



- (51) International Patent Classification:
G01T 1/29 (2006.01) *G21K 1/00* (2006.01)
- (21) International Application Number:
PCT/US2012/032215
- (22) International Filing Date:
4 April 2012 (04.04.2012)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
61/471,279 4 April 2011 (04.04.2011) US
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- (81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: ANNULAR-ARRAY TYPE BEAM-POSITION MONITOR WITH SUB-MICRON RESOLUTION AND A PARAMETRIC METHOD FOR OPTIMIZING PHOTO DETECTORS

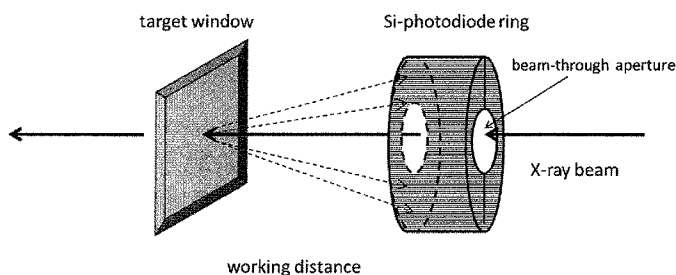


FIG. 2B

(57) Abstract: The present invention relates to the design and manufacture of devices for aligning beamline components and/or for real-time monitoring of an x-ray beam and/or a series of the beamline optical elements. More particularly, the present invention relates a novel annular-array type beam position monitor, an analytical method for designing and optimizing the beam position monitor in three dimensions, and a novel direct method for finding a beam centroid that enable sub-micron beam position sensitivity, high precision alignment and noise-free operation of the system.



TITLE**ANNULAR –ARRAY TYPE BEAM-POSITION MONITOR WITH SUB-MICRON
RESOLUTION AND A PARAMETRIC METHOD FOR OPTIMIZING PHOTO
DETECTORS**CROSS-REFERENCE TO A RELATED APPLICATION

[0001] This application claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application No. 61/471,279 filed on April 4, 2011, the content of which is incorporated herein in its entirety.

STATEMENT OF GOVERNMENT LICENSE RIGHTS

[0002] The present invention was made with government support under Grant No. DE-AC02-98CH10886 awarded by the U. S. Department of Energy (DOE). The United States government has certain rights in the invention.

BACKGROUND**I. FIELD OF THE INVENTION**

[0003] The present invention relates to the design and manufacture of a device for aligning beamline components and/or for real-time monitoring of a series of the beamline optics elements and/or the determination or monitoring of the x-ray beam position within the beamline. More particularly, the present invention relates to the design and manufacture of an annular–array type beam-position monitor that meets the stringent requirements for beam stability by significantly reducing the displacement- and angular-errors in the beam trajectory measurement.

II. BACKGROUND OF THE RELATED ART

[0004] Much of modern physical science is based on the understanding of matter at the atomic or molecular level of detail. Many forms of light (i.e. electromagnetic waves) have been developed as probes for acquiring the atomic and electronic structural information.

Synchrotron radiation is an example of such a structural tool. Synchrotron radiation is produced by accelerating charged particles (*e.g.* electron or proton) in particle accelerators and the synchrotron facilities are capable of generating radiation from visible, ultraviolet, and into the X-ray frequency portions of the spectrum. Compared to conventional light sources, synchrotron radiation is characterized by the properties of extremely high intensity and a high level of collimation at the sample target (*i.e.* high brilliance) which enables many experimental applications of light-matter interactions that would otherwise not be feasible. Once generated the light is conditioned by a beamline's particular optics to the desired characteristics necessary for experiments involving the interaction of radiation with matter. But prior to any experimental procedure it is imperative to know the position and direction of the incoming light beam. Without the knowledge of where the beam is positioned it becomes difficult to provide a consistent set of operating conditions for any experimental endeavor, especially where the sample is small. Minute beam fluctuations that may, for example, come from changes in magnet cooling water temperature, power supply instabilities and vibrations from sources outside the facility may cause changes in the photon flux and significantly reduce the efficiency of data acquisition. Therefore facilities throughout the world employ a variety of beam position monitors ("BPMs") to dynamically measure the centroid of the synchrotron radiation beam that is of interest to beamline users, *i.e.* the 1st moment of the Gaussian that approximates the central cone of the beamline source.

[0005] Briefly, the types of BPMs are: (1) fluorescent screens (Winick H., *World Scientific Publishing*, 1995, 256-257), (2) transition radiation monitors, (D. Xiang et al., *Phys. Rev. ST Accel. Beam*, **10**, 062801, 2007) (3) button or strip-line monitors, (F. Hinode et al., *Proceedings of Particle Accelerator Conference (PAC)* 1995) (4) flying wire, (S. Igarashi et al., *Nuclear Instruments and Methods A* 482(2):32-41, 2002), (5) split plate ionization chambers (Koyama, A., et al., *Rev. Sci. Instrum.* **60** 1989, 1953-1956; Schildkamp W. and

Pradervand, C., *Rev. Sci. Instrum.* **66**, 1995, 1956-1959), (6) filter/window combinations, (Bergonzo, P. et al., *J. Synchrotron Rad.* **6**, 1999, 1-5), and (7) blade type monitors. (Mortazavi, P. et al., *Nucl. Instrum. and Meth. A* **246** 1986, 389-393). Each is hereby incorporated herein by reference in its entirety. Billing, M. G. provides a thorough introduction to these types of beam position monitors (BPM) found within synchrotron facilities and discusses the advantages, disadvantages, and physical considerations undertaking in choosing a monitoring system. (Billing, M. G., *Nucl. Instrum. and Meth. A* **266**, 1988, 144-154, which is incorporated herein by reference in its entirety).

[0006] It is recognized in the art that what is generally needed is a position monitor that (1) causes little intensity perturbation downstream of its position, (2) is non-destructive to the synchrotron beam and (3) is suitable for continuous use. Moreover, it is necessary that the position monitor withstands high thermal loads and achieve submicron level spatial resolution while maintaining stability. By far the best possible means to accurately and precisely measure the synchrotron beam centroid is to terminate the beam. This can be accomplished either by terminating the synchrotron beam on a Cu or Ta block, or by intercepting the beam with an x-ray fluorescing screen. For either the block or the screen the x-ray fluorescence is detected by photodiodes, which records the changing intensity due to motions of the synchrotron beam on the block or screen. One example of such system is described in U.S. Patent No. 6,596,994 as shown in **FIG. 1**, the disclosure of which incorporated herein by reference in its entirety.

[0007] Therefore, it will be desirable to have a beam position monitor (BPM), and in particular an annular array-type beam position monitor, and a method of optimization of said beam position monitor that avoids the shortcomings of the prior art including inadequate spatial resolution and stability, the presence of small number of displacement- and angular-

errors in a radiation source that can degrade the end-station experiments, and a non-destructive intensity perturbation downstream of its position suitable for continuous use

SUMMARY OF THE INVENTION

[0008] Having recognized the shortcomings of the prior art, a novel annular-array type beam position monitor, an analytical method for designing and optimizing the beam position monitor in three dimensions, and a novel direct method for finding a beam centroid are provided that enables sub-micron beam position sensitivity, high precision alignment and noise-free operation of the system.

[0009] In particular, in one embodiment, a method is provided for positioning and optimizing a detector array and a fluorescent target in the annular-array type beam position monitor system by (1) determining an optimal working distance between the detector array and a secondary radiation target, (2) determining a radial displacement of the detector array from the center of the beam-through aperture on the annular photodetector array, (3) determining the optimal curvature of the array segments, (4) determining the optimal surface area of each photodetector segment, and (5) determining the widths and the radial displacement/position of the guard rings. This method can similarly be applied to BPM systems employing beams of electromagnetic radiation of frequencies other than X-rays, such as visible, and/or ultraviolet frequencies. This method can likewise be applied to BPM systems employing a target that emits secondary radiation in response to the incident radiation beam, *i.e.* a target that absorbs radiation of the incident beam frequency and re-emits incoherent, inelastically scattered, unpolarized, isotropic secondary radiation, such as fluorescence, luminescence, electrons or radiation emitted due to other secondary radiation mechanisms. There is no phase relation between the incident radiation and the secondary radiation. When the secondary radiation is electron radiation, the detector array may be composed of metallic elements.

[0010] In order to analytically determine the optimal configuration of the detector system, the given geometric configuration(s) must be fully parameterized. By exploring each parameter space within the parameterized analytical model of the system, an optimum working distance is determined and, thereby the secondary radiation target may be positioned appropriately for optimal performance.

[0011] In one embodiment, the model depends on the optimization of the total solid angle given by a parametric equation (11) exploring nine system dependent parameters

$$\Omega_{ring,tot,9} = \Omega_{tot,9}(\underbrace{\rho^*, \theta^*, z^*; \sigma_x, \sigma_y}_{\text{beam parameters (5)}}, \underbrace{\rho^-, \rho^+, \theta^+, \theta^-}_{\text{sensor parameters (4)}}) \quad (11)$$

[0012] These system dependent parameters include (1) radial positions and azimuthal angles ($\rho^+, \rho^-, \theta^+, \theta^-$) of each photodetector segment in the annular/polar array about the beam centroid, (2) a bi-Gaussian distribution (σ_x and σ_y are rms transverse beam sizes) of the beam centered around the beam centroid, although other multivariate non-Gaussian probability models of beam approximation are also envisioned and are available in the art, and (3) the coordinates (ρ^*, θ^*) of a flux of secondary radiation, *e.g.* fluorescence, at an axial working distance (z^*) from the plane of the annular array of the photodetectors.

[0013] To obtain an optimal working distance, a new solid angle, *i.e.*, a solid angle projected onto the flat sensor plane, may be calculated by multiplying the total solid angle by a projection factor. Subsequently, for pinning down the optimum position of a target, *i.e.*, the optimal working distance, the first-order derivatives ($d\Omega_{ring}/dz^*$) with respect to axial distance (z) may be calculated to find a local maximum. In one embodiment, an optimum working distance of the target from the annular/polar array may be determined by finding a zero-crossing.

[0014] According to another embodiment of the present invention, when the transverse beam sizes are on the order of tens of μm , or smaller, the point-source model may be used for the working-distance in the range of a few millimeters. The coordinates of a radiation source can be simplified with five parameters using the parametric equation (12):

$$\Omega_{ring,tot,5} = \Omega_{tot,5}(z^*; \rho^+, \rho^-, \theta^+, \theta^-) \quad (12)$$

[0015] This simplified model with a point source is valid only if the beam's dimensions are sufficiently smaller than the working distance of interest.

[0016] In another embodiment, a method is provided for determining the off-axis displacement of the inner radius of the detector, and the separation between the outer edge of the beam incident upon the target and the detector inner radius based on the calculated maximum spatial sensitivity. The method embodies a step of calculating *difference-over-sum* (Δ/Σ) as sweeping across the photodetector array along any transverse direction, as shown in Eqn. (15)

$$\frac{\Delta_{\Omega}}{\Sigma_{\Omega}} = \frac{\sum_{j=1}^n (\Omega_{n/2-j+1} - \Omega_j)}{\sum_{j=1}^{n/2} \Omega_j} \quad (15);$$

where the solid angle Ω_j is a function of a radial position and azimuthal angle ($\rho^+, \rho^-, \theta^+, \theta^-$) of each photodetector segment (j) in the annular/polar array about the beam centroid. The method further embodies the steps of calculating an absolute value of the slope in a *difference-over-sum* (Δ/Σ) which provides for a maximum spatial sensitivity in the transverse plane along the longitudinal axis of the beam. In other words, by varying the number of segments, their radial position and azimuthal angle, the highest value of the slope in a *difference-over-sum* (Δ/Σ) calculation provides for a maximum spatial sensitivity in the transverse plane along the longitudinal axis of the beam and the optimal axial displacement

(radial position, ρ) of the sensor segment in an annular sensor array along the transverse plane may be determined.

[0017] Once rms transverse beam sizes (σ_x and σ_y) of a beam centered around the beam centroid is known, the radius of a beam-through aperture in one embodiment is made large enough to accommodate the entire beam profile, *e.g.* a Gaussian distribution. Hence, the outer edge of an incident beam may not be intercepted by the aperture rim.

[0018] In another embodiment, a method is provided for optimizing the surface area of an annular detector array. The method embodies the step of calculating a surface area of the sensor segment in the annular photodetector array and the radial dimensions of the array by solving equation (13).

$$\begin{aligned}\Sigma_{pad} &= \frac{1}{2}\theta_s \Sigma_p \Delta_p = \frac{1}{2}\theta_s (\rho_+ + \rho_-)(\rho_+ - \rho_-) \\ &= \frac{1}{2}\theta_s \Delta_p (2\rho_- + \Delta_p)\end{aligned}\tag{13}$$

The method further embodies the step of optimizing the segment surface area and the radial dimensions of the annular photodetector array based on the capacitance matching. Optimizing the capacitance of each segment is achieved by adjusting radial positions (ρ_- and ρ_+) according to equation (13). The azimuthal angle (Θ_s) is constrained by the total number of sensor array segments.

[0019] In yet another embodiment, a method is provided for optimizing the curvature of the surface of an annular detector array in a BPM in order to maximize photodetector light collection efficiency. The method includes the steps of calculating the total solid angle and the optimal working distance. The calculated total solid angle describes the curved surface of a portion of a sphere having a radius equal to the optimal working distance and centered at the beam target intercept. The sphere of optimum radius defines the optimal curvature of the

photodetector array. Therefore, no projection factor, or a projection factor essentially equal to unity, is used to modify the curved surface described by the sphere of optimum radius because the photodetectors are designed to be aligned or coincide with the curved surface.

[0020] In yet another embodiment, a method for finding a beam centroid based on fitting data points representing photon counts registered at each of the photodetector segments is provided. In one embodiment, the segment-by-segment display of photon counts is fitted with a sinusoidal function. The amplitude of the sinusoidal function is a radial offset and its phase is a polar angle, which then can be converted to Cartesian coordinates of the beam centroid.

[0021] Various modifications of these methods, as well as a variety of uses in different applications, will be readily apparent to those skilled in the art, and the general principles, defined herein, may be applied to a wide range of embodiments. The optimization methods may be used to design a novel BPM system.

[0022] In one embodiment, the beam position monitor comprises a plurality of sensor segments that are sensitive to electromagnetic radiation and which are positioned in an annular array. This embodiment may also include a radiation target separated from the array of sensors by a working distance. To accurately and precisely measure the radiation beam centroid, *e.g.* the centroid of a synchrotron X-ray beam, the beam is intercepted by the target, preferably having a transmission rate of more than 90%. The remaining radiation is absorbed and re-emitted by the target. When absorption of an incident photon causes an electron in the target material to be elevated to a higher shell and then fall back down, a photon of energy equal to the difference of the two shells is emitted. In one embodiment, the backscattered photons can illuminate the annular array of photodetectors isotropically. Subsequently, an

electronic readout circuit counts photons from each of a plurality of segments, which record the varying intensities due to motions of the beam on the target surface.

[0023] The objectives, features and advantages of the present invention will be apparent from the following detailed description of the invention, which is to be read in conjunction with the accompanying drawings. The scope of the invention will be pointed out in the claims. The following drawings, taken in conjunction with the subsequent description, are presented to enable one of ordinary skill in the art to make and use the invention and to incorporate it in the context of particular applications.

[0024] Various modifications, as well as a variety of uses in different applications, will be readily apparent to those skilled in the art, and the general principles, defined herein, may be applied to a wide range of embodiments. Thus, the present invention is not intended to be limited to the embodiments presented, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein. Furthermore, it should be noted that unless explicitly stated otherwise, the figures included herein are illustrated schematically and without any specific scale, as they are provided as qualitative illustrations of the concept of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] **FIG. 1** illustrates a fluorescent screen based beam position monitor disclosed in Alkire, R. W. et al., 1997.

[0026] **FIG. 2A** illustrates an exemplary schematic of a beamline layout including a photon shutter, Beryllium (Be) windows, slits, double crystal monochromator (DCM), and a monochromatic fluorescent X-ray beam position monitor

[0027] FIG. 2B illustrates a conceptual schematic diagram showing a ring-array photodetectors and a fluorescent thin film as in FIG. 2A and the backward-scattering mode of operations of the ring array in relationship to the working distance.

[0028] FIG. 2C illustrates an AutoCAD drawing of a ring array of 32-segmented photodetectors, *e.g.*, Si PIN-junction photodiodes, with the upper and lower radial positions of 4.1088 mm and 2.5625 mm, respectively.

[0029] FIG. 2D illustrates a single photodetector segment of the ring array shown in FIG. 2A.

[0030] FIG. 3 illustrates a diagram of a solid angle that a differential surface area ($d\Sigma$) subtends at a source of radiation, P^* and the projection angle Ψ .

[0031] FIG. 4 illustrates a plot of a projection factor versus a working distance for the ring array with 32 photodetector segments and the upper and lower radial positions of 4.1088 mm and 2.5628 mm, respectively.

[0032] FIG. 5 illustrates an exemplary plot of a five-point Gaussian beam profile.

[0033] FIG. 6A illustrates a profile of total solid angles versus a working distance for an exemplary annular-array BPM. The upper trace indicates the projected total solid angle ($\Omega_{\text{tot,proj}}$) and the lower trace indicates the non-projected total solid angle (Ω_{tot}).

[0034] FIG. 6B illustrates a plot of the first order derivatives with respect to axial distance (z) of the profiles shown in FIG. 6A to determine the optimum working distances from the gradient of the total solid angle.

[0035] FIG. 7A illustrates a solid angle variations as a function of working distance for different beam sizes on linear-linear scale. The traces correspond to transverse beam sizes of 2 mm, 1 mm, 0.5 mm, 100 μm , 10 μm , 1 μm , and 0.5 μm , respectively.

[0036] FIG. 7B illustrates a solid angle variations as a function of working distance for different beam sizes of FIG. 7A on linear-log scale.

[0037] FIG. 8 illustrates a plot of a projected solid angle seen by a point-source beam and a Gaussian beam for the ring array of FIG. 2C.

[0038] FIG. 9 is a block diagram illustrating the optimization algorithm.

[0039] FIG. 10 illustrates a plot of peak projected total solid angles versus lower radial position of sensor segment. The peak solid angle of the photodetector sensor of FIG. 2C is denoted as Prototype I. The closer the radial position of a sensor segment is brought to a beam axis, the higher the peak solid angle is.

[0040] FIG. 11 illustrates a schematic of the beam position monitor with a virtual sphere where the optimal working distance is the radius of the virtual sphere.

[0041] FIG. 12 illustrates a schematic of a cross-sectional view of the Si-PIN junction photodiode and the target film.

[0042] FIG. 13A illustrates a design schematics of a photodetector sensor with 32-segmented Si PIN-junction photodiodes with surface area of each segment set at about 1.0 mm^2 and the upper and lower radial positions of 4.109 mm and 2.563 mm respectively.

[0043] FIG. 13B illustrates a design schematics of a photodetector sensor with 64-segmented Si PIN-junction photodiodes with surface area of each segment set at about 0.44 mm^2 and the upper and lower radial positions of 4.109 mm and 2.563 mm respectively.

[0044] FIG. 14A illustrates an exemplary annular array of multi-segmented photodetectors implemented on the electronic readout circuit with a single ASIC chip wire-bonded to the photodetector array.

[0045] FIG. 14B illustrates an exemplary annular array of multi-segmented photodetectors implemented on the electronic readout circuit with a double-ASIC chip wire-bonded to the photodetector array.

[0046] FIG. 15 illustrates an I-V characteristic curve.

[0047] FIG. 16 illustrates a C-V characteristic curve.

[0048] FIG. 17 illustrates plots of simulated $K_{\alpha 1}$ -absorption edge profiles for Co, Cr, Fe, and Mn.

[0049] FIG. 18 illustrates a plot of the first order derivatives with respect to axial distance (z) of the total solid angles for a system shown in FIG. 13B.

[0050] FIG. 19 illustrates a plot of difference-over-sum against transverse position for the photodetector sensor in comparison to that of quadrant X-ray BPM design.

[0051] FIG. 20 illustrates the method of finding a beam centroid by fitting the intensities using a sinusoidal fit function (exemplary sinusoidal plot of the intensity representing photon counts is shown).

[0052] FIG. 21 illustrates a sinusoidal plot of the intensity representing photon counts of 2,000 per second (A), 20,000 per second (B), or 200,000 per second (C) registered at each of the photodetector segments as a function of segment location on the annular array.

DETAILED DESCRIPTION OF THE INVENTION

[0053] The beam position monitor (BPM) comprises a plurality of electromagnetic radiation sensitive detector segments positioned in an annular array and a radiation target, separated from each other by a working distance. The detector segments may be sensitive to various forms of electromagnetic radiation, specifically including radiation generated by a synchrotron source such as visible, ultraviolet, and X-ray radiation in preferred embodiments.

The target of the beam position monitor may absorb frequencies of the incident radiation beam and re-emit secondary radiation, e.g. fluorescence, luminescence, or electrons, in response to intercepting the beam of radiation. The BPM may serve as a diagnostic device for aligning beamline components and for real-time monitoring of a series of the instantaneous beam positions. When the secondary radiation is electron radiation, the detector array may be composed of metallic elements.

[0054] An exemplary beamline layout, including a BPM and optical components is provided in **FIG. 2A**. It will be appreciated by those skilled in the art that to accurately and precisely measure the radiation beam centroid, e.g. the centroid of a synchrotron beam, the beam can be intercepted by a target, having a transmission rate sufficient to allow the majority of radiation to pass through. In one embodiment, the sufficient transmission rate is greater than 80%, with the transmission rate of greater than 90% being more preferred. The remaining radiation is absorbed and re-emitted by the target. When absorption of an incident photon causes an electron in the target film to be elevated to a higher atomic shell, this creates vacancies in the outer electron shells of the target material atoms. When the excited electrons fall back into the vacancies, a photon of energy equal to the difference of the two shells is emitted. This re-emitted photon may be imaged by photodetectors which record the changing intensity due to motions of the synchrotron beam on the screen.

[0055] In accordance with one embodiment of present invention as illustrated in **FIG. 9**, a novel method(s) is (are) provided for designing and optimizing a beam position monitor with an annular array configuration, e.g., a fluorescent-type X-ray beam-position monitor (XBPM), based on full parameterization of a peak solid angle projection at the detector. In another embodiment, a novel beam-position monitor is provided that utilizes an annular array of PIN-junction photodiodes. However, it is also envisioned that other annular, polygonal, rhombic oval or similar geometric shape configurations of photodetectors may be applied

depending on the requirements of the overall system, the beamline layout, and/or the requirement of the end user. In yet another embodiment, a method for finding a beam centroid based on fitting data points representing photon counts registered at each photodetector segment with a sinusoidal function is provided.

I. Method for Optimization of Photodetector Geometry

(a) Working Distance

[0056] In one embodiment of the present invention, by exploring each parameter space within the parametric analytical modeling of the system, an optimum working distance (z^*_{opt}) for transverse beam sizes ($\sigma_{\perp}$) of interest can be determined and, thereby set the limits on transverse beam sizes for the specific dimensions (Σ_{detector}) of the sensor in use.

[0057] FIG. 3 depicts a solid angle (Ω) that an infinitesimal surface area ($d\Sigma$) on a photodetector segment subtends at a source of fluorescence radiation. (DeCusatis, C., Handbook of Applied Photometry, AIP Press, New York, 1997; incorporated herein by reference in its entirety). A line-of-sight vector ($\vec{r}$) points to a differential surface area ($d\Sigma$) from a target source (P^*), such as a source of fluorescent radiation. The angle of θ results from a unit vector ($\hat{n}$) normal to a planar detector ring and the line-of-sight vector ($\vec{r}$). In this scenario, $P_d(x,y,z)$ denotes the Cartesian coordinates of a photodetector, *e.g.*, a Si PIN-junction photodiode, surface-area element ($d\Sigma$), and $P^*(x^*,y^*,z^*)$ denotes the coordinates of a source of target radiation. As illustrated in FIG. 3, a sphere centered at this target source (P^*) may be drawn. The solid angle may be defined as a surface area (*physical area*), normalized by the square of the radius ($\vec{r}^2$).

[0058] In one particular embodiment, an appropriate choice for the ring geometry of the photodetector array and a target may be the cylindrical coordinate system. First, a line-of-sight vector ($\vec{r}$) pointing to a surface element from a target source is defined. The line-

of-sight vector ($\vec{r}$) can be defined in terms of ρ , which denotes the radial coordinate component either in the cylindrical coordinates or in the polar coordinates (1):

$$r = |\vec{r}| = \sqrt{(\Delta\rho)^2 + (\rho\Delta\theta)^2 + (\Delta z)^2} \quad (1)$$

where $\Delta\rho \equiv \rho - \rho^*$, $\Delta\theta \equiv \theta - \theta^*$, and $\Delta z \equiv -z^*$. The differential solid angle ($d\Omega_{ring}$) in the cylindrical coordinates can be defined as (2):

$$d\Omega_{ring} = \frac{\vec{r} \cdot \hat{n}}{r^3} d\Sigma = \frac{\vec{r} \cdot \hat{n}}{r^2} d\Sigma = \frac{\cos\theta}{r^2} d\Sigma = \frac{z^*}{r^3} \rho d\rho d\theta \quad (2)$$

[0059] The n-parameter solid angle $\Omega_{ring,n}$ for applying to the ring geometry is derived in Eqn. (3):

$$\begin{aligned} \Omega_{ring} &= \iint d\Omega_{ring} = z^* \iint \frac{\rho d\rho d\theta}{r^3} \\ &= \int d\theta \int \underbrace{\frac{z^* \rho d\rho}{\left(\sqrt{(\Delta\rho)^2 + (\rho\Delta\theta)^2 + (\Delta z)^2} \right)^3}}_{I_\rho} \end{aligned} \quad (3)$$

[0060] The parameter I_ρ , defined in Eqn. (3), can be calculated according to Eqn. (4):

$$\begin{aligned} I_\rho &\equiv z^* \int_{\rho^-}^{\rho^+} d\rho \rho \left\{ (\Delta\rho)^2 + (\rho\Delta\theta)^2 + (\Delta z)^2 \right\}^{-3/2} \\ &= \left| \frac{z^* (\rho^* \Delta\rho - \Delta z^2)}{\left[\rho^{*2} (\Delta\theta)^2 + z^{*2} \{1 + (\Delta\theta)^2\} \right]} - \frac{1}{\sqrt{(\Delta\rho)^2 + \rho^2 (\Delta\theta)^2 + (\Delta z^*)^2}} \right|_{\rho^-}^{\rho^+} \\ &= I_{\rho^+} - I_{\rho^-} \end{aligned} \quad (4)$$

in which ρ^+ and ρ^- , respectively, represent the upper and lower radial positions of each photodetector segment. By substituting Eqn. (3) with Eqn. (4), a solid angle (Ω_{ring}) for a ring configuration as a function of the fluorescent-source coordinates in the cylindrical coordinates is defined (5):

$$I_{\rho\theta} = \int I_{\rho} d\theta = -\arctan \left[\frac{\Delta\theta(\rho^{*2} - (\rho^* \rho) + z^{*2})}{z^* \sqrt{(\Delta\rho)^2 + (\rho\Delta\theta)^2 + z^{*2}}} \right] \quad (5)$$

in which $\Delta\rho^{\pm} = \rho^{\pm} - \rho^*$ and $\Delta\theta^{\pm} = \theta^{\pm} - \theta^*$.

[0061] Employing these shorthand notations, a fully parameterized solid angle $\Omega_{ring,7}$ for a generalized point source beam may be defined as follows (6):

$$\begin{aligned} \Omega_{ring} &= \Omega_{ring,7} \underbrace{(\rho^*, \theta^*, z^*)}_{\text{beam parameters (3)}}; \underbrace{(\rho^+, \rho^-, \theta^+, \theta^-)}_{\text{sensor parameters (4)}} \\ &= \int_{\theta^-}^{\theta^+} d\theta \{ I_{\rho^+} - I_{\rho^-} \} \\ &= \left\{ -\arctan \left[\frac{\Delta\theta^+ (\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^+)^2 + z^{*2}}} \right] + \arctan \left[\frac{\Delta\theta^- (\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^-)^2 + z^{*2}}} \right] \right. \\ &\quad \left. + \arctan \left[\frac{\Delta\theta^+ (\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^+)^2 + z^{*2}}} \right] - \arctan \left[\frac{\Delta\theta^- (\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^-)^2 + z^{*2}}} \right] \right\} \quad (6) \end{aligned}$$

[0062] To obtain a new solid angle that is projected on to the flat sensor plane ($z = 0$), *i.e.*, projected solid angle ($\Omega_{ring,n,prj}$), the calculated above solid angle ($\Omega_{ring,n}$) is multiplied by a projection factor ($P(\psi)$) to obtain (7):

$$\Omega_{ring,n,prj} = P(\psi) \Omega_{ring,n} \quad (7)$$

$$P(\psi) = \cos\psi, \psi = \arctan[(\rho^+ + \rho^-)/(2 \cdot z^*)]$$

[0063] As illustrated in **FIG. 4**, in one particular embodiment, as a function of the working distance, the projection factor scales substantially down as the function of the working distance below a certain threshold, *e.g.*, ~5.0 mm, whereas at substantially long working distances, the projection factor is close to unity.

[0064] Next, for illustrative purposes, the profile of a Gaussian beam, *e.g.*, five-point, may be selected from 95%- and 68%-confidence levels and defined (8).

$$y(x^*) = G(x_0, \sigma_x; x^*) = \exp(-(x - x_0)^2 / (2\sigma_x)^2) \quad (8)$$

with x_0 and σ_x , respectively, being the horizontal position of a beam centroid and rms beam size, respectively. An ideal Gaussian distribution is symmetric around a beam centroid with no skewness. Hence, the selected five points are sufficient to represent an entire Gaussian distribution, as shown in **FIG. 5**. Although if the beam has skewness, the Gaussian distribution is not ideal and more than five points, *e.g.*, 6, 7, 8 . . . 100, may be required to represent the entire Gaussian distribution. In another embodiment, other multivariate non-Gaussian probability models of beam approximation may be used to define the distribution of the beam centered around the beam centroid.

[0065] Having found the Cartesian coordinates of the five points, using Eqn. (9), these coordinates can be converted to polar coordinates for substituting into Eqn. (7):

$$\left. \begin{aligned} \rho_G^* &= \sqrt{(x^*)^2 + (y^*)^2} = \sqrt{(x^*)^2 + G^2(x^*)^2} \\ \theta_G^* &= \arctan(y^* / x^*) = \arctan(G(x^*) / x^*) \end{aligned} \right\} \quad (9)$$

[0066] After summing up the solid angles subtended at each of five points from the Gaussian profile, the sum may be averaged over the number of points (N_G), and then multiply it by the number of pads/segments (N_{pad}). Accordingly, a total solid angle ($\Omega_{ring,tot,G}$) subtended by the secondary, *e.g.*, fluorescent, radiation of Gaussian profile with a certain beam size (σ_x or σ_y) is obtained (10):

$$\Omega_{ring,tot,G,prj} = \frac{N_{pad}}{N_G} \sum_{i=1}^{N_G} \Omega_{ring,i,G,prj} \quad (10)$$

where i and G denote the point index and Gaussian, respectively. In this way, an effective sensor area seen by the distribution of an entire Gaussian beam is computed analytically.

Consequently, the Eqn. (7) can be expanded with up to 9 parameters, including the dimensions of a Gaussian beam:

$$\begin{aligned}
 \Omega_{ring,tot,9} &= \Omega_{tot,9}(\underbrace{\rho^*, \theta^*, z^*; \sigma_x, \sigma_y}_{\text{beam parameters (5)}}, \underbrace{\rho^+, \rho^-, \theta^+, \theta^-}_{\text{sensor parameters (4)}}) \\
 &= -\arctan\left[\frac{\Delta\theta^+(\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^+)^2 + z^{*2}}}\right] + \arctan\left[\frac{\Delta\theta^-(\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^-)^2 + z^{*2}}}\right] \\
 &\quad + \arctan\left[\frac{\Delta\theta^+(\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^+)^2 + z^{*2}}}\right] - \arctan\left[\frac{\Delta\theta^-(\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^-)^2 + z^{*2}}}\right]
 \end{aligned} \tag{11}$$

[0067] Subsequently, using Eqn. (11), the influence of beam sizes on the solid-angle calculation can be investigated. For pinning down the optimum position, *i.e.*, the optimal working distance, the first-order derivatives ($d\Omega_{ring}/dz^*$) with respect to axial distance (z) may be calculated and zero-crossing provides for the optimal working distance in the position monitor of interest. The example set forth below also serves to provide further appreciation of the invention but is not meant in any way to restrict the scope of the invention.

(b) Working Distance - Point-Source Model

[0068] According to another embodiment of the present invention, for an *on-axis* beam, the coordinates of a fluorescent-source can be simplified with five parameters, *i.e.*, $\Delta\rho \equiv \rho^\pm$ and $\Delta\theta \equiv \theta^\pm$. Hence, the following parametric equation is obtained:

$$\begin{aligned}
 \Omega_{ring,tot,5} &= \Omega_{tot,5}(z^*; \rho^+, \rho^-, \theta^+, \theta^-) \\
 &= -\arctan\left[\frac{\theta^+ z^*}{\sqrt{(\rho^+)^2 + (\rho^+ \theta^+)^2 + z^{*2}}}\right] + \arctan\left[\frac{\theta^- z^*}{\sqrt{(\rho^-)^2 + (\rho^- \theta^-)^2 + z^{*2}}}\right] \\
 &\quad + \arctan\left[\frac{\theta^+ z^*}{\sqrt{(\rho^-)^2 + (\rho^- \theta^+)^2 + z^{*2}}}\right] - \arctan\left[\frac{\theta^- z^*}{\sqrt{(\rho^+)^2 + (\rho^+ \theta^-)^2 + z^{*2}}}\right]
 \end{aligned} \tag{12}$$

[0069] Using the odd identity of the arctan function, *i.e.*, $\arctan(-\theta) = -\arctan(\theta)$, Eqn.

(12) can be reduced to Eqn. (13) below:

$$\Omega_{ring, tot, 3} = \Omega_{tot, 3}(z^*; \rho^+, \rho^-, \theta^+)$$

$$= 2 \left(\arctan \left[\frac{\theta^+ z^*}{\sqrt{(\rho^-)^2 + (\rho^- \theta^+)^2 + z^{*2}}} \right] - \arctan \left[\frac{\theta^+ z^*}{\sqrt{(\rho^+)^2 + (\rho^+ \theta^+)^2 + z^{*2}}} \right] \right) \quad (13)$$

[0070] However, this simplified model with a point source is valid only if the beam's transverse dimensions are sufficiently smaller than the working distance of interest:

$$\frac{\sigma_x \sigma_y}{|\vec{r}|^2} \ll 1 \quad (14)$$

[0071] This condition implies that the point-source model is valid for the working-distance range of a few millimeters, only when the transverse beam sizes are on the order of tens of μm , or smaller. Otherwise, the beam is sizable from the sensor's standpoint. The example set forth below also serve to provide further appreciation of the invention but is not meant in any way to restrict the scope of the invention.

(c) Surface Area

[0072] In another embodiment, a method is provided for optimizing the surface area of an annular detector array in a beam position monitor of interest, *e.g.*, XBPM. The method embodies the steps of calculating a surface area of the sensor segment in the annular photodetector array and the radial dimensions of the array by solving equation (15)

$$\Sigma_{pad} = \frac{1}{2} \theta_s \Sigma_p \Delta_p = \frac{1}{2} \theta_s (\rho_+ + \rho_-)(\rho_+ - \rho_-)$$

$$= \frac{1}{2} \theta_s \Delta_p (2\rho_- + \Delta\rho) \quad (15)$$

where ρ^+ and ρ^- , respectively, represent the upper and lower radial positions of each photodetector segment. The segment surface area and the radial dimensions of the annular photodetector array may be optimized based on the calculated optimal working distance and the total solid angle of each segment. In particular, since the effective area seen by a beam with certain dimensions (*e.g.*, 0.5 mm) is reduced due to an optimization of the working distance, the surface area of each segment may be reduced without sacrificing the sensitivity of the beam position monitor by varying the upper and lower radial positions of each photodetector segment, which in turn will affect the projection factor and the resulting total projected solid angle.

(d) Radial Displacement

[0073] In some embodiments, the parameterized analytical model of the beam position monitor used to calculate the solid angle may also be used to explore the correlation between the solid angle and the radial positions of the photodetector segments where the optimal working distance is held constant. As shown in **FIG. 10**, the peak solid angles ($\hat{\Omega}$) for one exemplary system with 32 segments, a constant surface area and beam size, exponentially increase as the position of each segment gets closer to the beam axis. In comparison to the peak solid angle ($\hat{\Omega}_1$) calculated in Example 1, the predicted gains of peak solid angle over at each lower radial position is indicated in **FIG. 10**.

(e) Photodetector Calibration

[0074] Typically, calibration of the photodetector array response versus beam position may be determined by using a technique referred to as the difference over the sum. For example, a calibration of the beam in one particular direction, *e.g.*, 0° , may be computed by subtracting the photodetector signal in the segment in this location from the photodetector signal in the counterpart segment on the opposite side of the annular array, *e.g.*, 180° , then

dividing by their sum. Essentially, in a system with 32 segments and with independent readouts, 16 separate directions may be monitored simultaneously. Alternatively, in a system with 64 segments, 32 separate directions may be monitored simultaneously.

(f) Spatial Sensitivity

[0075] Calculation of *difference-over-sum* (Δ/Σ) as sweeping along either of the two transverse directions (x, or y) may also be used to determine the spatial sensitivity of the photodetector array. Exploiting symmetric property in geometrical configuration of an annular photo array, each individual segment in the *difference-over-sum* can be incorporated in the calculation as shown in Eqn. (16) for an exemplary system with 32 segments:

$$\begin{aligned} \frac{\Delta_{\Omega}}{\Sigma_{\Omega}} &= \frac{\{(\Omega_{16} - \Omega_1) + (\Omega_{15} - \Omega_2) + \dots + (\Omega_9 - \Omega_8)\} + \{(\Omega_{17} - \Omega_{32}) + (\Omega_{18} - \Omega_{31}) + \dots + (\Omega_{24} - \Omega_{25})\}}{\Omega_1 + \Omega_2 + \Omega_3 + \dots + \Omega_{31} + \Omega_{32}} \\ &= \frac{\sum_{j=1}^8 (\Omega_{17-j} - \Omega_j) + \sum_{k=17}^{24} (\Omega_k - \Omega_{49-k})}{\sum_{j=1}^{32} \Omega_j} \end{aligned} \quad (16)$$

[0076] Because of the symmetry around the scanning axis, the segments in one half of the annular array have the same solid angle as the counterparts in another half of the annular array. Therefore, the *difference-over-sum* calculation shown in Eqn. (16) can be simplified to Eqn. (17)

$$\frac{\Delta_{\Omega}}{\Sigma_{\Omega}} = \frac{\sum_{j=1}^n (\Omega_{n/2-j+1} - \Omega_j)}{\sum_{j=1}^{n/2} \Omega_j} \quad (17)$$

[0077] The *difference-over-sum* calculation describes the sensitivity of photon counts detected at two counterpart photodetector segments symmetric around the reflection axis (y, or x axis) while an X-ray beam is stepping across a transverse direction (either x, or y). The difference in photon counts detected at two segments are more distinct and pronounced, while the total sum (Σ_{Ω}) of the photon counts registered at all of photodetector segments, *e.g.*, 32,

64, etc., is preserved and used as a normalization factor. Since the difference/sum is a normalized signal, it is inherently independent of beam intensity and photon energy. In addition, because the entire beam is used in the measurement, the true center-of-mass is measured. The slope of *difference-over-sum* curve may be used as an indirect measure of position sensitivity of the photodetector. As shown in **FIG. 15**, as a beam approaches to each end, the sensitivity curve converges to an upper- and a lower-bound value. In other words, according to this method the photodetectors should be positioned within the linear regions of the slope to achieve the highest spatial sensitivity.

(g) Curvature

[0078] In yet another embodiment, a method is provided for optimizing the curvature of the surface of an annular detector array in a BPM in order to maximize photodetector light collection efficiency. The method includes the steps of calculating the total solid angle and the optimal working distance. The calculated total solid angle describes the curved surface of a portion of a sphere having a radius equal to the optimal working distance and centered at the beam target intercept. The sphere of optimum radius defines the optimal curvature of the photodetector array as shown in **FIG. 11**. Therefore, because the projection factor is essentially equal to unity, it can be ignored and not used to modify the curved surface described by the sphere of optimum radius because the photodetectors are designed to be aligned or closely coincide with the curved surface.

[0079] A detector array of any curvature between the disclosed planar annular detector array and an annular detector array of optimal curvature will improve photodetector light collection efficiency over the planar configuration. Even a detector array with a surface curvature defined by a sphere having a radius less than the working distance of the sphere of

optimum radius by not more than 5 percent could theoretically give improved photodetector collection efficiency over the planar configuration.

[0080] In some practical implementations, each detector segment can be aligned to coincide with a plane tangent to the surface of the sphere of optimum radius to approximate a spherical detector surface. In other practical implementations, each detector segment can be aligned to be parallel to a plane tangent to the surface of the sphere of optimum radius, where the center of the detector segment dips below the tangent point of the surface of the sphere of optimum radius by some distance with the edges of each detector segment lying some distance above the surface.

[0081] In the embodiments where the detector array approximates a spherical surface, the detector segments of the array may comprise isometric polygons, *e.g.* an array of isosceles triangles, an array of isometric rhombuses, an array of interspersed isometric pentagons and hexagons, or any other array configuration of isometric polygons forming an approximate spherical surface. Alternatively, the detector segments may have essentially the same shape as those depicted in **FIG. 2D**, but rather than comprising a planar detector the outer radius of the detector array may be tilted towards the target, such that the surface of the detector segments coincide with respective planes tangent to the spherical surface defined by the total solid angle. Each tangent point representing the intersection of the surface of a detector segment with the spherical surface defined by the total solid angle would lie on a circle. In a preferred embodiment, the tangent points would represent the intersection of the spherical surface of the total solid angle with the center of each respective detector segment.

II. Photodetector Design

[0082] In another embodiment of the present invention, the beam position monitor may comprise a plurality of radiation sensitive segments positioned in an annular array and a

radiation target separated from the plurality of radiation sensitive segments by a working distance. The radiation sensitive photodetector segments may be specifically tuned to be responsive to particular frequencies emitted from the target materials when it intercepts the beam of, for example, synchrotron radiation. This assembly may serve as a diagnostic device for aligning beamline components and for real-time monitoring of the instantaneous photon beam position.

[0083] FIG. 12 depicts a schematic of an exemplary photodetector array, *e.g.* an annular array of photodiodes, in relation to the target film, *e.g.* a target film that re-emits secondary radiation upon intercepting the incident radiation beam. In various embodiments, the optimal spectral sensitivity of the photodetector array can be tuned to visible, ultraviolet, or X-ray frequencies. In certain embodiments, the target film can provide fluorescent back-scattering from 4 to 8 keV to the photodetector array when illuminated by an incident X-ray beam. The photodetector array may comprise any number of PIN diodes such as 32 (see FIG. 13A) or 64 (see FIG. 13B) PIN diodes, *e.g.*, Si-PIN-junction diodes, positioned in annular conformation (*e.g.*, “doughnut”) around a beam-through aperture at the center. However, other permutations of PIN diodes in an annular array are also envisioned, and the number depends on the desired efficiency and available resources. Accordingly, in some embodiments, the number of photodiode segments may be constrained by an integer multiple of the number of channels on the circuitry directly connected to the annular photodetector array. For example, HERMES4 ASIC chips have 32 available channels (see FIG. 14A). Hence, in this particular embodiment, the photodetector ring may be designed and fabricated to have a multiple of 32 as the number of segments, *e.g.*, 32, 64, 96, etc.

[0084] Due to a monolithic structure, the photodetectors can be precisely and contiguously positioned to form an unbroken ring structure and each of the photodetector segments can be wire-bonded to each of the ASIC channels on the readout circuit as shown,

for example, in **FIG. 14A**. For instance, in a photodetector array in one embodiment with 32 segments, each segment is about 0.192 radian wide ($\sim 11^\circ$) as shown in **FIG. 13A**. In a photodetector array in another embodiment with 64 segments, each segment is 0.096 radian wide ($\sim 5.5^\circ$) as shown in **FIG. 13B**. In these embodiments, all the segments have the same size regardless of their position within the annular array. However, the size of each photodetector segment may vary depending on the specific model chosen. For example, in one embodiment, the photodetector array may incorporate the photodetector segments of two or more width profiles. In other embodiments, the photodetector array may also incorporate multiple concentric rings of annular photodetector arrays, wherein the inner radius of one ring is greater than the outer radius of another ring. In other embodiments the multiple concentric rings of annular photodetector arrays may have the same number of photodetector segments or the different rings may have different numbers of photodetector segments. In still further embodiments, the multiple concentric rings of photodetector segments may be angled so as to be aligned or to coincide with the curved surface of the peak solid angle as closely as possible.

[0085] In one embodiment, the photodetector array is curved as shown in **FIG. 11**. A virtual sphere of a radius of the optimum distance that may range from 2 mm to 10 mm is drawn from the target. It is envisioned that the photon-detection efficiency should be enhanced if the annular-array photodetector segments are embedded on the curved surface whose curvature radius closely matches the radius of the optimum sphere. In one embodiment, the radius of the virtual sphere is about 3 mm and the photodetector segments lie on the curvature of the sphere.

[0086] The area size of photodetector segment in the beam position monitor depends on the number of segments in the array and the upper and lower radial positions, which in turn depend on the rms size of the beam. In one embodiment, the lower radial position may

range from about 1 mm to about 3 mm, whereas the upper radial position may range from about 3.5 mm to about 6 mm. Preferably, the lower radial position may range from about 2 mm to about 3 mm, whereas the upper radial position may range from about 4 mm to about 5 mm. More preferably, the lower radial position is about 2.5 mm and the upper radial position is about 4.1 mm. In one embodiment, the surface area of the photodetector segment is set to a value to match the capacitance of the readout electronics. Depending on the combination of the upper and lower position and the number of segments within the array in light of the matched capacitance of the readout electronics, the surface area of each segment may range from about 0.2 mm^2 to about 2.0 mm^2 with a range of about 0.3 mm^2 to 0.6 mm^2 being preferred for a 64-segment array and a range of about 0.9 mm^2 to about 1.2 mm^2 being more preferred for a 32-segment array.

[0087] In one particular embodiment, the number of segments within the annular array is 32 and each photodetector segment has a surface area that measures approximately 1 mm^2 . In another particular embodiment, the number of photodetector segments within the annular array is 64 and each photodetector segment has a surface area that measures approximately 0.44 mm^2 . Table 1 provides a summary of these exemplary embodiments.

Table 1: *Geometrical parameters of the Prototype-II sensors*

	Prototype-32	Prototype-64
no. of segments	32	64
surface area/pad (mm^2)	1.0	0.44
lower radial position (μm)	2562.5	2562.5
upper radial position (μm)	4108.8	4108.8

[0088] Achieving the desired level of detector performance requires a detailed electrical characterization of the photodetector of the position-monitoring system. Those skilled in the art will appreciate that the inherent noise is reduced by reducing capacitance, followed by the segmentation of a photodetector array in parallel connections. I-V

characteristics are acquired by sweeping the DC reverse-bias voltage, V_{rb} from 0 (V). One main design consideration for the embodiment including a ring-array of Si photodiodes is to ensure that most of an incident photon, e.g. of X-ray frequency, is absorbed within the depletion region of a reverse-biased junction. Because of the considerable width of depletion region (a few hundred μm), the Si-PIN junction may be selected. As shown in **FIG. 15**, leakage current measured from one segment is linear against the increasing reverse bias voltage on a log-log scale. Up to the operational bias voltage of 100 (V), the leakage current is measured to be held below 100 pA with a bias voltage of 150 V applied at room temperature. As **FIG. 16** shows, the depletion region is created at around 200 (V) from the C-V characteristic.

[0089] The guard rings encircling the ring array of photodetector segments can isolate each of the detector segments from the inactive region. As one way to set a limit on the maximum bias voltage, a multiple guard-ring structure is introduced to the design of the photo-detector sensors. In so doing, the structure of multiple guard rings helps to control the potential gradient. As Fig. 2C illustrates, the photodetector array may further comprise a plurality of concentric guard rings around (1) the inner periphery of the polar photodetector array formation, (2) the outer periphery of the polar photodetector array formation, or (3) the inner and the outer periphery of the polar photodetector array formation. The number of inner and/or outer guard rings will depend on the electric leakage of the photodetector array and may range from 1 to 5 guard rings per each periphery, with 3 being preferred. It should be noted that the number of guard rings depends on how to control the potential gradient. The total width of the inner and outer guard rings, summed together, should be comparable to the total thickness of the depletion depth of the photodetectors at full bias.

[0090] As illustrated in **FIG. 2A**, the target may be positioned downstream of the photodetector array. The target can be a metal film free-standing or coated onto any thin

suitable material transparent to the incident radiation, including ceramics such as silicon nitride (Si_3N_4) which is transparent to X-ray radiation. The position of the metal film is approximated based on the method provided above for the optimization of the working distance.

[0091] The choice of material for the target film is crucial for optimizing signal according to the beam energy available at each beamline. Three primary criteria must be considered when selecting the film. The first criteria are yield, *i.e.*, the amount of radiation re-emitted per unit of incident radiation intensity. For secondary radiation, where the beam photon energy is sufficient to excite the secondary radiation, the yield is the amount of radiation re-emitted per unit of incident radiation that is absorbed. In the case of fluorescence as the type of secondary radiation, the yield increases with atomic number. Second, the energy of the re-emitted secondary radiation should occur in a region where the spectral sensitivity on the photodetector, *e.g.* PIN photodiode, is relatively high. Finally, it is advantageous to select an element that has no absorption edge in the operating energy range. In the case of fluorescence as the type of secondary radiation, the energy separation between fluorescence $K_{1\alpha}$ edge and a beam kinetic energy should be sufficiently large. Furthermore, the film material must be chemically stable, able to tolerate high doses of radiation and be easily manufactured into a film of uniform thickness without voids. Because it is desirable to preserve the transmission rate of the radiation beam, *e.g.* synchrotron X-ray radiation beam, at or greater than 90%, the film has thickness of preferably 50 to 1000 nm for beam kinetic energies ranging from 200 eV to 100 keV, with 100 nm to 500 nm comprising a more preferred range. Some materials which meet these requirements are Cr^{24} , Fe^{26} , Mn^{25} , Ti^{22} , or Co^{27} , or alloys thereof. The emission energies of these materials are low ranging between 4.5 and 7.5 keV as shown in **Table 2** (also see **FIG. 17**) with absorption rate range between 2 and 14 % and fluorescence yield of 0.214 to 0.406. In one preferred embodiment, a ~ 500 nm-

thick film of Ti^{22} , Cr^{24} , Mn^{25} , and Fe^{26} for the beam energy of 8 keV may be used. However, the thickness desired depends on the beam photon energy employed.

Table 2, Parameters of the target film at 500 nm thickness

Material	Absorption Rate (%)	K-absorption Edge (keV)	Fluorescence Yield
Ti^{22}	4.6	4.96	0.214
Cr^{24}	8.6	5.99	0.275
Mn^{25}	9.4	6.539	0.308
Fe^{26}	11.3	7.112	0.340
Co^{27}	13.3	7.709	0.373

III. Method for Finding a Beam Centroid

[0092] In yet another embodiment, a method for finding a beam centroid is provided based on fitting data representing photon counts registered at each of the photodetector segments. As illustrated in FIG. 20, the method relies on the fact that the maximum beam intensity ($I_{\max}$) is acquired when a beam centroid is positioned on the photodetector annular array axis at the working distance (z^*). The working distance (z^*) also can be referred to as the shortest radial distance possible (R_0). Since, the beam intensities of the diametrically opposing segments (I_i^{top} and I_i^{bot}) inversely correlate with its corresponding radial distances (R_i^{top} and R_i^{bot}), i.e., the distance between the center of the segment and the contact point between the beam and the target, it is possible to deduce the radial distance (R_i) of any segment in the annular array by solving Eqn. (18),

$$R_i = R_0 \sqrt{I_{\max} / I_i} \quad (18)$$

[0093] However, to extract the polar coordinates of the beam on the target plane, which is defined as a distance (p) of the beam centroid at the target from the annular array segment and a polar angle (or azimuth; ϕ) of each segment, the Eqn. (19) gives,

$$\begin{aligned}\rho &= \rho_0 - \rho_i \\ &= \rho_0 - \sqrt{R_0^2 + R_i^2} \\ &= \rho_0 - \sqrt{R_0^2 + R_0^2 \frac{I_{\max}}{I_i}}\end{aligned}\tag{19}$$

where $\rho_i = \sqrt{R_0^2 + R_i^2}$ and $2\rho_0 = D_{\text{sensor}}$. For a beam centroid that is located at the annular array axis, in one embodiment, a radial offset, *i.e.*, distance from the annular array segment to the beam centroid, ($p\sin(\phi)$), is given as an amplitude of a sinusoidal function, where the phase of the sinusoidal function is a polar angle (ϕ) that defines each segment location in the annular array. Any deviation in the amplitude from the sinusoidal function will indicate that the beam is off axis and its location should be adjusted. For example, **FIG. 21** illustrates a sinusoidal function for 32 data points representing photon counts registered at each of 32 photodetector segments and converted based on Eqn. (19). A beam centroid can then be extracted as one of the fit parameters. The statistical uncertainty is governed by Poisson statistics. Thus, in one embodiment, acquiring more than 40,000 photons per second at each photodetector segment can keep the statistical uncertainty below 0.5%. As illustrated in **FIG. 21**, the statistical uncertainty goes down as the number of photons per second at each photodetector segment goes up: 2,000 (see **FIG. 21A**), 20,000 (see **FIG. 21B**) and 200,000 (see **FIG. 21C**).

[0094] The systematic uncertainty is mostly governed by inherent electronic noise and misalignments of the BPM system. Noise-free operation and high-precision alignment of the BPM system are experimentally demonstrated by utilizing a background event estimation.

For example, this approach can utilize an EGS4-based Monte Carlo photon-transport package to estimate inelastic and elastic scattering arising from ambient scattering. Implementing both geometric parameters of the BPM system and beamline parameters allows estimating both inelastic and inelastic scattering events that comprise background events at a given energy and beamline condition. The numerical calculations show that background events are not significant and cannot be of concern. These background estimations provide important information on systematic uncertainties when data fitting is performed for finding a beam centroid.

EXAMPLES

[0095] The examples set forth below serve to provide further appreciation of the invention but are not meant in any way to restrict the scope of the invention.

Example 1

[0096] To demonstrate the applicability of the working distance optimization methodology, a beam position monitor was designed with annular array of 32 PIN-junction photodiodes with the lower radial position (ρ^-) of 2.5625 mm and the upper position (ρ^+) of 4.1088 mm of each photodiode segment from the center of the array. The transverse beam size ($\sigma_\perp$) was 0.5 mm. Using Eqn. (7), a projection factor was calculated as a function of working distance z^* as illustrated in **FIG. 4**. Using Eqn. (11), the influence of beam sizes on the solid-angle calculation was investigated and the projected total solid angle ($\Omega_{tot,prj}$) and the total solid angle (Ω_{tot}) were compared as illustrated in **FIG. 6A**. Approximately 40% reduction, due to the projection factor (see **FIG. 4**), is found in the peak solid angles. However, the two calculations ($\Omega_{tot,prj}$ and Ω_{tot}) converge at large working distance because the projection factor approaches unity.

[0097] For pinning down the optimum working distance, the first-order derivatives with respect to axial distance (z) were calculated. The results are plotted in **FIG. 6B**. Because of the projection factor, the optimum distance is shifted to about 6.0 mm from about 3.0 mm. In other words, for the exemplary system with the lower radial position (ρ^-) of 2.5625 mm and the upper radial position (ρ^+) of 4.1088 mm of each photodiode segment from the center of the array, the optimal working distance that would provide the highest spatial sensitivity is at about 3.0 mm.

[0098] **FIG. 7** illustrated a plot of the profiles for solid angles versus working distance as a function of beam sizes. Moving from top to bottom, each of the traces on the plot corresponds to transverse beam sizes ($\sigma_\perp$), 2 mm, 1 mm, 0.5 mm, 100 μm , 10 μm , 1 μm , and 0.5 μm , respectively - rms beam sizes over four orders of magnitude were explored in calculations. As shown in the plots on both linear scale (**FIG. 7A**) and log scale (**FIG. 7B**), the solid-angle profiles are essentially identical for the beam sizes below 10 μm . Accordingly, in this exemplary embodiment, the performance of the beam position monitor can be expected to be optimized for the rms beam sizes below 10 μm where optimum working distance is about 7 mm.

Example 2

[0099] For the system provided in Example 1, the calculations may be simplified if the beam's transverse dimensions are sufficiently smaller than the working distance of interest. As provided in Example 1, the working distance is about 3.0 mm for a Gaussian beam, whereas the transverse beam size ($\sigma_\perp$) employed was 0.5 mm. To demonstrate the applicability of the point-source model, as illustrated in **FIG. 8**, the solid-angle profiles of a point-source beam and a Gaussian beam are compared. The projected solid angle with a Gaussian beam, which is considered an actual case, peaks at around 3.0 mm. Similarly, the

point-source beam also peaks at around 3.0 mm. However, the effective area seen by a beam with, for example, $\sigma_{\perp} = 0.5$ mm is reduced by $\sim 27\%$ compared with a point-source beam, in particular, around the optimum working distance. But, at larger distances, both calculations converge since the point-source model is a limiting case of the Gaussian model. This demonstrates that point source model may be reliably used to estimate the optimal working distances if the beam's transverse dimensions are sufficiently smaller than the working distance of interest.

Example 3

[00100] **FIG. 13B** depicts the ring array of 64 photodetector segments that were designed and fabricated at in-house facilities. Boron ions are implanted on the front side of the wafer through 1 kÅ oxide, forming a p-n junction. Phosphorous ions are implanted on the back side to make an ohmic contact with the front side. All 64 segments, configured as a polar array, were positioned between an inner ring radius of 2562.5 μm and an outer ring radius of 4108.8 μm . The active surface area of each segment is about 0.44 (mm^2), and each photodiode is 470- μm thick. **Table 4** provides a summary of the fabricated ring array.

[00101] **Table 4**, *Parameters of the 64-segment annular array.*

Active Surface Area	0.44 (mm^2)
Electrode Separation	470 (μm)
Carrier (Dopant) Concentration (Nd)	2.93×10^{13} (cm^{-3})
Leakage Current (ID)/segment at 150 V	91 (pA)
Detector Capacitance (Cdet) at 150 V	1.5 (pF/ mm^2)

[00102] In the fully-depleted mode, the photodiodes are operated with reverse bias voltage of about 100 volt. An X-ray beam that impinges on a target, results in partial absorption and re-emission of secondary radiation, which scatters backward to illuminates the backside of the photodetector array isotropically. The photodetector was devised for both back-side and front-side illumination.

[00103] Simulations have been conducted to determine the optimal working distance of the fabricated beam position monitor with 64 segments. As illustrated in **FIG. 18**, based on the parameterization method provided above, it was determined that the optimal distance is about 3 mm.

[00104] In one embodiment, an application-specific integrated circuit (ASIC), *e.g.*, HERMES4, may be designed for photon-counting application. For example, a HERMES4 utilizing CMOS technology provides 32 channels, a charge pre-amplifier, a high-order charge shaper, discriminators, an array of five 10-bit global DACs, and counters per channel as illustrated in **FIG. 14A**. In a preferred embodiment, to prevent bonding-wires from obscuring the incident beam in the center of the annular array as illustrated in **FIG. 14A**, a double-ASIC may be used as illustrated in **FIG. 14B**. The HERMES4 may be designed to read out input signals generated by the Si-photodiode sensor. The measured electronic resolution is about 15 rms e^- at a peaking time of 4 μ sec. The gain settings available on HERMES4 are 750 mV/fC and 1,500 mV/fC. The settable peaking times are 0.5, 1, 2, and 4 μ sec. Stray capacitance may be reduced by direct Al-wire wedge-bonding between the 32 channels and sensor pads. The present invention can also be configured to operate with other application specific integrated chips (ASIC), field programmable gate arrays (FPGA), complex programmable logic devices (CPLD), and similar circuits and chips.

[00105] For the purpose of minimization of the effects arising from air scattering, in one embodiment, the BPM may be housed in a vacuum chamber, where the pressure of 10^{-6} torr and below is preferably maintained. On each side of the vacuum chamber in the direction of the beam, circular windows, transparent at the frequencies of the beam, may be mounted to allow for unobstructed transmission of the incident beam through the beam position monitor housed within the vacuum chamber. In the case of an X-ray beam, Beryllium windows may be used. To further reduce background events from inherent noise

arising from the semiconductor sensor and electronics, the BPM may be manufactured to operate at low temperature, e.g., below -40°C. In one embodiment, a Peltier-cooling module, coupled to a thermo-sensor, may be attached to the Cu-support frame on the rear side of the ring photodetectors and the cooling water may flow through the Cu support to extract heat deposited on the heat sink. A series of experimental measurements demonstrated that the inherent noise at low temperatures may be halved compared to background noise at room temperature.

[00106] It will be appreciated by persons skilled in the art that the present invention is not limited to what has been particularly shown and described. Rather, the scope of the present invention is defined by the claims which follow. It should further be understood that the above description is only representative of illustrative examples of embodiments. For the reader's convenience, the above description has focused on a representative sample of possible embodiments, a sample that teaches the principles of the present invention. Other embodiments may result from a different combination of portions of different embodiments.

[00107] The description has not attempted to exhaustively enumerate all possible variations. The alternate embodiments may not have been presented for a specific portion of the invention, and may result from a different combination of described portions, or that other undescribed alternate embodiments may be available for a portion, is not to be considered a disclaimer of those alternate embodiments. It will be appreciated that many of those undescribed embodiments are within the literal scope of the following claims, and others are equivalent. Furthermore, all references, publications, U.S. Patents, and U.S. Patent Application Publications cited throughout this specification are hereby incorporated by reference as if fully set forth in this specification.

CLAIMS:

1. A method of positioning a detector array and a uniform target of a beam position monitor (BPM) by determining an optimal working distance between the detector array and the target, comprising,
 - (a) identifying a direction and a longitudinal axis of a beam about a beam centroid;
 - (b) defining a beam profile (σ_x and σ_y) around the beam centroid;
 - (c) identifying the distribution of a plurality of secondary radiation sensitive photodetectors in an annular array of the BPM positioned in the direction of the beam and in a plane transverse to the longitudinal axis of the beam;
 - (d) identifying a radial position ($\rho^+, \rho^-, \theta^+, \theta^-$) of each photodetector segment in said annular array from the center of a beam-through aperture made on the photodetector plane;
 - (e) identifying the axial position of a uniform target that intersects the beam's longitudinal axis and upon irradiation by the beam generates a secondary radiation to be detected by the plurality of photodetectors in the annular array;
 - (f) identifying coordinates (ρ^*, θ^*) of the beam location on the target at an axial working distance (z^*) from the annular array of the photodetectors;
 - (g) determining a total solid angle Ω_{ring} according to a parametric equation (1):

$$\begin{aligned}
 \Omega_{ring, tot, 9} &= \Omega_{tot, 9} \underbrace{(\rho^*, \theta^*, z^*; \sigma_x, \sigma_y)}_{\text{beam parameters (5)}}; \underbrace{\rho^+, \rho^-, \theta^+, \theta^-}_{\text{sensor parameters (4)}} \\
 &= -\arctan \left[\frac{\Delta\theta^+ (\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^+)^2 + z^{*2}}} \right] + \arctan \left[\frac{\Delta\theta^- (\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^-)^2 + z^{*2}}} \right] \\
 &\quad + \arctan \left[\frac{\Delta\theta^+ (\rho^{*2} - (\rho^* \rho^-) + z^{*2})}{z^* \sqrt{(\Delta\rho^-)^2 + (\rho^- \Delta\theta^+)^2 + z^{*2}}} \right] - \arctan \left[\frac{\Delta\theta^- (\rho^{*2} - (\rho^* \rho^+) + z^{*2})}{z^* \sqrt{(\Delta\rho^+)^2 + (\rho^+ \Delta\theta^-)^2 + z^{*2}}} \right] \quad (1)
 \end{aligned}$$

- (h) calculating a projected total solid angle $\Omega_{ring, prj}$ by multiplying the total solid

angle Ω_{ring} and a projection factor $P(\psi)$, where $P(\psi) = \cos \psi$ and

$$\psi = \left| \left(\rho^+ + \rho^- \right) / \left(2 \cdot z^* \right) \right|;$$

- (i) determining the working distance (z^*) at which the projected solid angle $\Omega_{ring,prj}$ has the highest value, wherein said working distance is an optimal axial working distance; and
 - (j) positioning said detector array and said uniform target about the beam's centroid at said optimal axial working distance (z^*) along the beam's axis.
2. The method according to claim 1, wherein determining the working distance (z^*) at which the projected solid angle $\Omega_{ring,prj}$ has the highest value comprises, calculating a first order derivative of the projected solid angle $\Omega_{ring,prj}$, and determining its zero-crossing; wherein the zero crossing defines the optimal axial working distance (z^*).
 3. The method according to claim 1, wherein the beam is an X-ray beam and the BPM is an X-ray beam position monitor (XBPM).
 4. The method according to claim 3, wherein the secondary radiation generated by said uniform target upon exposure to the X-ray beam is a fluorescent radiation and the BPM is a fluorescent-type annular array XBPM.
 5. The method according to claim 1, wherein the secondary radiation generated by said uniform target upon exposure to the beam is a luminescent radiation or an electron radiation and the BPM is respectively a luminescent-type annular array BPM or an electron-radiation type BPM.
 6. The method according to claim 1, wherein the beam profile is a Gaussian distribution.
 7. The method according to claim 1, wherein the photodetector is a radiation sensitive photodiode.

8. The method according to claim 7, wherein the photodiode is a Silicon based photodiode.
9. The method according to claim 1, wherein the step determining the total solid angle Ω_{ring} according to a parametric equation (1) is simplified to parametric equation (2),

$$\begin{aligned} \Omega_{ring, tot, 5} &= \Omega_{tot, 5}(z^*; \rho^+, \rho^-, \theta^+, \theta^-) \\ &= -\arctan\left[\frac{\theta^+ z^*}{\sqrt{(\rho^+)^2 + (\rho^+ \theta^+)^2 + z^{*2}}}\right] + \arctan\left[\frac{\theta^- z^*}{\sqrt{(\rho^+)^2 + (\rho^+ \theta^-)^2 + z^{*2}}}\right] \\ &\quad + \arctan\left[\frac{\theta^+ z^*}{\sqrt{(\rho^-)^2 + (\rho^- \theta^+)^2 + z^{*2}}}\right] - \arctan\left[\frac{\theta^- z^*}{\sqrt{(\rho^-)^2 + (\rho^- \theta^-)^2 + z^{*2}}}\right] \end{aligned} \quad (2)$$

wherein beam dimensions is sufficiently small compared to the working distance of interest.

10. A method for finding a beam centroid using a beam position monitor (BPM) with an annular detector array and a uniform target, comprising,
- recording a beam intensity (I_i) on a photodetector segment in the annular detector array BPM;
- determining a working distance (z^*) between the annular detector array and the uniform target;
- determining a maximum beam intensity (I_{max}) for a radial distance that equals to the working distance (R_0);
- calculating a radial distance (R_i) of the segment in the annular array according to Eqn. (18),

$$R_i = R_0 \sqrt{I_{max} / I_i}$$

(18)

calculating polar coordinates (p_i, ϕ_i) of the beam on a plane of the uniform target

according to Eqn. (19),

$$\rho_i = \rho_0 - \sqrt{R_0^2 + R_0^2 \frac{I_{\max}}{I_i}}$$

(19)

where p_0 is the distance between a longitudinal axis of the annular array at the uniform target and the photodetector segment; and

fitting polar coordinates for each photodetector segment of the annular array BPM on a sinusoidal function, wherein an amplitude and a phase of the sinusoidal function provides the position of the beam centroid as a radial offset and a beam's polar angle, respectively.

11. The method according to claim 10, wherein the step of recording the beam intensity (I_i) on the photodetector segment in the annular detector array BPM comprises acquiring 40,000 or more photons per second.
12. A method of adjusting a beam position in a synchrotron radiation beamline comprising

fitting the polar coordinates for each photodetector segment of the annular array BPM on a sinusoidal function according to claim 10, wherein the beam centroid corresponds to the annular array axis;

monitoring for deviations of the radial coordinates of the beam centroid from the sinusoidal function;

adjusting the position of the beam to fit the sinusoidal function.
13. A method of optimizing the radial displacement of a detector array in a beam position monitor (BPM), comprising,

(a) calculating *difference-over-sum* (Δ/Σ) as sweeping along either of the two transverse directions (x, or y) according to Eqn. (17);

$$\frac{\Delta_{\Omega}}{\Sigma_{\Omega}} = \frac{\sum_{j=1}^n (\Omega_{n/2-j+1} - \Omega_j)}{\sum_{j=1}^{n/2} \Omega_j}$$

(17)

(b) calculating an absolute value of the slope in a *difference-over-sum* which provides for a maximum spatial sensitivity in the transverse plane along the longitudinal axis of the beam, and

(c) determining the radial displacement (position) of the fluorescence sensitive photodiode segment in an annular photodetector array on the transverse plane.

14. A method of optimizing the surface area and detector capacitance of an annular detector array in a beam position monitor (BPM) comprising the steps of:

(a) determining an optimal working distance according to claim 1;
 (b) determining a surface area of the fluorescence sensitive photodiode segment in the annular photodetector array and the radial dimensions of the annular photodetector array according to (3)

$$\begin{aligned} \Sigma_{pad} &= \frac{1}{2} \theta_s \Sigma_{\rho} \Delta_{\rho} = \frac{1}{2} \theta_s (\rho_+ + \rho_-) (\rho_+ - \rho_-) \\ &= \frac{1}{2} \theta_s \Delta_{\rho} (2\rho_- + \Delta\rho) \end{aligned} \quad (3)$$

and

(c) optimizing the segment surface area and the radial dimensions of the annular photo array based on the peak solid angle.

15. A method of optimizing the curvature of an annular array of photodetector segments in a beam position monitor (BPM) comprising the steps of:

(a) calculating the total solid angle according to claim 1;
 (b) calculating the optimal working distance according to claim 1;

- (c) configuring the photodetector segments in said annular array to coincide with the semi-spherical surface with a radius equal to the optimal working distance and defined by the total solid angle.
16. A method of optimizing the curvature of an annular array of photodetector segments according to claim 15, wherein the photodetector segments coincide with planes tangent to the semi-spherical surface defined by the total solid angle.
17. A beam-position monitor (BPM) comprising
- an annular- array of photodetector segments having an inner and outer diameter and defining a transverse plane to longitudinal axis of a beam, the annular- array comprises a plurality of photodetectors segments equally partitioned between the inner and outer diameter in a polar array formation, and
- a thin film target of uniform thickness intersecting the longitudinal axis of the beam positioned along the longitudinal axis at a predefined distance from the annular photodetector array that allows for substantial pass-through transmission of the beam,
- wherein upon irradiation of the thin film target by an incident beam, the target generates secondary radiation about the beam axis detected by the photodetectors in the annular array.
18. The BPM of claim 17, wherein the annular array of photodetector segments are configured to coincide with a semispherical surface with a radius equal to the optimal working distance and defined by the total solid angle.
19. The BPM of claim 18, wherein the annular array photodetector segments coincide with planes tangent to the semi-spherical surface defined by the total solid angle.
20. The BPM of claim 17, wherein the beam is an X-ray beam.
21. The beam-position monitor of claim 17, wherein the secondary radiation is a fluorescent radiation, a luminescent radiation, or an electron radiation.

22. The BPM of claim 17, wherein the annular-photodetector array comprises 32 or 64 photodetector segments.
23. The BPM of claim 17, wherein the photodetector is a Silicon based PIN-junction type photodiode.
24. The BPM of claim 17, wherein the surface area of the photodetector segment is about 1.0 mm^2 .
25. The BPM of claim 17, wherein the surface area of the photodetector segment is about 0.44 mm^2 .
26. The BPM of claim 24, wherein the annular-photodetector array comprises 32 photodetector segments.
27. The BPM of claim 25, wherein the annular-photodetector array comprises 64 photodetector segments.
28. The BPM of claim 17, wherein an upper and lower radial positions of each photodetector segment in the annular photo array is about 2.5625 mm and about 4.1088 mm, respectively, from a center of the array.
29. The BPM of claim 17, wherein the optimum working distance ranges from 2 to 10 mm.
30. The BPM of claim 29, wherein the optimum working distance is about 3.0 mm.
31. The BPM of claim 17, further comprising a plurality of concentric guard rings around the inner periphery of the annular photodetector array formation, around the outer periphery of the annular photodetector array formation; or around the inner and the outer periphery of the annular photodetector array formation.
32. The BPM of claim 31, wherein the number of guard rings at inner, outer or both peripheries is 3 and the total width of all of the guard rings, summed together, is on

the same order as the total thickness of the depletion depth of the photodetector segments at full bias.

33. The BPM of claim 17 further comprising an electronic readout system for collecting data from the plurality of photodetectors in the annular photodetector array.
34. The BPM of claim 33, wherein the electronic readout system comprises one or more double-ASIC (application-specific integrated circuit) chips.
35. The BPM of claim 17, wherein the thin film target is sufficiently thin to allow a transmission rate of greater than 85 %.
36. The BPM of claim 35, wherein the transmission rate is greater than 90 % at 8 keV.
37. The beam-position monitor of claim 17, the thin film target has thickness in the range of 50 nm and 1000 nm.
38. The BPM of claim 37, the thin film target thickness is about 500 nm.
39. The BPM of claim 17, the thin film target is made from Cr²⁴, Ni²⁸, Fe²⁶, Mn²⁵, Ti²², Co²⁷ or Mo⁴², or an alloy thereof.
40. The BPM of claim 17, a single layer of the thin film target is deposited on a substrate window by sputtering.

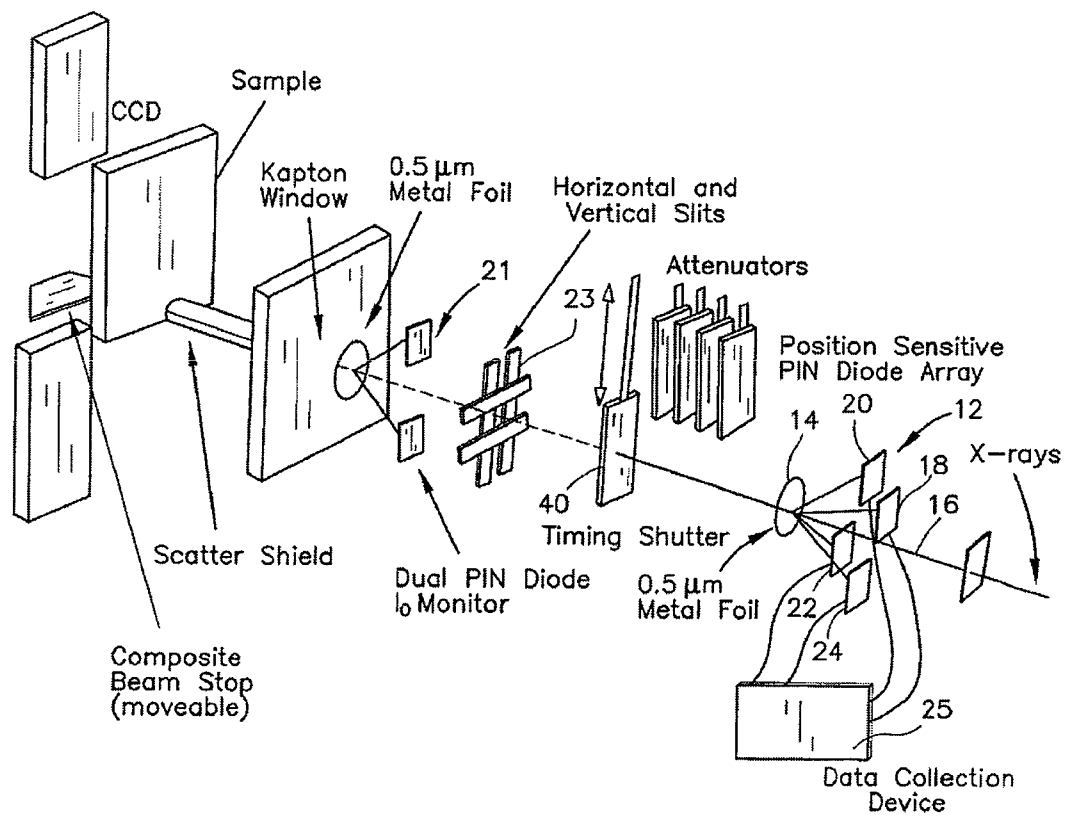


FIG. 1 (PRIOR ART)

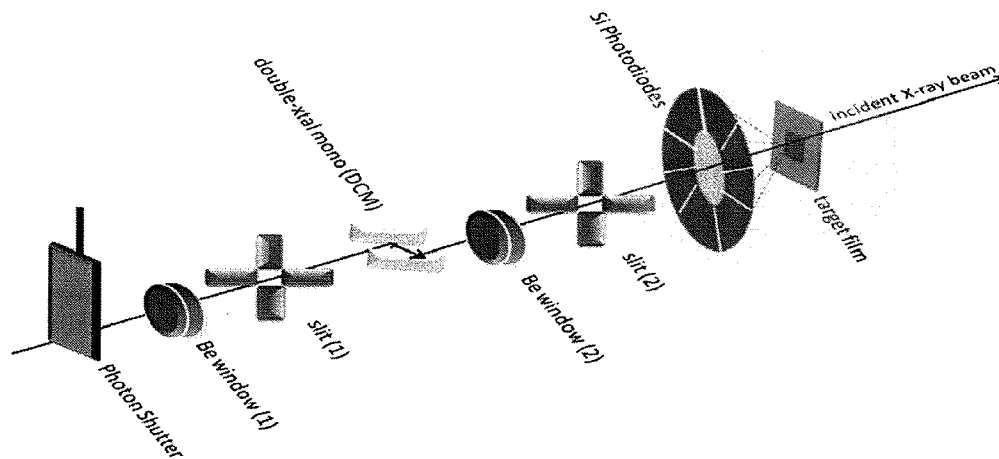


FIG. 2A

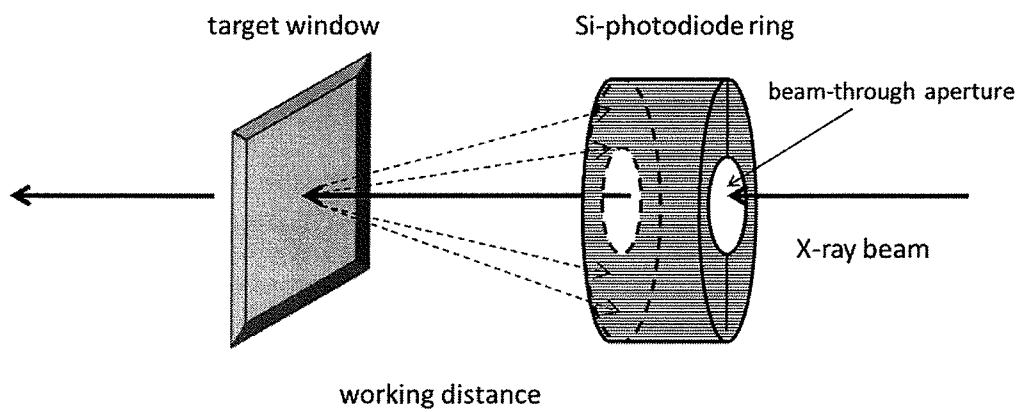


FIG. 2B

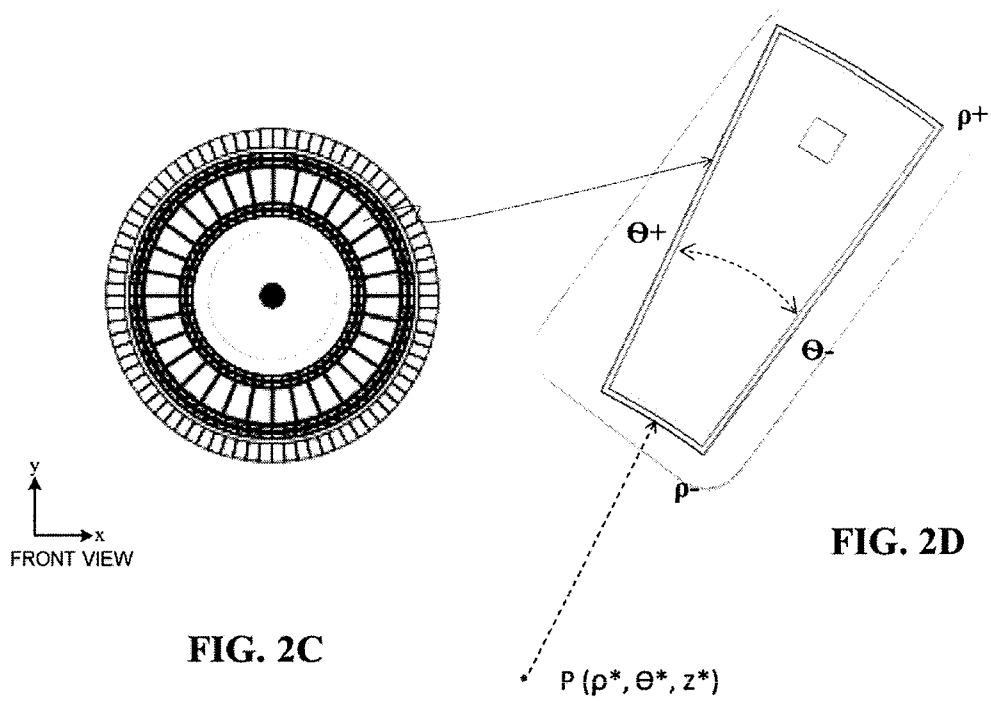


FIG. 2C

FIG. 2D

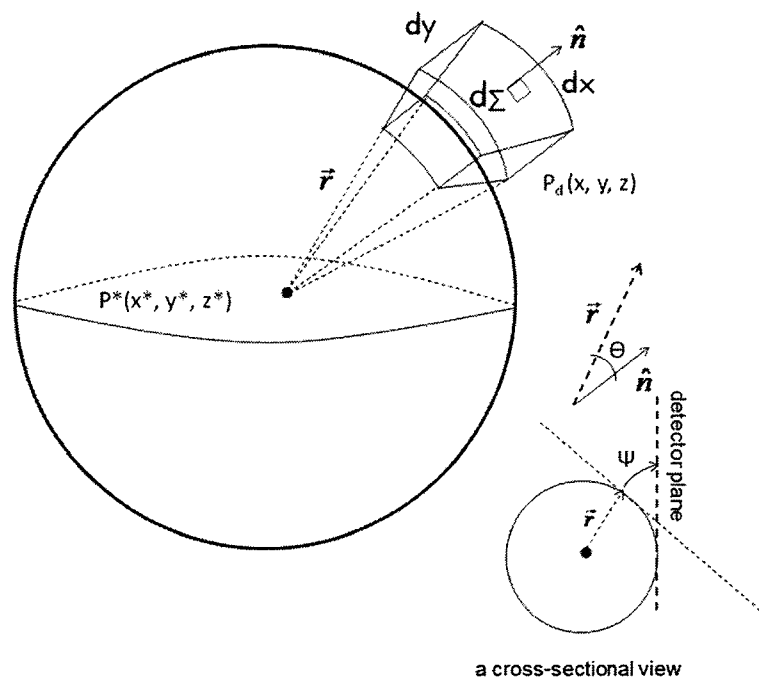


FIG. 3

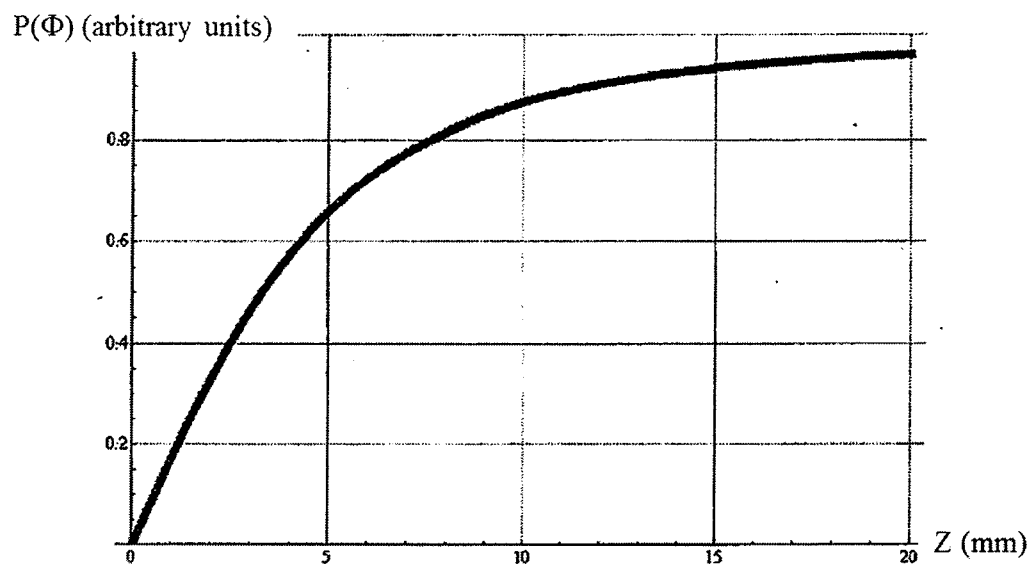


FIG. 4

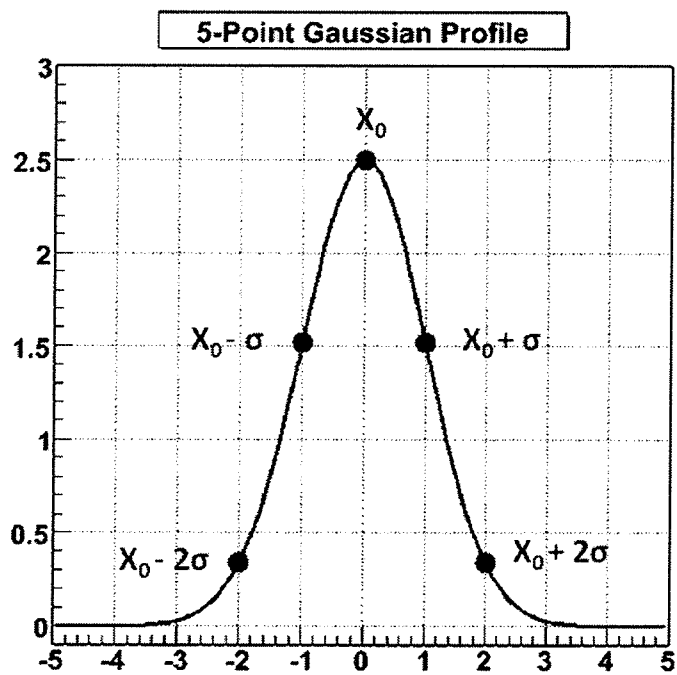


FIG. 5

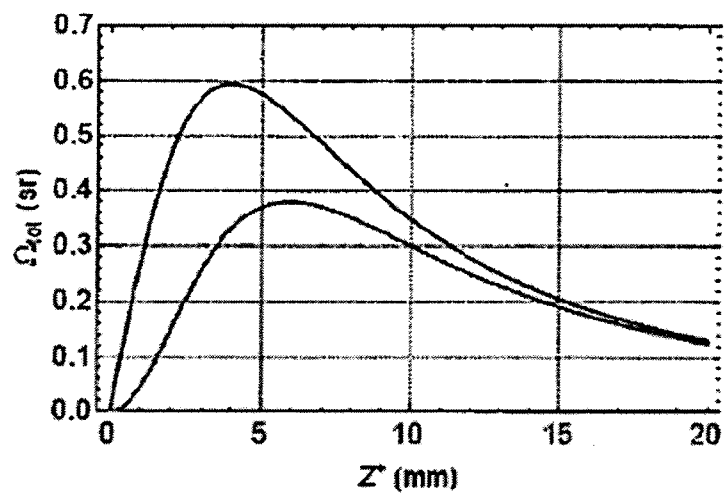


FIG. 6A

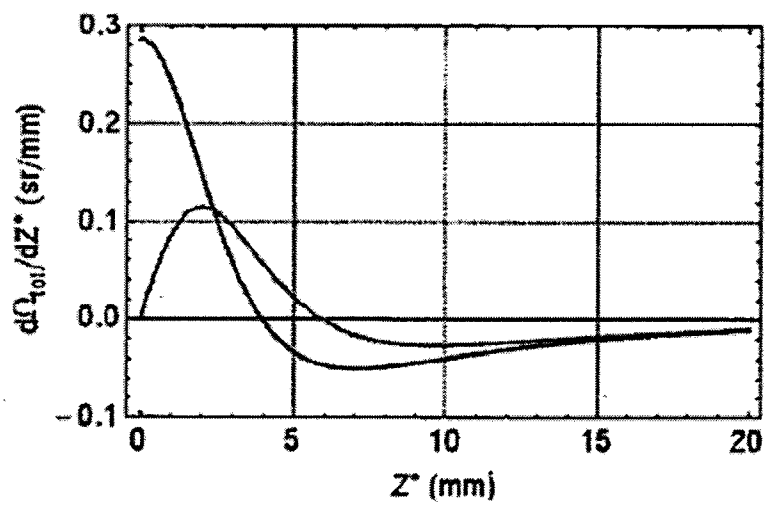


FIG. 6B

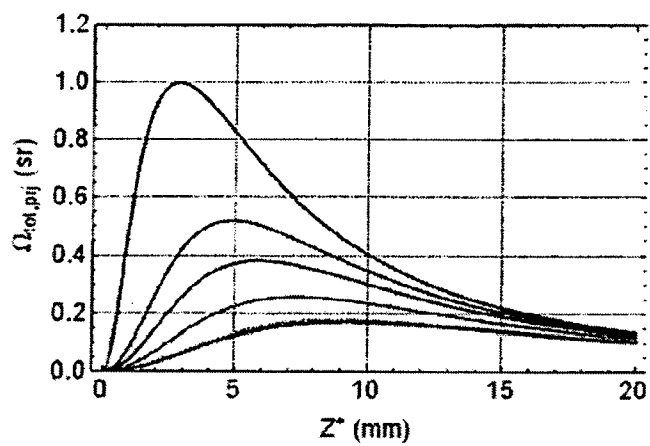


FIG. 7A

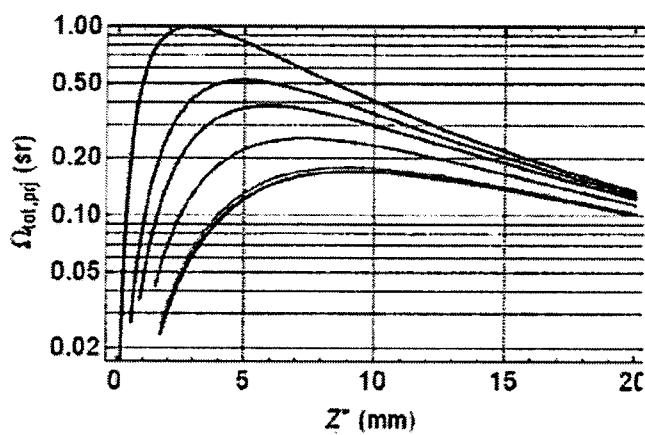


FIG. 7B

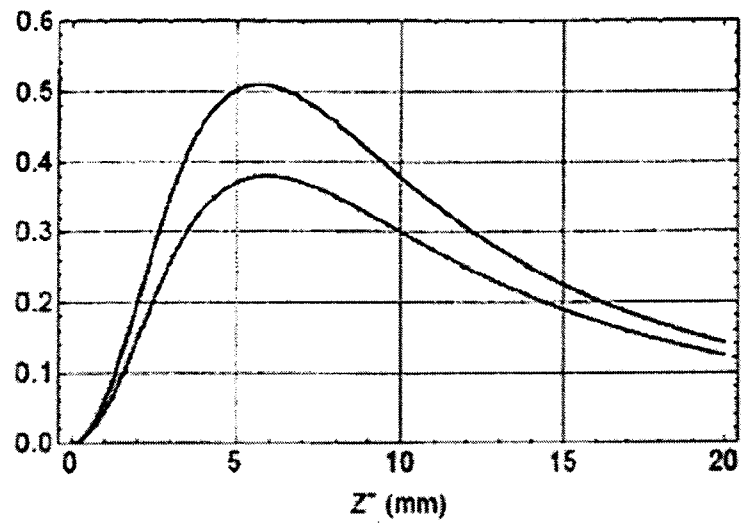


FIG. 8

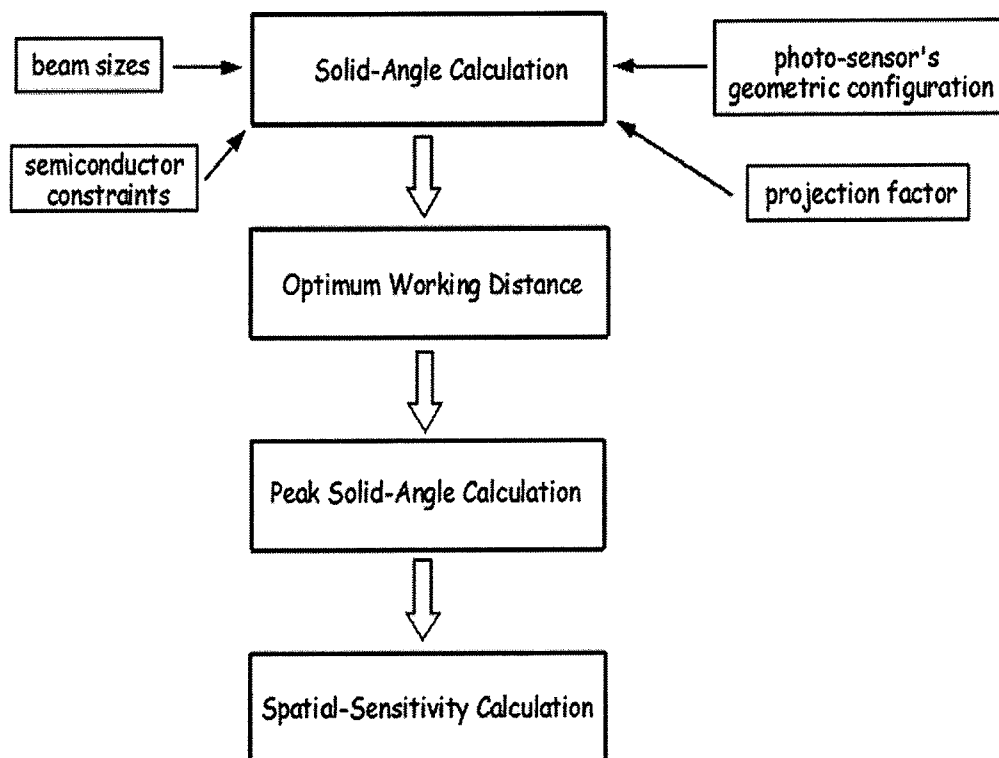


FIG. 9

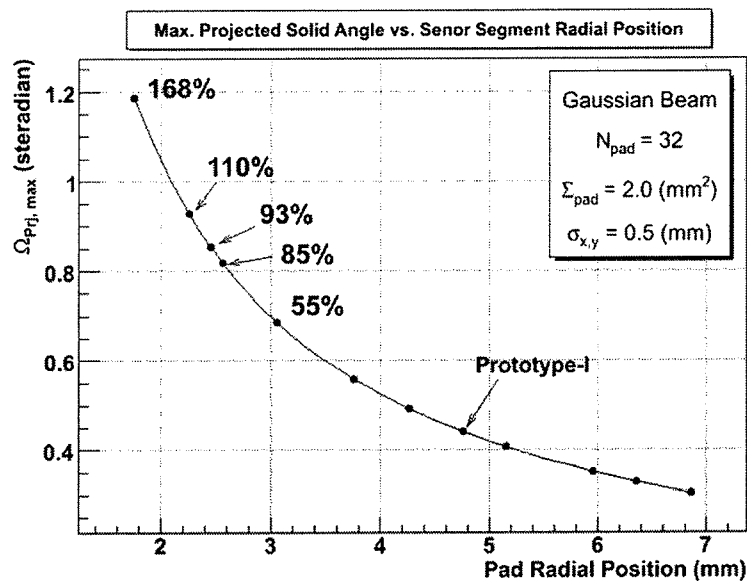


FIG. 10

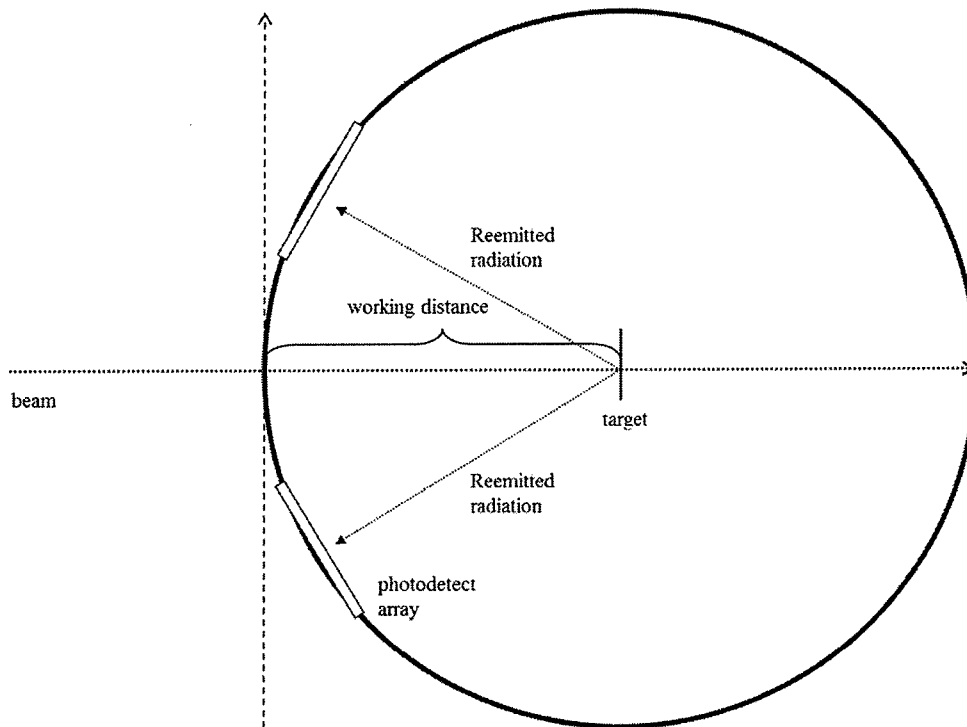


FIG. 11

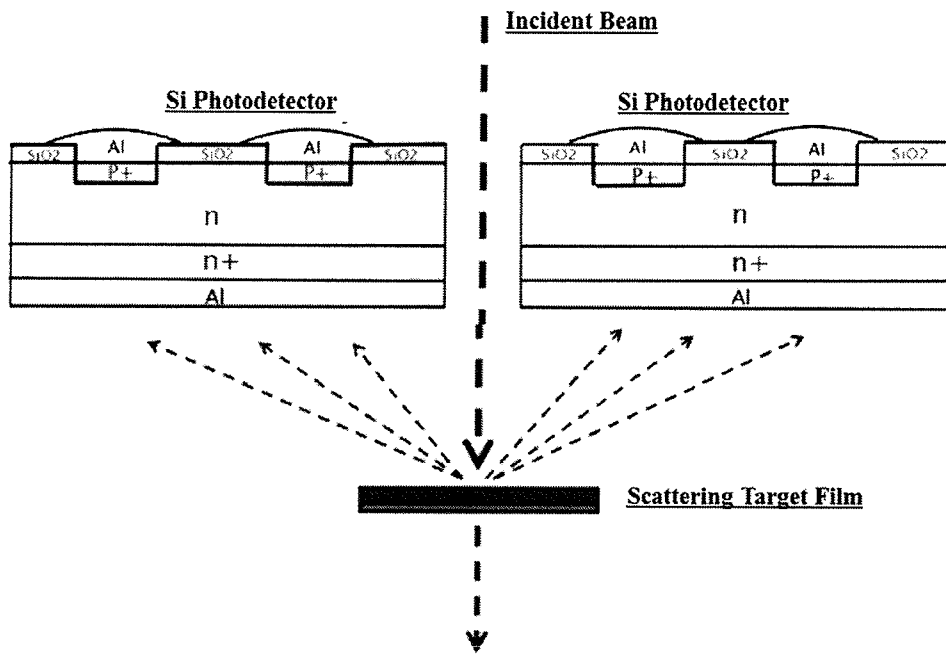


FIG. 12

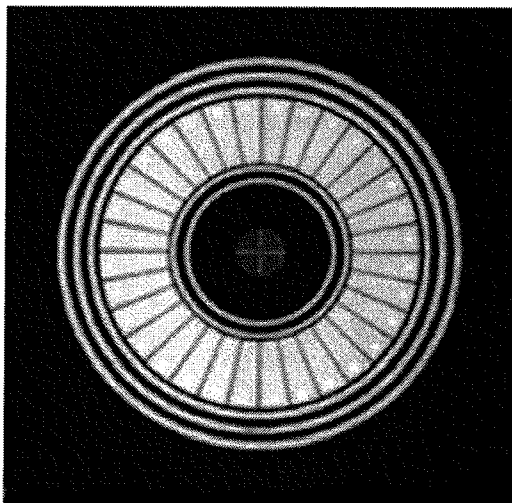


FIG. 13A

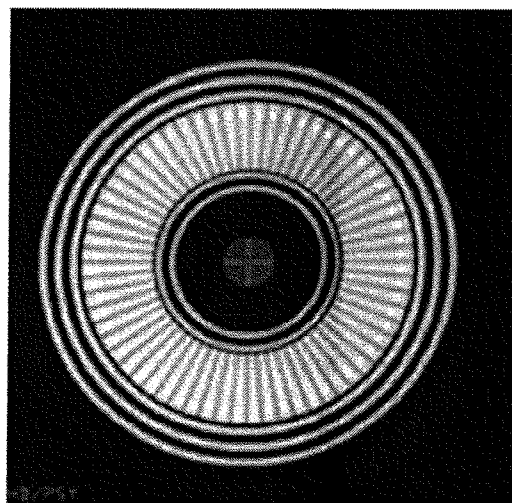


FIG. 13B

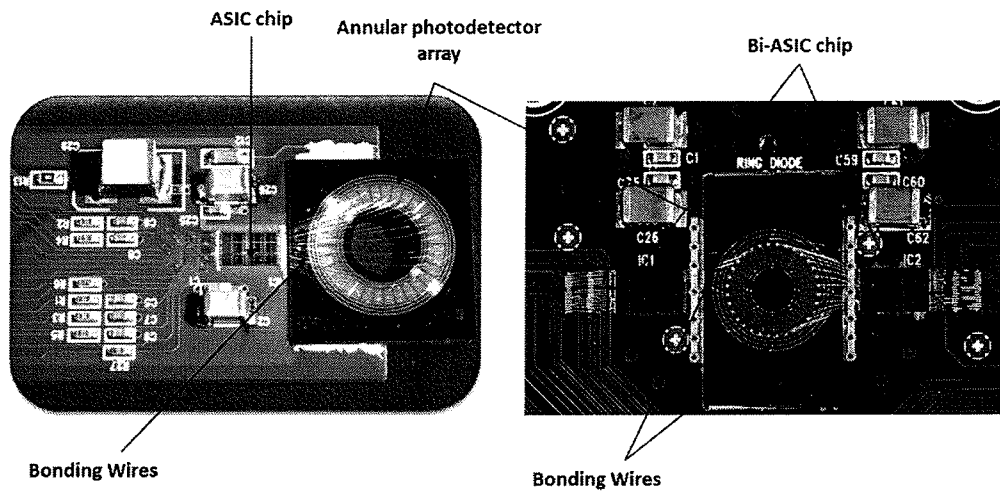


FIG. 14A

FIG. 14B

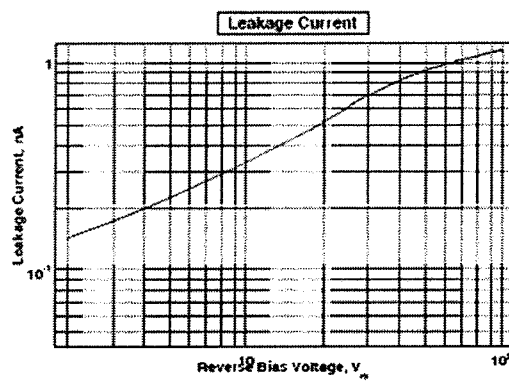


FIG. 15

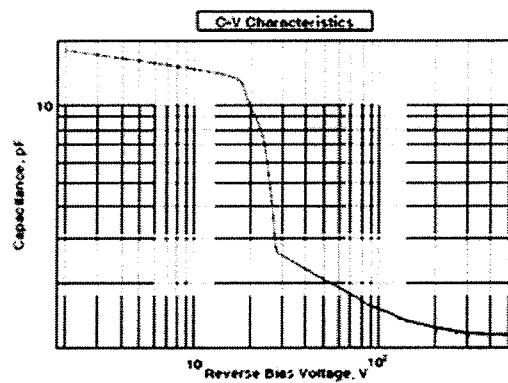


FIG. 16

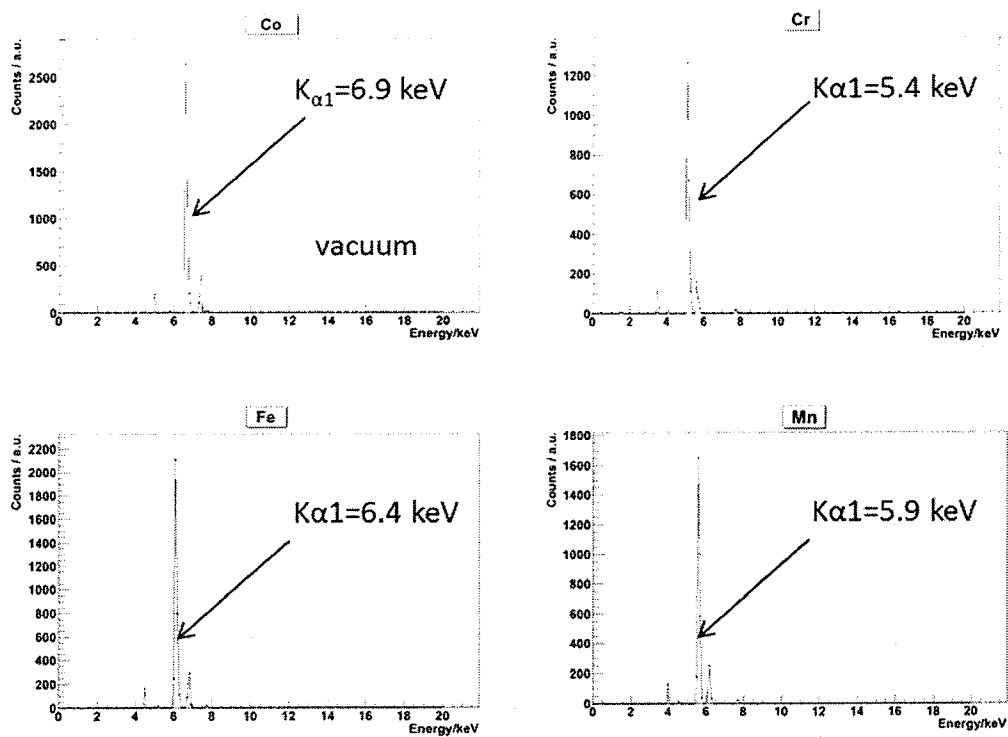


FIG. 17

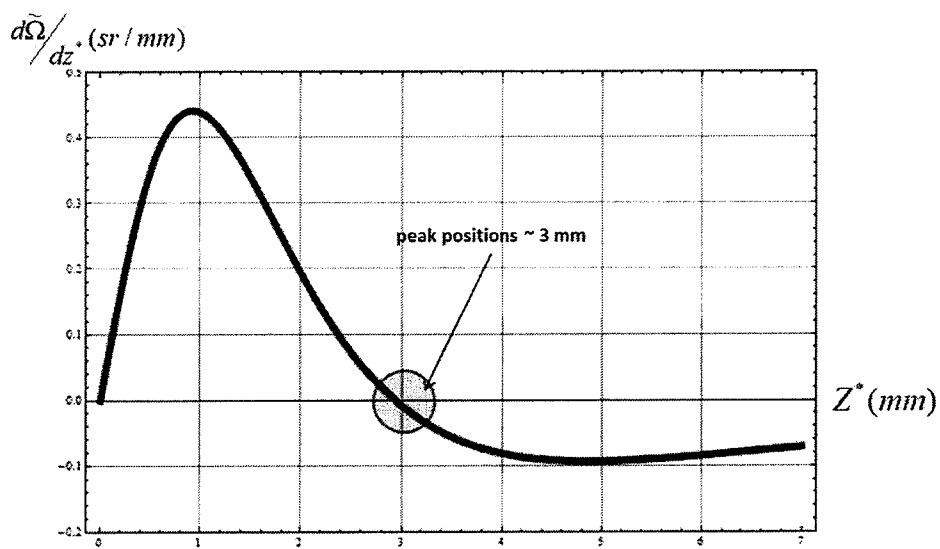


FIG. 18

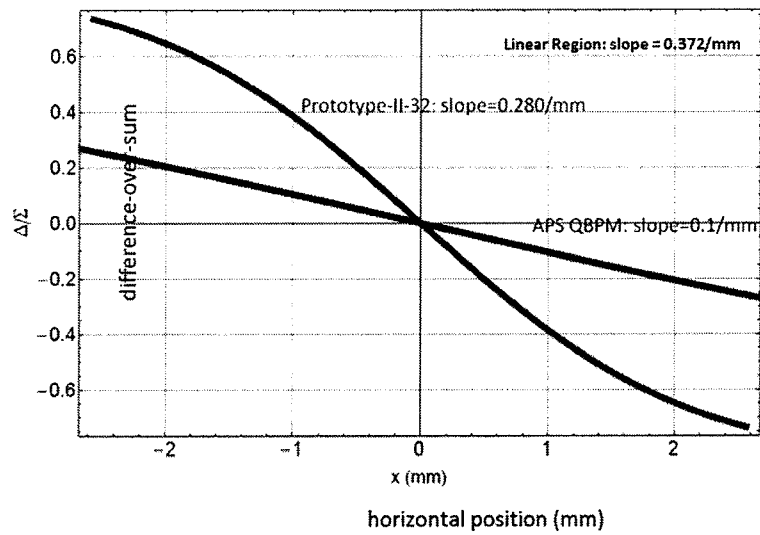


FIG. 19

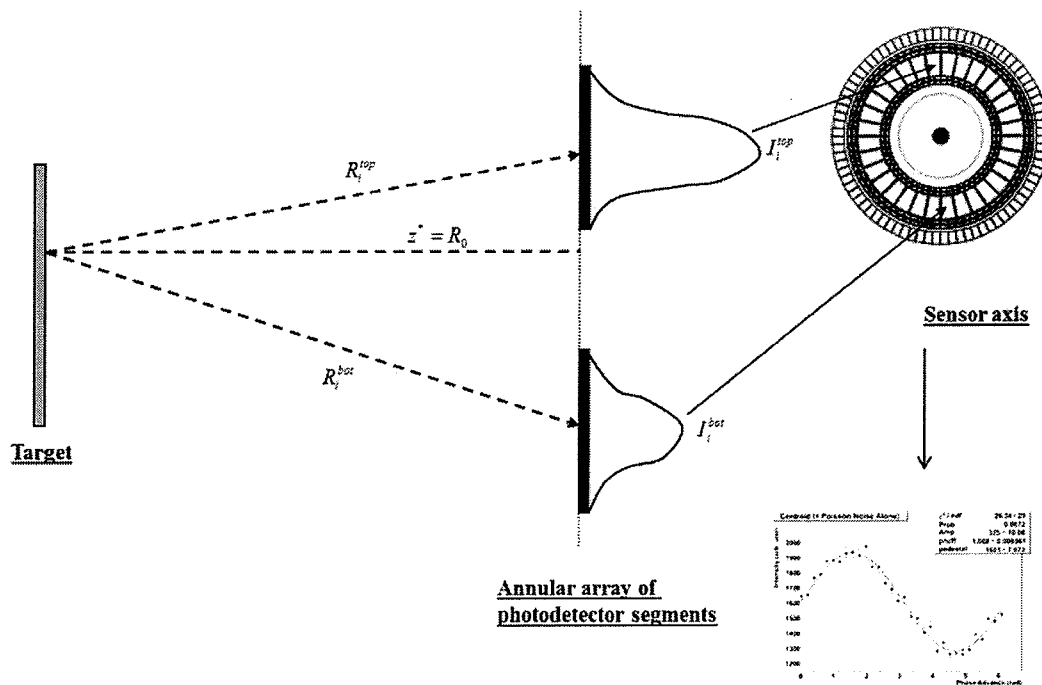


FIG. 20

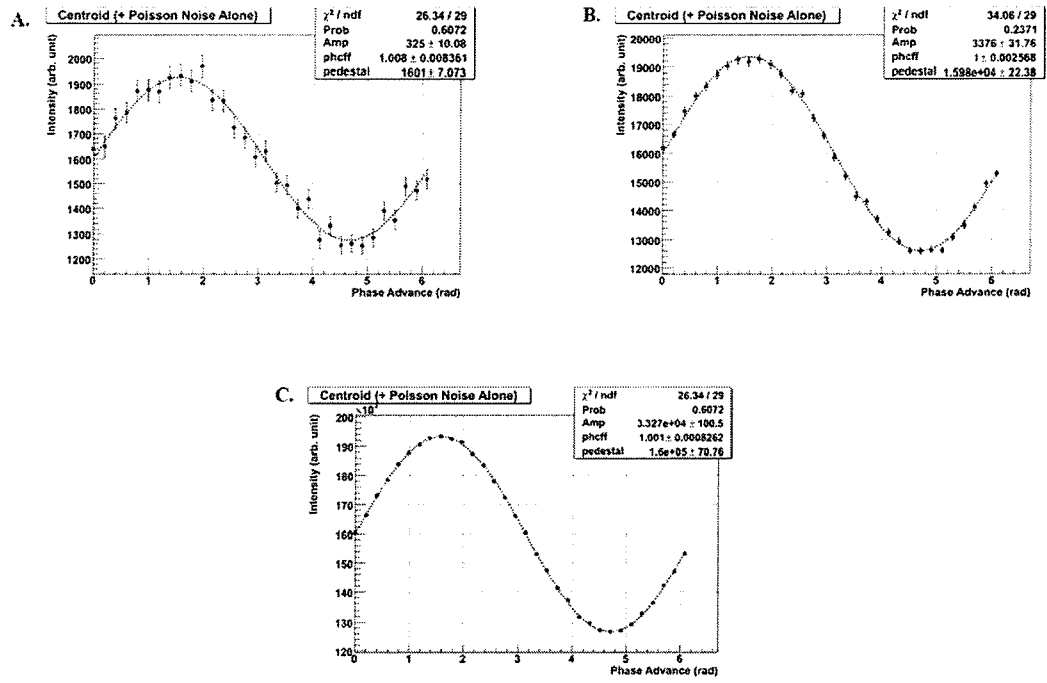


FIG. 21

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/032215**A. CLASSIFICATION OF SUBJECT MATTER****G01T 1/29(2006.01)i, G21K 1/00(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01T 1/29; G01T 1/202; C09K 11/65

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: detector, beam, position, monitor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010-0219350 A1 (KOJI KOBASHI et al.) 02 September 2010 See paragraph [0068] - paragraph [0095]; abstract and figures 1-10.	1-40
A	US 05717214 A (HIDEO KITAMURA et al.) 10 February 1998 See column 12, line 47 - column 22, line 43; abstract and figures 1-19c.	1-40
A	US 05387795 A (TUNCER M. KUZAY et al.) 07 February 1995 See abstract and figures 1-13.	1-40



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search

18 JUNE 2012 (18.06.2012)

Date of mailing of the international search report

09 JULY 2012 (09.07.2012)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

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