a function of time in an idealized example where the disturbance consists of motion at only one frequency and an amplitude that is larger than an electron beam spot radius. Fig. 4 shows the normalized absorbed current as a function of time in a more realistic example where the disturbance comprises two frequencies of different amplitude and also some white noise. Fig. 5 shows the frequency spectrum of the disturbance illustrated in Fig. 4. Fig. 6 schematically illustrates a target with an electron beam directed to an edge between a first and a second region. Fig. 7 is a flow chart illustrating a method according to the principles disclosed herein. Fig. 8 is a graph showing the position of an edge between two regions of different backscatter probabilities as identified according to principles described herein; Fig. 9 is a graph showing the power spectrum of a disturbance present in the position shown in Fig. 8. Fig. 10 is graph showing the position of an edge in the form of a circle between two regions of different backscatter probabilities as identified according to principles described herein; Fig. 11 is a graph showing the power spectrum of a disturbance present in the position shown in Fig. 10. Fig. 12 schematically shows an electron-impact X-ray source.

Detailed description

[0013] As an introductory example, consider an X-ray target as schematically shown in Fig. 6 comprising a diamond substrate and a tungsten (W) target layer deposited on top of the substrate. During normal operation of the X-ray source, the electron beam spot is directed towards the target layer for production of X-ray radiation. In this example the diamond substrate is considered to be sufficiently thick so that all electrons impacting on the target are either backscattered or absorbed, i.e., no electrons are transmitted through the target. This assumption is realistic for most practical implementations since transmission of electrons through the entire target is normally not desired. A first region of the substrate is bare, i.e., not covered by the target layer, so that the diamond substrate is exposed as illustrated on the left side in Fig. 6. A second region is covered by the W layer as illustrated on the right side in Fig. 6. An edge is thus formed between the first

region and the second region. Assuming different backscatter probabilities for the exposed diamond substrate and the W layer, the variation in absorbed target current may be calculated by considering the fraction of the electron beam spot impacting the respective region of the target. For a circular electron beam spot (illustrated by a circle in Fig. 6) this corresponds to calculating the area of a circular segment. In this simplified example the electron intensity distribution is assumed to be a perfect top-hat distribution, i.e., the intensity of the electron beam is equal to a constant value inside the circle and zero outside of it. In a more realistic case, the intensity distribution may be approximately gaussian and the electron beam spot size may be defined by the full width at half maximum.

[0014] Assuming that the fraction of the electron beam that impacts the target layer is α the absorbed current may be written

$$I_{abs} = I_{beam}(\alpha(1 - \eta_t) + (1 - \alpha)(1 - \eta_s)) \quad (1)$$

where I_{beam} is the electron beam current, η_t and η_s are the backscatter probabilities of the target layer and the substrate respectively. The fraction α may be calculated for a deviation from the perfect alignment between the edge and the center of the electron beam by the well-known formula for the area of a circular segment

$$A_{seg} = \frac{R^2}{2}(\theta - \sin \theta) \quad (2)$$

where R is the radius of the electron beam spot and θ is the central angle of the segment which in turn may be expressed as a function of the distance x between the electron spot center and the edge (where $|x|$ is assumed to be smaller than R)

$$\theta = 2 \cos^{-1} \frac{x}{R} \quad (3)$$

[0015] Thus, by dividing the segment area with the total electron beam spot area and plugging in the expression for θ from (3) the fraction may be written as

$$\alpha = \frac{A_{seg}}{A_{circ}} = \frac{R^2}{2\pi R^2}(\theta - \sin \theta) = \frac{1}{2\pi} \left(2 \cos^{-1} \frac{x}{R} - \sin \left(2 \cos^{-1} \frac{x}{R} \right) \right) \quad (4)$$

This expression may be generalized to other values of x (as long as the entire electron beam spot is on the target).

$$\alpha = \begin{cases} 0, & x \geq R \\ \frac{1}{2\pi} \left(2 \cos^{-1} \frac{x}{R} - \sin \left(2 \cos^{-1} \frac{x}{R} \right) \right), & -R < x < R \\ 1, & x \leq -R \end{cases} \quad (5)$$

[0016] The absorbed current normalized to the electron beam current is illustrated in Fig. 1. For large positive values of x , i.e., when the electron beam impacts only on the bare diamond substrate, the absorbed current is independent of position and determined by the backscatter probability of the diamond substrate. For large negative values of x the absorbed current is also independent of position but instead determined by the backscatter probability of the target layer. For $x=0$ (i.e., with the electron spot centered on the edge between the two regions) the absorbed current is most sensitive to the electron beam position. The sensitivity will be larger for larger differences between the backscatter probability for the target layer and the substrate respectively.

[0017] To illustrate a time series of absorbed target current, Fig. 2 shows the normalized target current in an idealized example where the disturbance is a motion at one frequency only and has an amplitude that is smaller than the radius of the electron spot. As can be seen, the target current will then fluctuate between a maximum and a minimum value at the frequency of the disturbance. If the amplitude of the disturbance is larger than the radius of the electron beam spot then there will be periods during which the electron beam impacts only one of the substrate and the target layer respectively, and during these periods there will be no change in the detected target current due to the disturbance. An example of an idealized time series for the target current in this latter situation is shown in Fig. 3.

[0018] Two special cases may be identified regarding the relative size of the electron beam spot and the magnitude of the spatial disturbance. In a first case, if the electron beam spot is significantly smaller than the magnitude of the disturbance the spot will for most of the time impact either only the substrate or only the target layer. The absorbed current as a function of time will in this case alternately take on a maximum and a minimum value similar to what is shown in Fig. 3. In other

words, α will be either 0 or 1 in accordance with equation (5) above. To determine the magnitude of the disturbance in this case the electron beam spot may be intentionally moved in a direction substantially perpendicular to the edge and a new time series of absorbed current may be recorded. If the disturbance is still detected it may be inferred that the magnitude of the disturbance is larger than the distance the electron beam spot was moved (i.e. larger than the amplitude of the electron beam movement). By repeating this procedure a number of times, for example using different electron beam movement amplitudes, the magnitude of the disturbance may be determined.

[0019] In a second case, where the electron beam spot is large as compared to the magnitude of the disturbance, the ratio x/R in equation (5) above is small and may to a first order be approximated as

$$\alpha \approx \frac{1}{2} - \frac{2x}{\pi R}, x \ll R \quad (6)$$

[0020] The magnitude of the disturbance may in this case be estimated by studying the peak-to-peak value of the absorbed current as a function of time. From equation (1) above it is evident that the maximum value that the peak-to-peak current may attain is given by the difference between the backscatter probability for the target layer and the exposed substrate, respectively, multiplied by the beam current. This current difference may be determined by recording the absorbed current with the electron beam spot only impacting the target layer and the substrate, respectively. For a situation where the electron beam spot is intersected by the edge between the target layer and the substrate during the entire time while recording a series of absorbed current, readings of the peak-to-peak value will correspond to two displacements x_1 and x_2 with fractions α_1 and α_2 respectively in accordance with equation (5). The peak-to-peak value of the absorbed current may thus be written

$$I_{pp} = I_{beam}(\alpha_2 - \alpha_1)(\eta_t - \eta_s) = I_{pp,max}(\alpha_2 - \alpha_1) = I_{pp,max} \frac{2}{\pi R} (x_1 - x_2) \quad (7)$$

where in the last equality the linear expansion according to equation (6) above has been used. From this it can be deduced that the magnitude of the displacement, i.e., the difference between the two displacements corresponding to the peak-to-peak value in the absorbed current, is directly proportional to the ratio between the observed peak-to-peak absorbed current and its maximum attainable value.

$$x_1 - x_2 = \frac{\pi R}{2} \frac{I_{pp}}{I_{pp,max}} \quad (8)$$

[0021] Furthermore, in the limit where the disturbance is small as compared to the electron beam spot size, the sensitivity in the absorbed current to positional displacement may be obtained by inserting (6) in (1) and taking the derivative with respect to the displacement x .

$$\frac{dI_{abs}}{dx} = \frac{2(\eta_t - \eta_s)}{\pi R} I_{beam} \quad (9)$$

Thus, the larger the difference in backscatter probability the more sensitive the absorbed current will be to disturbances.

[0022] To quantify the sensitivity of the absorbed current the following expressions for backscatter probability η_B and electron penetration depth R_e may be used.

$$\eta_B(Z, E) = 2^{-\frac{9}{\sqrt{Z}}} \cdot \left(1 - e^{-\left(\frac{0.7 \cdot d \cdot Z^{0.667}}{R_e(Z, E)} \right)} \right), \quad (10)$$

$$R_e(Z, E) = 2.76 \cdot 10^{-10} \cdot \frac{A \cdot E^{1.67}}{\rho \cdot Z^{0.89}} \quad (11)$$

where E is the electron energy in eV, Z is the atomic number, d is the thickness of the layer, A is the atomic weight, and ρ is the density. For a thin layer of target material deposited on top of a substrate the following expression may be used to calculate the effective backscatter probability

$$\eta_{eff} = \eta_s + \eta_B \cdot \left(1 - \frac{\eta_s}{\eta_{B0}}\right) \quad (12)$$

where η_s is the backscattering probability for the substrate, η_{B0} is the bulk backscattering probability for the target layer material, and η_B is the backscattering probability for the target layer according to equation (10).

[0023] For the example mentioned above with a layer of tungsten (W) deposited on top of a diamond substrate for an acceleration voltage of 160 kV a backscatter probability for the exposed diamond of 7.8% may be calculated, whereas for a 0.5 μm thick W layer on top of the substrate a backscatter probability of 14% is obtained. Thus, the absorbed current is expected to go from 86% of the beam current when impacting on the W layer to 92.2% of the beam current when impacting on the diamond substrate. If the electron beam is positioned such that it impacts on the edge between the target layer and the exposed substrate, a change in relative absorbed target current of the order of 4% of a position change normalized to the radius of the electron beam spot size can be expected in the limit of small displacements (as calculated by equation (9)). Correspondingly, by differentiating the curve shown in Fig. 1 and assuming an electron beam spot diameter of 300 nm, a fractional current change of 0.3% per nm displacement may be calculated.

[0024] Of special interest is the frequency content of the absorbed current with the electron beam positioned at the edge between the target layer and the exposed substrate. Identification of particular frequencies indicates that a systematic disturbance is present. Such disturbance could be mitigated either by finding and removing the source of the disturbance or by applying compensation to the electron beam by deflecting it to counteract the positional disturbance introduced. This of course requires that the compensation comprises not only the correct frequency but also the correct amplitude and phase (i.e., it starts synchronized with the disturbance). An alternative may be to inform the user that given the circumstances (e.g., externally induced vibrations) the expected X-ray source performance may not be attained unless suitable corrections are applied.

[0025] To illustrate this, Fig. 4 shows the normalized absorbed target current as a function of time for a disturbance comprising two frequencies and also some white noise. The frequency spectrum of the disturbance is shown in Fig. 5. As will be understood, the frequency content can be obtained using, for example, a fast Fourier transform. A disturbance of a particular frequency may be further characterized by repeated measurements with the electron beam spot located at different positions to determine the amplitude of the frequency component (provided the electron beam spot is sufficiently small as discussed above). Furthermore, measurements may be repeated at different sampling frequencies to ensure that the identified frequency is the correct one and not the result of aliasing.

[0026] When determining disturbances using an edge between two regions of different electron backscattering probabilities as disclosed herein, information will only be obtained about disturbances in a direction normal to the edge. Therefore, in order to obtain complete two-dimensional information about the any disturbance, it is proposed to make at least two measurements, using two different edges that are non-parallel.

[0027] To rule out other possible sources of variation in the absorbed target current than a relative motion between the target and the electron beam spot (i.e. displacement between the intended and the actual targets positions for the spot), a time series of target currents registered with the electron beam directed to a uniform region of the target may be obtained. According to equation (5) the absorbed current is then expected to be constant as function of time (as long as the entire electron beam spot impacts on the uniform part of the target). If a variation in the absorbed current is detected despite this then some other source of the variation must be sought. One reason for such a variation may be variations in the emission current of the electron source, another may be noise in the measurement arrangement. If the magnitude of a particular peak in the frequency spectrum of the absorbed current collected with the electron beam directed towards the edge is substantially the same as the magnitude of that particular peak in frequency spectrum of the absorbed current collected with the electron beam directed towards a uniform part of the target, then it may be inferred that the source of that frequency component is not relative motion between the target and the electron beam.

[0028] In other words, investigations of disturbances can be made by comparing a measurement across an edge, as described above, with a measurement made while the electron beam is directed to a region of the target having a uniform electron backscatter probability. Properties of a time series of target currents registered with the electron beam directed at the edge is then compared with properties of a time series of target currents registered with the electron beam directed at the uniform region of the target. Any mechanical disturbance will appear in the time series registered with the electron beam directed at the edge but will not influence the time series registered with the electron beam directed at the uniform region. Hence, if the properties (e.g. frequency content) of the two time series do not differ, then it can be deduced that the disturbance is not mechanical. If, on the other hand, the properties of the two time series do indeed differ, then it can be inferred that there is a mechanical fault state.

[0029] With reference to Fig. 7, a method according to the principles disclosed herein thus comprises controlling S701 an electron beam to be directed towards and form a spot at an intended target position on a target, the electron beam thereby forming a spot on the target at an actual target position, the target comprising a first edge between regions of different electron backscatter probabilities. In a typical example, the target will comprise a diamond substrate having

deposited thereon a tungsten target layer. The edge may be formed between a bare region of the substrate and a region comprising the target layer. A first series of values is measured S702, indicative of an electric current absorbed in the target as a function of time, with the electron beam spot directed towards the intended target position and overlapping the first edge. Based on the first series of values, a first quality measure indicative of a displacement between the intended target position and the actual target position is then calculated S703.

[0030] In some embodiments, in order to obtain two-dimensional information about any displacement between the intended target position and the actual target position, the target comprises a second edge between regions of different electron backscatter probabilities, wherein the first edge and the second edge are non-parallel. Two-dimensional information about displacement between the intended and actual target positions may then be obtained by measuring S704 a second series of values indicative of an electric current absorbed in the target as a function of time with the electron beam spot directed towards an intended target position such that it overlaps the second edge; and calculating S705 a second quality measure indicative of a displacement between the intended target position and the actual target position based on the second series of values.

[0031] Preferably, the method also comprises extracting S706 a frequency spectrum from the first series of values, e.g. using a fast Fourier transform, and determining S707 a type of disturbance based on peaks in the frequency spectrum that have magnitudes significantly surpassing a noise level. The method may also comprise controlling S708 the electron beam to reduce displacement between the intended target position and the actual target position, i.e. to counteract the disturbance.

[0032] The method may comprise repeated scanning of the electron beam spot (the intended target position) over a region comprising an edge separating two regions with different electron backscatter probability while measuring a quantity indicative of the absorbed target current. In each such scan the edge may be identified, e.g., as the point where a derivative of the target current attains a local maximum value. In an ideal case, i.e., when no relative motion between the target and the electron beam spot is present (intended and actual target positions are the same), the edge will be at substantially the same position for each scan. If a disturbance (i.e., a deviation between intended and actual target positions) is present the observed edge position will vary. The source of the disturbance may be any type of relative motion between the electron beam and the target. Provided that the time for performing one scan is short as compared to relevant time scales for the disturbance the successive scans may be seen as samples of the edge position relative to the scanned region. The deviations from an average value of the samples may be analyzed to quantify and characterize the disturbance in similar ways as discussed above. The procedure may, of course, be repeated for a second edge in order to obtain two-dimensional information as described elsewhere herein.

[0033] In a further alternative the electron beam may be scanned over some known feature on the target, e.g. a straight line separating two regions with different backscatter probabilities or a circle separating an interior region from an exterior region, while registering the absorbed target current. In this way, an image of the feature may be created based on the measured values. Such procedures may be advantageous during alignment of the electron beam and adjustment of the electron beam spot size. By analyzing deviations of edge positions from expectations detected from such scans, disturbances of the target relative to the electron beam may be identified. As an example, consider a circle scanned by a plurality of equidistant line scans. The points identified as being on the edge of the circle may be analyzed to determine disturbances along the scan direction as well as perpendicular to it. For each scan over the circle two edge transitions may be detected thus giving two positions for each scan. Analyzing the average position of two transitions for each respective scan as compared to the average position of all scans gives information about disturbances along the scan direction. Analyzing the distance between the two transitions for each respective scan as compared to the expected distance for a circle gives information about disturbances perpendicular to the scan direction. An alternative way of analyzing the data may be to calculate the distance from each detected edge transition to the average center position for all transitions. These distances comprise information about disturbances in all directions, although it is not possible to separate contributions to the total disturbance from different directions. A further alternative for assessing data from an image obtained by scanning the electron beam over a circle may be to transform the image to polar coordinates (centered at the observed center of the circle), identify the circumference of the circle and analyze how the observed radius varies along the circle. In a general case several sources may contribute to such a variation, most notably, astigmatism, coma aberration, target imperfections, and unintended relative displacement of the target and the electron beam spot during the scan. Different metrics may be applied to differentiate between these contributions and to characterize the electron beam spot. Results from this type of analysis may be used to decide to perform a measurement with the electron beam directed towards an edge as discussed above to isolate and potentially quantify the contribution from relative displacement between the target and the electron beam spot.

[0034] An advantage of not scanning the electron beam over an edge to acquire data on a relative disturbance between the target and the electron beam is that imperfections in target production do not influence the measurement. Another advantage may be that the sample rate can be selected freely based on the desired frequency range. In embodiments where the electron beam is scanned during measurement it may be difficult to detect high frequency disturbances since the sample rate is limited by the time required for scanning.

[0035] Fig. 8 illustrates an example where a straight, slightly angled, edge separating two regions with different backscatter probability has been identified by a plurality of scans with an electron beam. In this example the scanning interval was set to 100 μ s, i.e., every 100 μ s the electron beam completes a scan from right to left over the edge. Effectively, this yields a sampling frequency of 10 kHz for identifying the edge. Between each scan the electron beam is moved 0.1 μ m in a direction perpendicular to the scan direction, i.e., upwards in the figure. Each point in the figure corresponds to a determination of the edge location based on the data obtained from one electron beam scan. In this example the edge locations were calculated by adding a periodic disturbance to the x-position with amplitude 0.1 μ m and frequency 100 Hz. White noise with an amplitude of 2.5 μ m (5 μ m peak to peak) was also added. After deducting a linear fit from the data, to obtain the deviations from the straight line, the power spectrum shown in Fig. 9 was calculated by applying a fast Fourier transform. As can be seen, the periodic disturbance is recovered despite the noise. The effective sampling frequency used in this example is 10 kHz (one scan line per 100 μ s), which implies that periodic disturbances up to about 5 kHz can be resolved according to the Nyquist-Shannon theorem.

[0036] Fig. 10 shows an image obtained in a similar way as that in Fig. 8. In this case the edge is a circle enclosing one region having a different backscatter probability than the region outside the circle. The observed positions are generated by adding a periodic disturbance with amplitude 0.1 μ m and frequency of 100 Hz in the X-direction and another periodic disturbance with amplitude 0.1 μ m and a frequency of 175 Hz in the Y-direction. White noise with an amplitude of 0.15 μ m (0.3 μ m peak to peak) was also added. The circular marker corresponds to the nominal circle center and cross marker corresponds to the center calculated from the observed edge positions. By analyzing the mean value of the X-positions for each pair of edge locations from the same electron beam scan, the frequency spectrum for the X-displacements may be obtained. Since the electron beam scan is fast (repeats every 100 μ s) as compared to the disturbance (shortest period time 5.7 ms) the edge may be considered as fixed during each scan. Thus, displacement of the circle in the X-direction may be detected as a displacement of the detected edge as compared to the average X-position for all scans. The fast Fourier transform of this dataset is shown as a solid line in Fig. 11, where the 100 Hz disturbance is recovered. By analyzing the distance between the two edge positions for each scan a corresponding analysis for the Y-direction may be performed. The expected distances may be readily calculated from the knowledge that the edge is circular in shape. The fast Fourier transform of this dataset is shown as a dashed line in Fig. 11, where the 175 Hz disturbance is recovered. The recovered amplitude of the disturbance is about 0.1 μ m for the 100 Hz disturbance, i.e., the X-direction, as seen from Fig. 11. The amplitude for the Y-direction is a bit smaller than expected, which can be attributed to a mismatch between the sampling frequency (10 kHz) and the frequency of the disturbance (175 Hz). This is an example of a potential drawback of embodiments based on scanning the electron beam over the edge, since the choice of sampling frequency is limited both by the electron optical system and the frequencies to be detected.

[0037] A further extension of the method may be to perform an analysis of disturbance levels as discussed in connection with Fig. 10 above each time an image of some known feature is generated as part of alignment and/or focusing of the electron beam, and, if some predefined limit is exceeded, position the electron beam spot at an edge and perform an analysis as discussed above in connection with Fig. 4. In this way the stability of the electron beam position in relation to the target is monitored without undue interference with the source operation.

[0038] Fig. 12 schematically shows an electron-impact X-ray source 120, comprising an electron beam generator 102 arranged to provide an electron beam 104. The X-ray source also comprises a target 106 that comprises at least a first edge between regions of different electron backscatter probabilities. An electron optic system 108 is provided for focusing and positioning the electron beam on the target 106. A detector 110 is provided for detecting a value indicative of an electric current absorbed in the target 106. A controller 112 is provided and is configured to control the electron optic system 108 to direct the electron beam 104 towards and form a spot at an intended target position on the target 106, the electron beam thereby forming a spot on the target 106 at an actual target position. The controller 112 is further configured to measure a first series of values indicative of the electric current absorbed in the target 106 as a function of time with the spot directed towards the intended target position and overlapping the first edge, and to calculate a first quality measure indicative of a displacement between the intended target position and the actual target position based on the first series of values.

[0039] In some embodiments, the target 106 comprises both a first and a second edge between regions of different electron backscatter probabilities, wherein the first and the second edge are non-parallel. Thereby, displacements between the intended and the actual target positions can be determined in two dimensions. For example, the edge may take the form of a circle.

[0040] The controller may be configured to extract a frequency spectrum from the detected values of the absorbed target current and determine a type of disturbance in the X-ray source based on the frequency spectrum. The controller may also control the electron beam to counteract the disturbance, i.e. to reduce the displacement between the intended target position and the actual target position.

[0041] In conclusion, an electron-impact X-ray source and a corresponding method have been disclosed for determining displacements between an intended and an actual target position for the electron beam. Disturbances in the X-ray source can thereby be detected, categorized and/or characterized. The frequency contents of a time series of such displacements can provide useful information about fault states in the X-ray source. For periodic disturbances, the X-ray

source, e.g. the electron beam, can be controlled to counteract the disturbance. Further, an operator can be alerted about the presence of a fault state in the X-ray source or its environment.

Claims

1. A method for identifying disturbances in an electron-impact X-ray source, comprising:

controlling an electron beam to be directed towards and form a spot at an intended target position on a target, the electron beam thereby forming a spot on the target at an actual target position, the target comprising a first edge between regions of different electron backscatter probabilities;
measuring a first series of values indicative of an electric current absorbed in the target as a function of time with the electron beam spot directed towards the intended target position and overlapping the first edge;
calculating a first quality measure indicative of a displacement between the intended target position and the actual target position based on the first series of values.

2. The method of claim 1, wherein the target comprises a second edge between regions of different electron backscatter probabilities, the first edge and the second edge being non-parallel, the method further comprising:

measuring a second series of values indicative of an electric current absorbed in the target as a function of time with the electron beam spot directed towards the intended target position and overlapping the second edge;
calculating a second quality measure indicative of a displacement between the intended target position and the actual target position based on the second series of values.

3. The method of any one of the preceding claims, wherein the first edge and/or the second edge is a straight line.

4. The method of claim 1 or 2, wherein the first edge and the second edge are portions of a common circle.

5. The method of any one of the preceding claims, wherein the intended target position is maintained stationary during the measuring of the first series of values.

6. The method of any one of the preceding claims, further comprising:

extracting a frequency spectrum from the first series of values; and
determining a type of disturbance in the X-ray source based on the frequency spectrum.

7. The method of claims 1-4 wherein

the intended target position is repeatedly scanned over the first edge when measuring the first series of values;
and
wherein calculating the first quality measure comprises:

determining, for each of a plurality of scans and based on the values measured during each respective scan, an edge position at which the intended target position coincides with the first edge; and
calculating a difference between the edge position determined for each respective scan from an average edge position for the plurality of scans.

8. The method of any one of the preceding claims, further comprising controlling the electron beam to reduce displacement between the intended target position and the actual target position.

9. An electron-impact X-ray source, comprising:

an electron beam generator arranged to provide an electron beam;
a target comprising a first edge between regions of different electron backscatter probabilities;
an electron optic system arranged to focus and position the electron beam; and
a controller configured to

control the electron optic system to direct the electron beam towards and form a spot at an intended target

position on the target, the electron beam thereby forming a spot on the target at an actual target position;
 measure a first series of values indicative of an electric current absorbed in the target as a function of time with
 the spot directed towards the intended target position and overlapping the first edge;
 calculate a first quality measure indicative of a displacement between the intended target position and the
 actual target position based on the first series of values.

10. The electron-impact X-ray source of claim 9, wherein the target comprises a second edge between regions of different electron backscatter probabilities, the first edge and the second edge being non-parallel, the controller further configured to:

measure a second series of values indicative of an electric current absorbed in the target as a function of time with
 the spot directed towards the intended target position and overlapping the second edge;
 calculate a second quality measure indicative of a displacement between the intended target position and the
 actual target position based on the second series of values.

11. The electron-impact X-ray source of claim 9 or 10, wherein the or each edge is a straight line or a portion of a circle.

12. The electron-impact X-ray source of any one of claims 9-11, wherein the controller is further configured to:

extract a frequency spectrum from the first series of values;
 determine a type of disturbance based on the frequency spectrum.

13. The electron-impact X-ray source of any one of claims 9-12, wherein the controller is further configured to control the electron beam to reduce displacement between the intended target position and the actual target position.

14. The electron-impact X-ray source of any one of claims 9-13, wherein the target comprises

a substrate and
 a target layer arranged on top of the substrate, the target layer being configured to generate X-ray radiation by
 interaction with the electron beam; wherein the or each edge separates a first region where the substrate is
 exposed and a second region comprising the target layer.

15. The electron-impact X-ray source of claim 14 wherein

the substrate comprises beryllium or a carbon material such as diamond; and
 the target layer comprises a material selected from tungsten, rhenium, molybdenum, vanadium, and niobium.

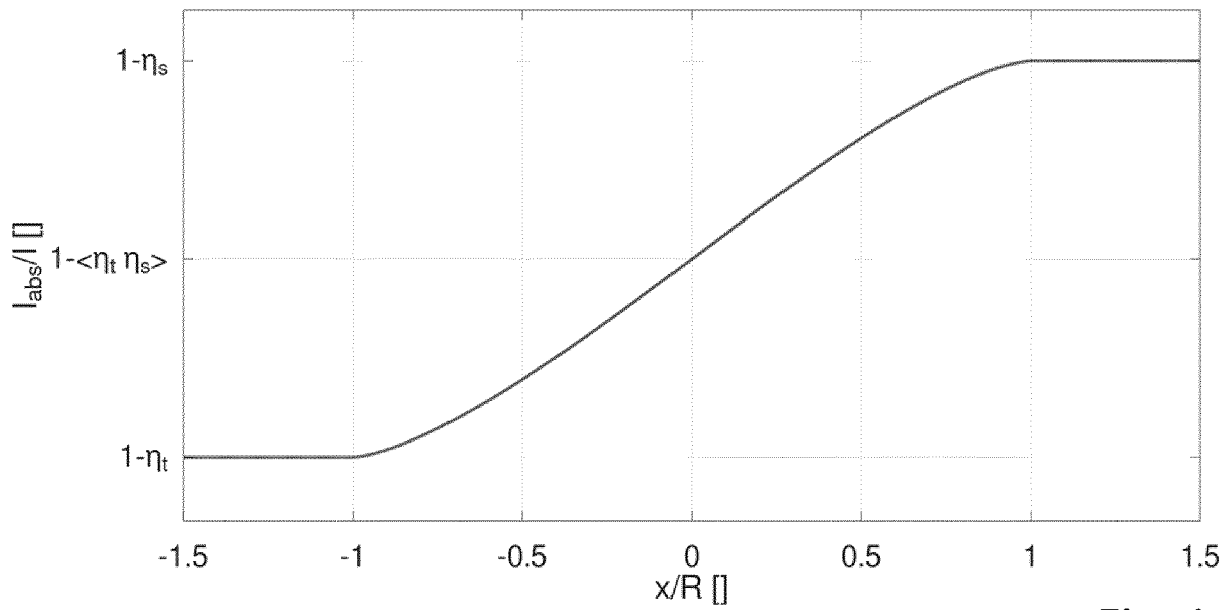


Fig. 1

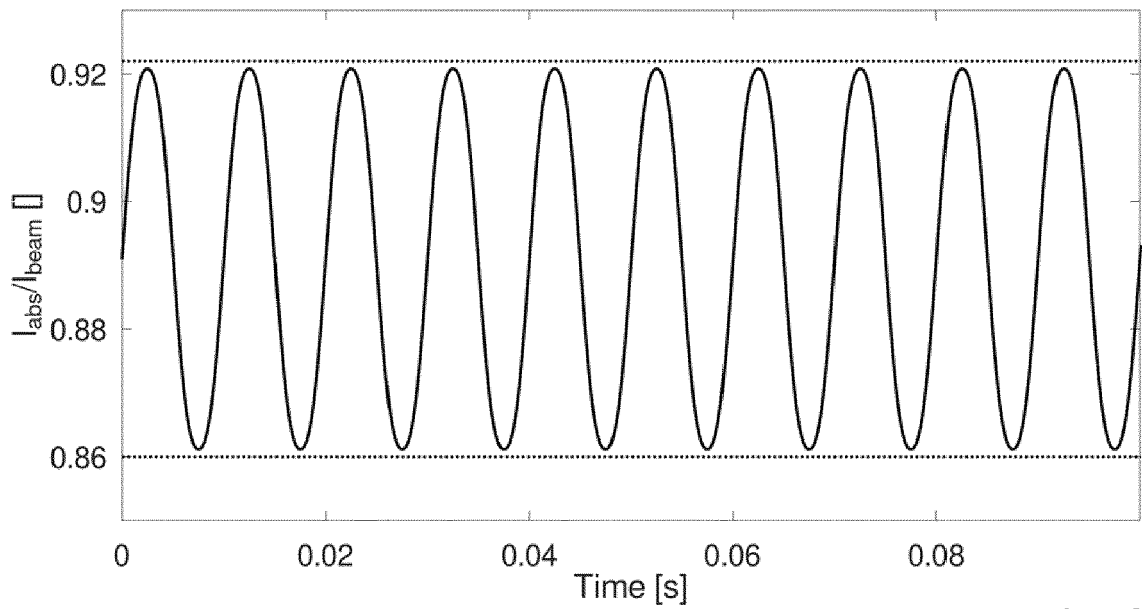
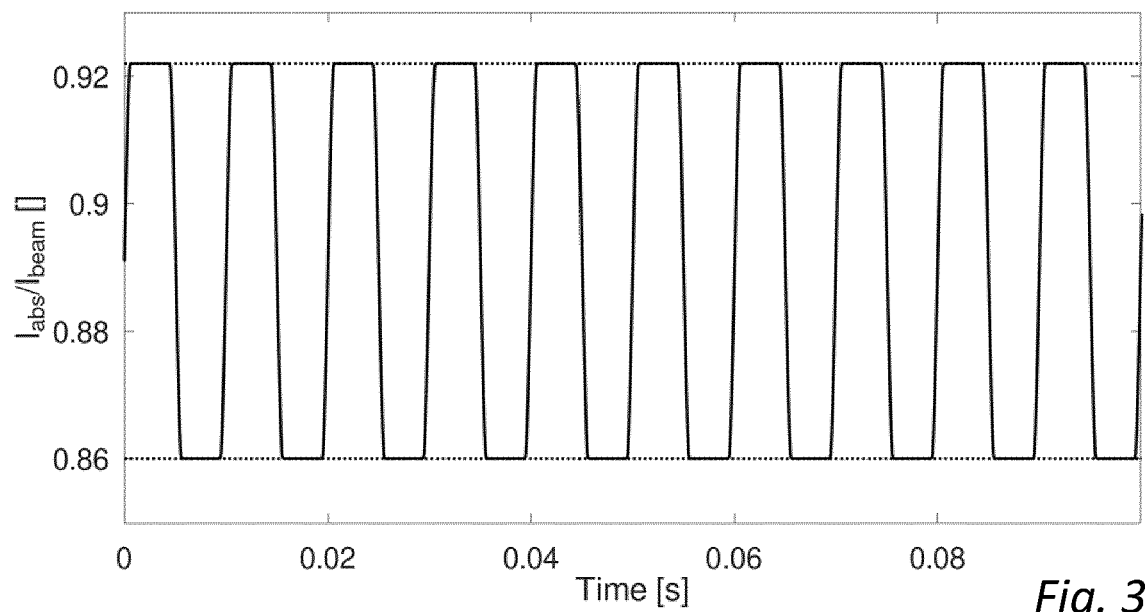
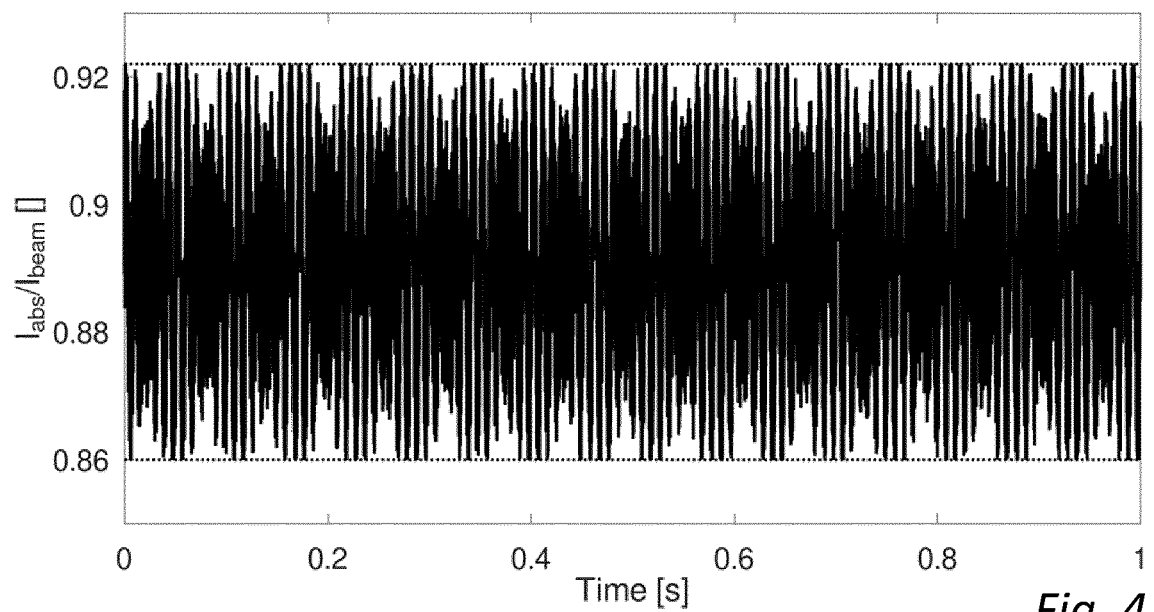


Fig. 2

*Fig. 3**Fig. 4*

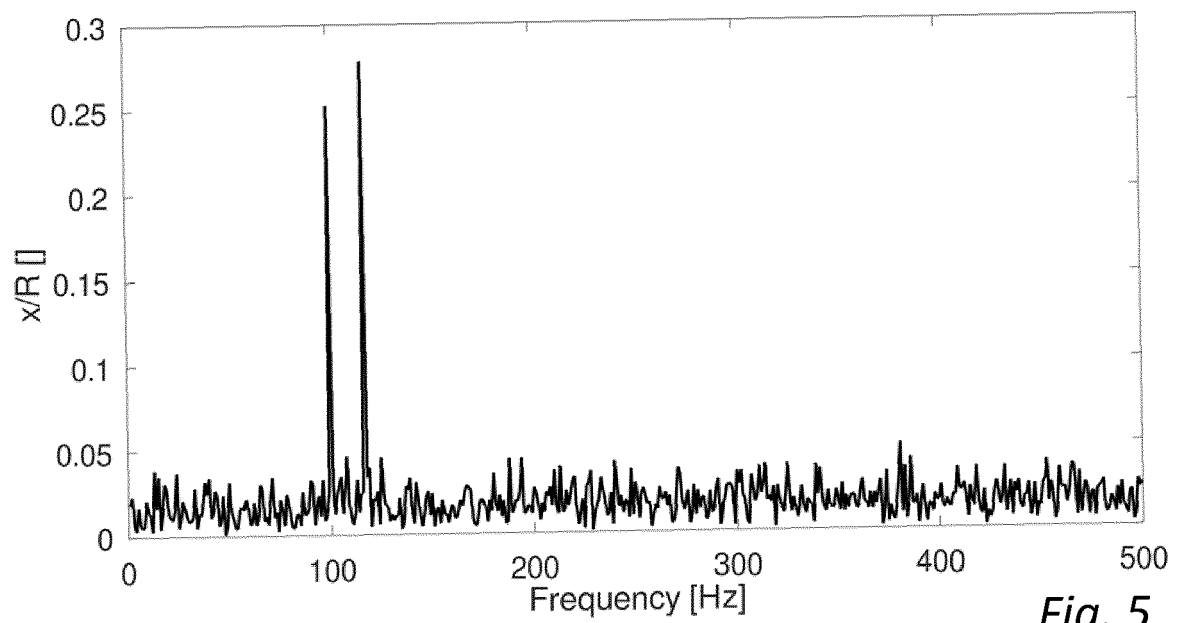


Fig. 5

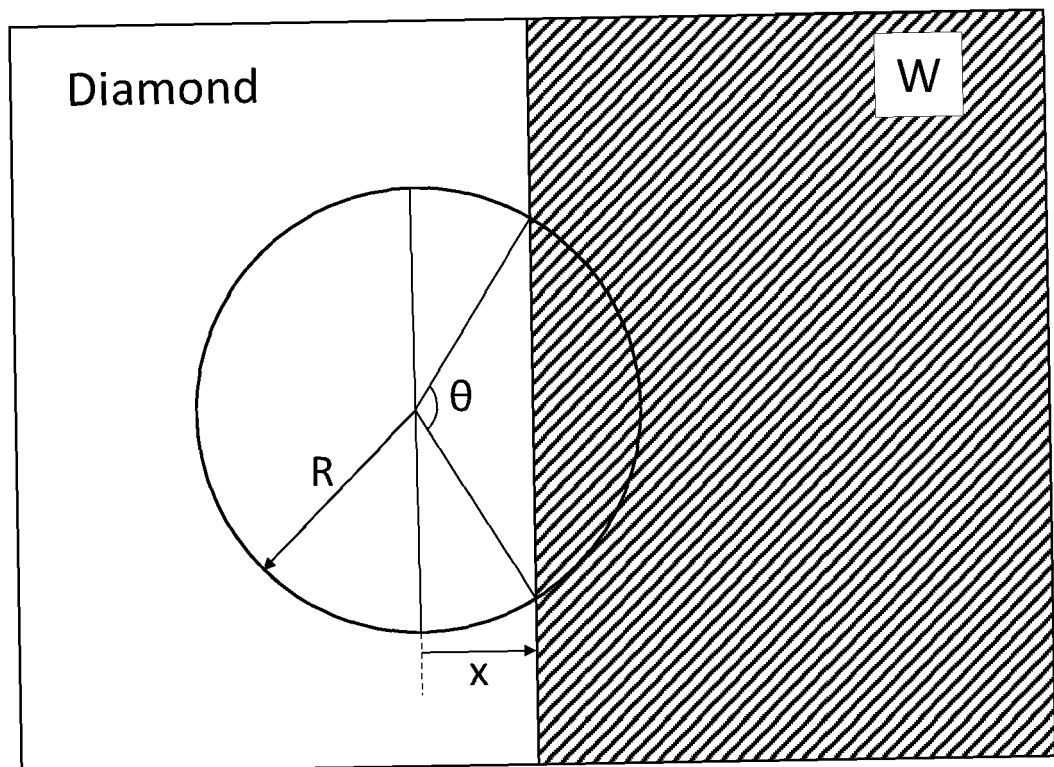


Fig. 6

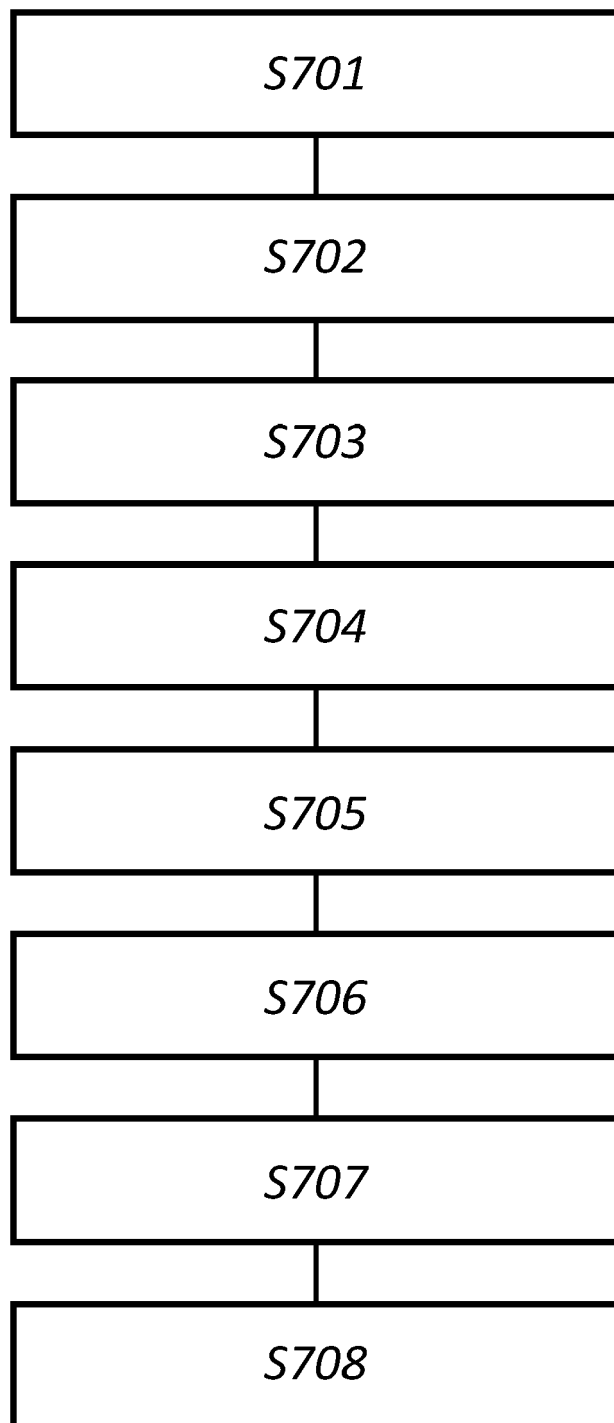
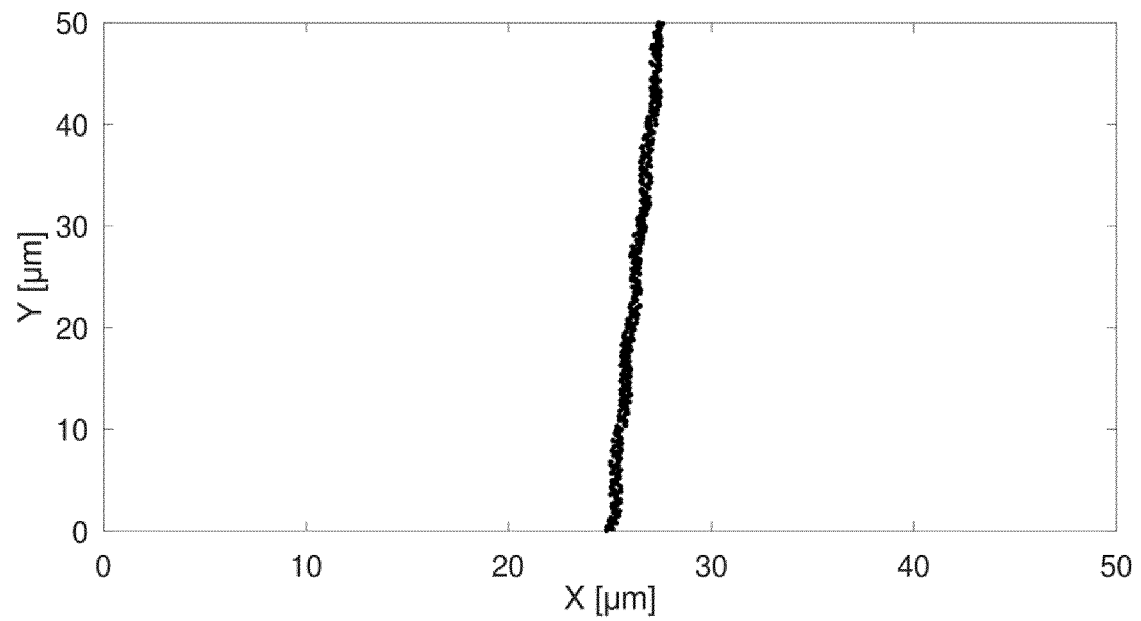
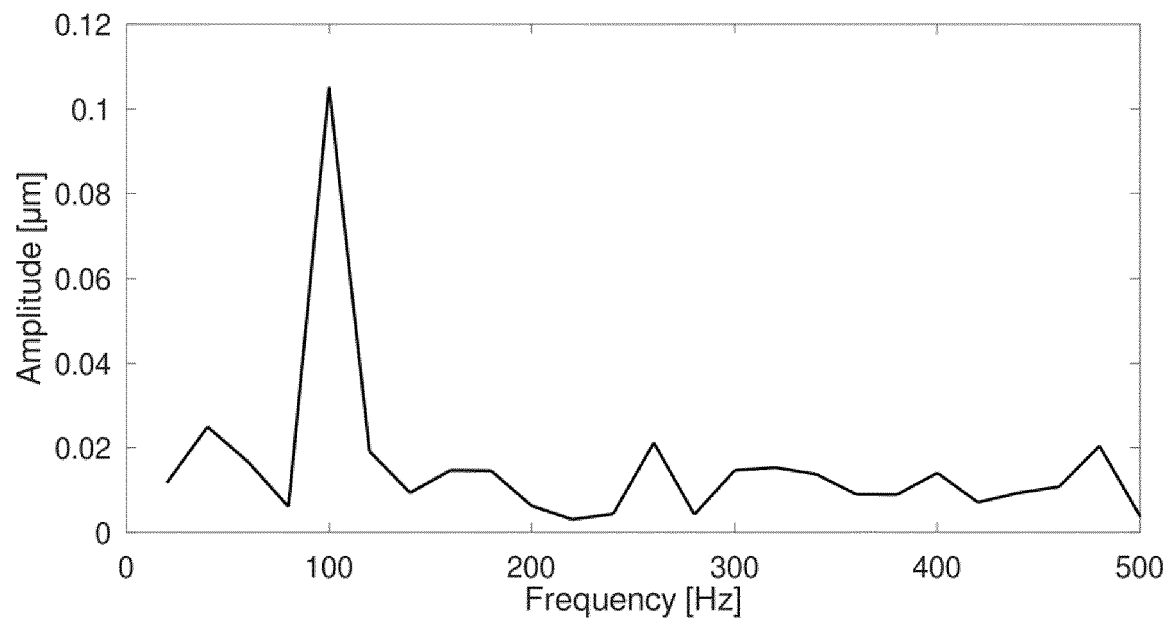
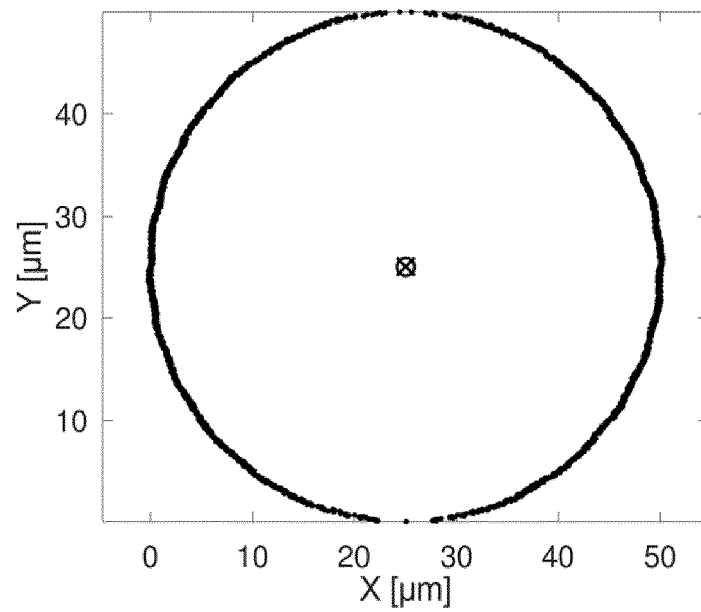
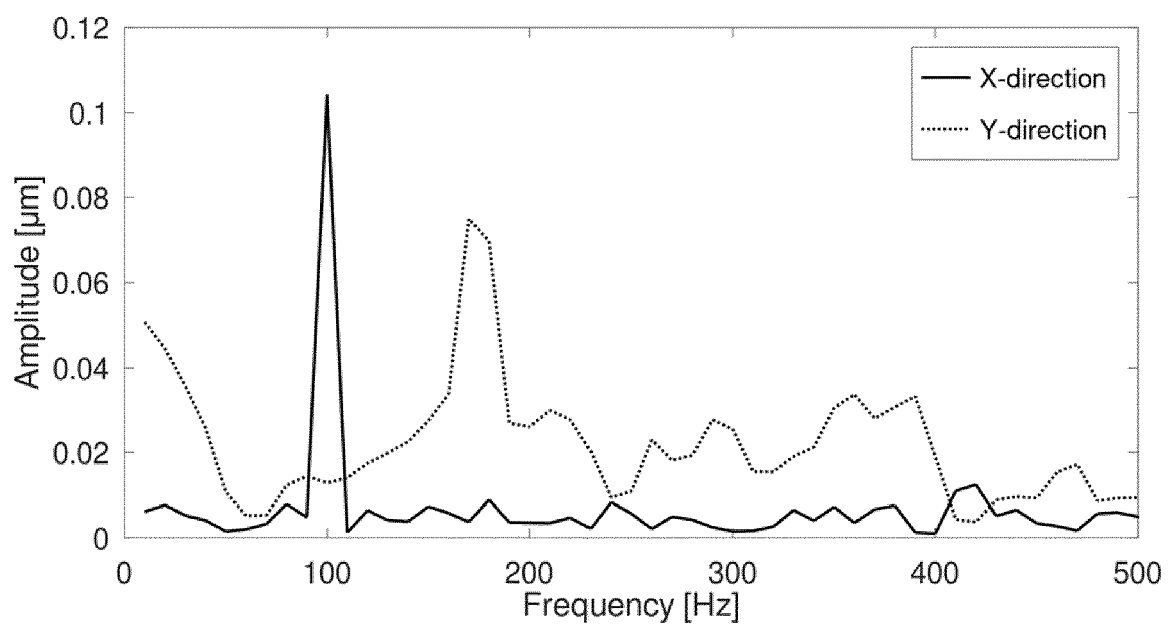


Fig. 7

*Fig. 8**Fig. 9*

*Fig. 10**Fig. 11*

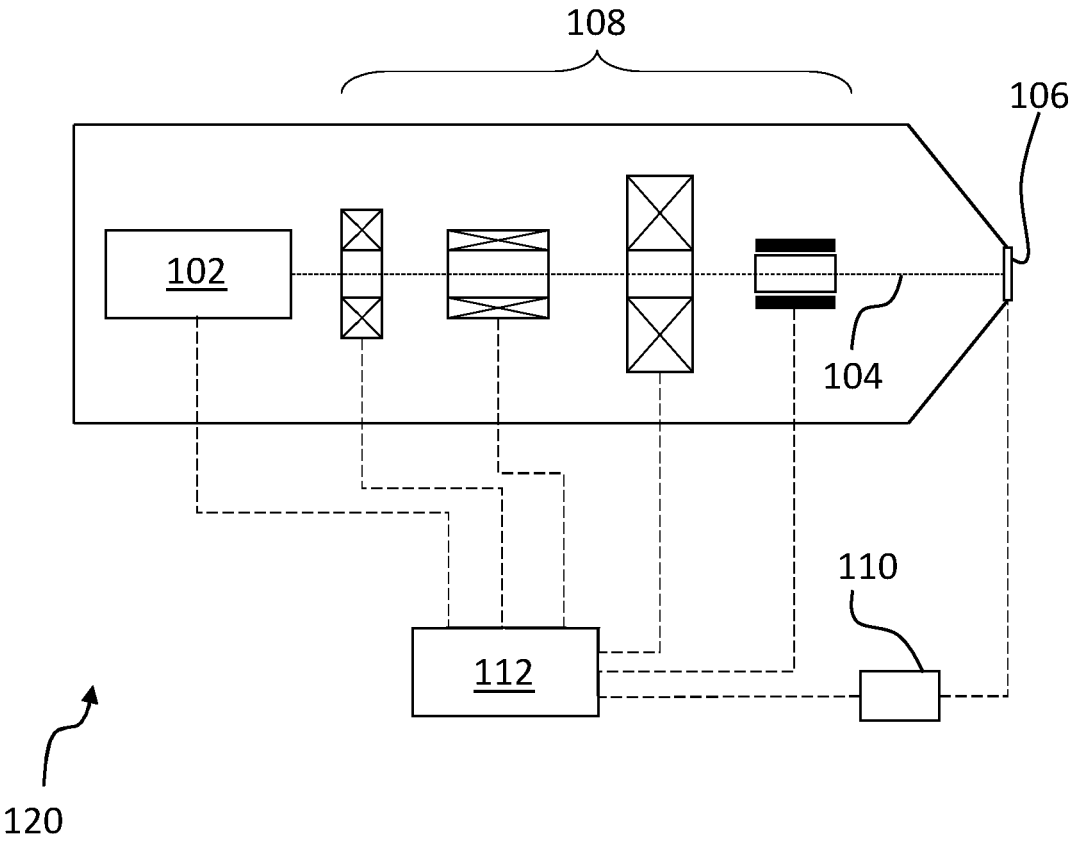


Fig. 12



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Application Number

EP 23 18 4066

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Place of search Munich		Date of completion of the search 30 November 2023	Examiner Giovanardi, Chiara
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