Transmissive x-ray beam position monitors with submicron position- and submillisecond time resolution

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We present the development of fast transmissive center-of-mass x-ray beam position monitors with a large active area, based on a thinned position sensitive detector in both a duo- and a tetra-lateral variant. The detectors were tested at BESSY beamlines BL14.1, KMC-1, and KMC-2 and yielded signal currents of up to 3 μA/100 mA ring current at 10 keV photon energy using the monochromatic focused beam of BL14.1. The active area sizes were 1 × 1 and 3 × 3 mm² for the duo-lateral and 5 × 5 mm² for the tetra-lateral devices, with the duo-lateral detectors currently being available in sizes from 1 × 1 to 10 × 10 mm² and thicknesses between 5 and 10 μm. The presented detectors’ thicknesses were measured to be 5 and 8 μm with a corresponding transmission of up to 93% at 10 keV and 15% at 2.5 keV. Up to a detection bandwidth of 10 kHz, the monitors provide submicron position resolution. For lower detection bandwidths, the signal-to-noise reaches values of up to 6 × 10⁴ at 10 Hz, corresponding to a position resolution of better than 50 nm for both detector sizes. As it stands, this monitor design approach promises to be a generic solution for automation of state-of-the-art crystal monochromator beamlines. © 2008 American Institute of Physics. [DOI: 10.1063/1.2938400]

I. INTRODUCTION

High brightness x-ray beams are indispensable probes for chemical and structural properties of matter on an atomic scale. Most applications such as protein crystallography,1 high kinetic energy photoemission,2 and x-ray microtomography,3,4 as well as extended x-ray fine structure analysis with micrometer resolution5 and microfluorescence analysis6 are performed at contemporary x-ray monochromators and demand excellent beam stability. When moving further toward higher brilliance, microfocus and automated beamline operation, continuous beam monitoring, and feedback schemes become crucial. With protein crystallography and crystal volumes as low as 20 mm³,1,6 it is the differential measurement of the photodiode surface resistance by comparing the photocurrents at a split anode and cathode in the duo-lateral or a fourfold split anode in the tetra-lateral detector case. Beam-occluding one-dimensional PSDs (so-called lateral diodes) have successfully been used as position monitors for synchrotron radiation.8 At BESSY beamlines, they have been employed in horizontal beamline stabilization schemes8 in the soft x-ray range. In order to extend the performance of PSDs to two spatial dimensions and to transmission operation, two-dimensional (2D) duo- and tetra-lateral PSDs with active areas of up to 100 mm² have been developed. First prototypes [see images in Figs. 1(a) and 2(a)] have recently been studied at the BESSY double crystal monochromator (DCM) beamlines BL14.1 and KMC-1 as well as with a microfocus setup at beamline KMC-2 with very promising results, as described below.

II. EXPERIMENTAL

A. Duo- versus tetra-lateral design

The two design principles are laid out in Figs. 1 and 2. In a duo-lateral PSD, both the cathode and anode are split in orthogonal directions with respect to each other. This design thereby isolates the channels for the spatial directions and minimizes cross-talk between the vertical and horizontal electrodes and thus results in a smaller absolute position detection error and greater linearity compared to a tetra-lateral type. In a tetra-lateral detector, just the anode is split, but fourfold instead of twofold. In the present design, the elec-
tode contacts are point contacts in the corners of a square active area.

In both designs, intensity fluctuation due to variations in the incoming radiation cancel in the computation of a so-called difference-over-sum position signal or asymmetry $A$. The relations differ depending on the design of the electrodes. For a duo-lateral detector, the asymmetry signal from each electrode pair $(E)$ in transverse direction $x$ is computed with the following relation:

$$A_{xE} = \frac{I_{E2} - I_{E1}}{I_{E1} + I_{E2}},$$

with $I_{Ei}$ being the electrode currents measured at contacts 1 and 2 of anode or cathode, $x_E$ the distance from the detector center in the direction of the respective electrode.

For the tetra-lateral detector with point contacts in the corner of a square active area, a similar relation can be derived by summing the top (T) and bottom (B) $(\Sigma_{top}=I_T+I_{TR}, \Sigma_{bottom}=I_B+I_{BR})$ or left (L) and right (R) $(\Sigma_{left}=I_T+I_{TL}, \Sigma_{right}=I_R+I_{BR})$ electrode currents before computing the difference-over-sum signal, respectively,

$$A_x = \frac{\Sigma_{left} - \Sigma_{right}}{\Sigma_{left} + \Sigma_{right}},$$

$$A_y = \frac{\Sigma_{top} - \Sigma_{bottom}}{\Sigma_{top} + \Sigma_{bottom}},$$

where $x$ is assumed to be in the horizontal and $y$ in the vertical direction, with the corresponding lengths $L_x$ and $L_y$ of the active area. An ideal PSD features the relation $A_{\xi} = 2\xi/L$ with $L$ the length of the active detector area in the respective direction $\xi$. Deviations from the ideal case will be discussed below.

![Figure 1](image1.png)

**FIG. 1.** (Color online) (a) Visible transmission microscope images of a duo-lateral transmissive PSD-XBPM with $3 \times 3 \text{mm}^2$ active area (Serial No. 2513-15B). Left: detector and holder; right: zoom of active area. (b) Corresponding wiring scheme.

B. Detector manufacturing and mounting

The duo-lateral detectors were fabricated on $n$-type float zone silicon with a resistivity of 1 k$\Omega$cm. In order to mechanically support the 5–10 $\mu$m thick detector, the wafers were selectively thinned to leave a $11.5 \times 11.5 \text{mm}^2$ membrane surrounded by a 2 mm wide ‘picture frame’ of 130 $\mu$m thick silicon. The thinning process is able to achieve a peak-to-peak thickness variation across a 100 mm diameter wafer of ±1 $\mu$m. The endpoint of the thinning process is able to produce detectors with a thickness of 5–10 $\mu$m.

Figure 3(a) shows a cross section of the duo-lateral detector which consists of a front side boron implanted resistive layer with a sheet resistance of 20 k$\Omega$/square acting as the $p$-$n$ junction, and a resistive back side phosphorus implanted cathode of 5 k$\Omega$/$\square$. The resistive layers are imaged with aluminum electrodes at opposite ends, the front and back being orthogonal to provide $x$-$y$ outputs. High-dose implants with a sheet resistance of 80 $\Omega$/square are incorporated under the aluminum to provide Ohmic contacts. A range of active areas of $1 \times 1$, $3 \times 3$, $5 \times 5$, and $10 \times 10 \text{mm}^2$ were fabricated at the request of beam users. For testing and comparison with the duo-lateral detectors, one tetra-lateral prototype was fabricated. In the case of the tetra-lateral design, the role of front and back sides are reversed from the duo-lateral case. Figure 3(b) shows a duo-lateral detector mounted on a 1.5 mm thick, double sided alumina ceramic designed to facilitate single sided output of the flying leads.

C. Detectors, beamlines, and setup

Four different PSD-XBPMs were examined in the present work. The first was a $3 \times 3 \text{mm}^2$ duo-lateral detector (Serial No. 2513-1D). First results obtained from this device...
are published in Ref. 10. To increase the cathode position resolution, a limitation of this first prototype, a new design approach for the duo-lateral detectors was adopted with high-dose implants with a doping density of approximately $10^{20} / \text{cm}^3$ underneath the electrodes (resistive implant). These new detectors have intercathode resistances of around 5 kΩ and provide equal sensitivity in both spatial directions.

Two such devices were investigated: A 1 mm² duo-lateral detector (Serial No. 2513-15A) and a 3 x 3 mm² duo-lateral detector (Serial No. 2513-15B). The fourth device was a 5 x 5 mm² tetra-lateral detector (Serial No. 2513-16). All PSDs were mounted on a $X/Y/Z$ translation stage with four ground-free electrical feedthroughs. The ground connection for the tetra-lateral detector was connected to the translation stage support.

Device specifications for the PSDs under investigation in the present publication are listed in Table I. The device capacitances for all devices observed are in the range of 100 pF. Along with interelectrode resistances of around 10 kΩ, typical time constants for the detectors in the millisecond regime can be estimated.

In the measurements at BESSY beamline KMC-1, the anode and cathode currents were detected via four Keithley electrometers (models 6517A and 6514, Fig. 1 bottom) and the BESSY data acquisition computer via general purpose interface bus (GPIB). At BESSY beamline BL14.1, a four-channel current-voltage converter connected to 16 bit analog-to-digital converters (ADCs) or a digital oscilloscope (LeCroy 350 MHz) was used. Frequency dependent performance was measured with a portable FFT analyzer (Ono Sokki CF-3400).

The first duo-lateral PSD-XBPM prototype (Serial No. 2513-1D) was tested at the BESSY double crystal monochromator beamline KMC-1. This beamline is on a bending magnet source and covers an energy range from 1.7 to 2 keV [InSb and Si (111) crystals] at a maximum flux of $0.6 \times 10^{12}$ photons/s at 300 mA ring current. The beam cross section at the monitor position (1 m upstream of the beam focus) was $\sim 500 \times 500 \mu \text{m}^2$ ($h \times v$ FWHM) and the spectral resolution $E/\Delta E = 5 \times 10^3$ at 5 keV.

The measurements with an improved duo-lateral PSD-XBPM (Serial No. 2513-15B) and with a tetra-lateral PSD-XBPM prototype (Serial No. 2513-16) were performed at the BESSY double crystal monochromator macromolecular crystallography beamline BL14.1. This beamline is operated at the −40 mrad port of a 7 T superconducting wavelength shifter source and covers a photon energy range from 5.5 to 15 keV at a maximum flux of $0.4 \times 10^{12}$ photons/s at 300 mA ring current. The beam size at the monitor position (1 m upstream of the beam focus) was $\sim 300 \times 200 \mu \text{m}^2$ ($h \times v$ FWHM) and the spectral resolution $E/\Delta E \approx 5 \times 10^3$ at 10 keV.

For surface mapping measurements, a capillary optics setup at 8 keV, 15 μm beam size and $10^6$ photons/s at the BESSY beamline KMC-2 was employed.

### III. RESULTS

#### A. Photocurrents

The total photocurrent $I_0$ expected from a thinned PSD using the sum signal detected at the anodes can be estimated from

$$I_0 = A \frac{E_{\text{ph}}}{w} q \Phi,$$

with the absorption $A$ in the depletion layer, the photon energy $E_{\text{ph}}$, the elementary charge $q$, and the photon flux $\Phi$. $w$ is the mean energy for creation of an electron-hole pair; for Si, it is 3.63 eV. For a 3 x 3 mm² duo-lateral PSD with a thickness of 8 μm, the x-ray absorption, photocurrents and photon flux were measured as a function of photon energy. For flux measurements an ion chamber was employed (Oxford Danfysik IC PLUS 50). The photo current calculated from Eq. (4) under the assumption of a fully de-
pleted detector coincides well with the actually measured values (see Fig. 4). The predicted currents had to be corrected for absorbing windows between flux measurement and PSD entry window, in this case a Kapton and a Be window, as well as the PSD detector itself. Thickness values for these windows were taken from the device specifications. Deviations of the predicted photocurrent at low energies can largely be attributed to deviations of the window absorptions from the specified values.

The depth of the depletion layer \(x_d\) can be estimated from

\[
x_d = \sqrt{\frac{2\varepsilon_s}{q} \left( \frac{1}{N_n} - \frac{1}{N_d} \right) (\phi_i - V_j)},
\]

with the dielectric constant for Si \(\varepsilon_s\), the elementary charge \(q\), the donor and acceptor doping densities \(N_n\) and \(N_d\), the external junction voltage \(V_j\) and the built-in potential \(\phi_i\), which, in turn, can be calculated from

\[
\phi_i = V_i \ln(N_d N_n/n_i^2),
\]

with the thermal voltage \(V_i = kT/q\), and the intrinsic carrier density \(n_i\).

Since the detectors have a \(p-i-n\) layer structure, with a broad \(n\) layer separating a strongly doped \(p^+\) layer and a strongly doped \(n^+\) layer, the lower doping density of the intermediate \(n\) layer dominates the depletion layer depth. For a temperature \(T = 300\) K, a typical bulk donor doping density \(N_n = 4\times10^{12}/\text{cm}^3\), a typical acceptor doping density \(N_d = 5\times10^{19}/\text{cm}^3\) and literature values for intrinsic carrier intensities for Si, \(15\) for an external junction voltage \(V_j = 0\) V, a depletion layer depth of 16.3 \(\mu\)m can be calculated. Therefore, for thicknesses of 5–10 \(\mu\)m, the detectors operate under full depletion conditions even for zero biasing, avoiding the higher leakage currents associated with higher junction voltages. The calculations are supported by the experimental finding that increasing the bias voltage does not increase the measured currents.

**B. Dark currents**

Dark currents arise from thermally generated electron-hole pairs being separated by the built-in potential. Since the number of thermally generated carriers scales with the volume of the depletion layer, the dark currents scale with the active area. Values obtained for the detectors under test are compiled in Table 1.

Generally, due to the resistive nature of the detector back side, duo-lateral PSDs exhibit higher dark currents than tetralateral PSDs. The tetralateral PSD prototype (Serial No. 2513-16), however, was fabricated as a first testing device on the same wafer as the duo-lateral devices for ease of production and pricing considerations. It therefore lacks a high-dose back side implant that would be added in a dedicated tetralateral production process. Such an implant to lower the sheet resistance from 5 k\(\Omega/\square\) to values in the region of 10 \(\Omega/\square\) is expected to significantly lower the dark currents. At the current stage, the tetralateral device still has larger dark currents than the duo-lateral devices since its larger area is the dominating effect. In the next generation of detectors, a dedicated tetralateral PSD production is planned to realize the advantage of this design.

Static dark current offsets do not influence relative position measurements but only absolute position detection. Stable offsets can be corrected easily. At low x-ray fluxes of \(10^7\) photons/s, however, the photocurrent reaches the offset levels, thereby defining a limit for a reasonable function of the PSD based on regular DC-measurements as discussed below.

**C. Detector transmission**

For the \(3\times3\) mm\(^2\) duo-lateral PSD (Serial No. 2513-15B), the transmission between 5 and 15.5 keV was recorded at beamline BL14.1 (Fig. 5, circles). The measured values correspond to a thickness of 8 \(\mu\)m. The transmission curve for a \(3\times3\) mm\(^2\) duolateral PSD (Serial No. 2513-1D) was recorded over the photon energy range of the KMC-1 beamline (Fig. 5, solid line). The transmission values of 15% at 2.5 keV, 84% at 6 keV and 93% at 10 keV correspond to a Si thickness of \(\sim 5\) \(\mu\)m.

A scan over the whole detector area reveals a peak-to-peak transmission variation below 2%, corresponding to a thickness variation below \(\pm 0.2\) \(\mu\)m. A variation in thickness results in a variation in responsivity. As long as the beam size is smaller than the characteristic length of the variation, the
effect on position resolution can be neglected. This is so because the partitioning of the generated charge due to the different surface resistances between beam position and the electrodes is independent of the absolute charge. To obtain a quantitative estimate of the influence of thickness variation on position detectability, one has to include the exact beam shape. To use a PSD as a precise intensity monitor, the thickness variation would need to be measured and the detector calibrated for it.

D. Position resolution

In general, all center-of-mass-type monitors have in common that they employ a position response \( R(x) \) which changes if the beam is displaced in \( x \). The relation between beam displacement and response can be described as a spatial convolution between the beam intensity distribution \( f_b(x) \) and an intrinsic detector sensitivity function \( f_d(x) \):

\[
R(x) = \int_{-\infty}^{\infty} f_b(x-x')f_d(a,x')dx',
\]

where \( \sigma \) is the rms dimension of the beam and \( a \) is the characteristic dimension of the monitor. Ideally, a monitor should approach the property \( R(x) = f_d(a,x) \) for \( \sigma \to 0 \), achieving a calibration independent of the beam shape. Indeed, this is the most attractive feature of PSDs, where \( f_d(a,x) \) is precisely determined by the underlying semiconductor technology. In one dimension, assuming that \( x = 0 \) at the center of a lateral PSD, the current from anode \( 1 \) is given by \( I_1 = I_0 S_1(x) \), with \( S_1(x) = x/2 + 1/2 \) and \( I_2 = I_0 S_2(x) \), with \( S_2(x) = -x/2 + 1/2 \) from the adjacent anode \( 2 \). Employing the intensity balance (difference over sum) in one dimension, one finds \( f_d(L,x) = 2x/L \) for \(-L/2 < x < L/2\), where \( L \) is the length of the active area.

Values expected from the model for zero and for real beam dimensions are depicted in Fig. 6. For transmissive PSDs, the beam shape does not influence the calibration (slope=2/L curve) but only the length of the linearity range as long as \( \sigma < L \). Compared to other monitor approaches, this is a unique feature of PSDs, since a beam-based calibration including additional motion stages, encoders, etc., introducing a lack in stability, can be avoided. Furthermore, high resolution is expected over a large linear range of up to \( L = 10 \) mm even though the beam size is orders of magnitude smaller, a drawback of quadrant type devices \(^{17,18}\) where the monitor dimension has to be matched to the beam size \( a = \sigma \) in order to preserve a reasonable resolution and full feedback capability.

For scans of the beam across the detector area, the detector was moved against the fixed beam in both horizontal and vertical directions via the manipulator stage. In addition, horizontal sweeps of the beam were performed via the roll axis of the second monochromator crystal of the DCM of beamlines BL14.1 and KMC-1. The current signals observed during such a horizontal sweep are shown in Fig. 7(a), depicting the low cross-talk between horizontal (measured at the anode side) and vertical (cathode side) directions.

A linear fit to the observed difference-over-sum position dependence of a horizontal sweep across the detector is shown in Fig. 7(b). The large region of excellent linearity over almost the entire 3 mm of the active area highlights one of the great advantages of the PSD design in its use as an XBPM. Even though the fit was limited to the central linear range, the effective length \( L \) can be precisely determined. The slight deviation of the slope from the expected value of \( 2/L=2/(3 \) mm\)\)=0.666 mm\(^{-1}\) is due to a reduction of the apparent active region by the electrodes (width of electrodes=50 \( \mu \)m). The partial covering of the active area by the electrodes reduces its size and thereby increases the...
slope to (0.702 ± 0.002) mm$^{-1}$ corresponding to a length of (2.850 ± 0.008) mm.

A much more precise measurement [Fig. 8(a)] and analysis [Fig. 8(b)] using a beam size of only 15 µm, although at a much lower photon flux of $10^8$ photons/s, was used to determine the effective length $L$ of the 1 × 1 mm$^2$ duo-lateral detector (Serial No. 2513-15A) with 1 µm precision. Again, the linearity range is limited to (0.921 ± 0.001) mm by the width of the contact areas. Due to the smaller beam spot, the sweep pattern much more closely resembles that expected for an ideal PSD (Fig. 6). The PSD function of the detector in a microfocus 6 mm behind a capillary is further demonstrated by the complete 2D mappings in Fig. 9. By a fast computation of sum and difference-over-sum, the two separate current measurements A and B allow for a determination of the $I_0$ signal and the center-of-mass of the beam, which is important for feedback purposes.

In contrast to the duo-lateral, the standard tetra-lateral PSD design entails a significant amount of cross-talk between the vertical and horizontal directions.\textsuperscript{19,20} This can be demonstrated by comparing the horizontal cross-talk signals during vertical sweeps and vertical cross-talk signals during horizontal sweeps of the beam across the detector area [see Eq. 2]. The sweep traces separation was adjusted manually to (0.5 ± 0.1) mm.

Such transmissive pin cushion-corrected tetra-lateral devices should soon become available. On the other hand, since the pin cushion effect is a built-in nonlinearity, it can also be corrected numerically.

E. Resolution limits

In measurements on real x-ray beamlines, the separate contributions of beam instabilities and detector noise are hard to distinguish. Due to the arm lengths employed by the optical setups of the synchrotron beamlines, beam position variations due to residual seismic excitations of the optical elements will invariably be larger than the beam monitor resolution. Hence, a separate setup optimized for minimal seismic influences was designed. A battery-powered light-emitting diode white light source, a pinhole, and the PSD detectors on a translation stage were mounted onto a vibration-damping table in the BESSY metrology laboratory. The signal-to-noise (S/N) performance of the detectors was then measured at different detection bandwidths using the FFT analyzer.

It shall be stressed that the position determination in a PSD is effected by the differential measurement of the generated electron and hole currents. Whether the electron-hole pairs were generated by x-rays or by visible light therefore has no direct influence on the achievable position resolution.
Furthermore, the signal current levels were kept equal to those in the x-ray measurements. Thus, noise properties determined in a vibrationally stabilized setup using visible light are transferable to x-ray exposure.

From Eq. (1) and simple Gaussian error propagation, under the assumptions $I_1 = I_2$ and $\sigma_{I_1} = \sigma_{I_2}$, one can derive a simple relation for the dependence of position resolution $\sigma_x$ on the S/N of the current signal $I/\sigma_I$:

$$\sigma_x = \frac{L}{2\sqrt{2}} \frac{\sigma_I}{I}$$

(8)

in the center of a square duo-lateral detector of length $L$. For the duo-lateral detector under test with $L=3\,\text{mm}$, to obtain a position resolution of $\sigma_x = 1\,\mu\text{m}$ the S/N of the current signal $I/\sigma_I$ must be approximately 1000. A similar relation can be derived for tetralateral detectors.

For a $3 \times 3\,\text{mm}^2$ duo-lateral detector (Serial No. 2513-15B, anode and cathode side) and a $5 \times 5\,\text{mm}^2$ tetra-lateral detector (Serial No. 2513-16, anode side), the S/N performance over a broad detection bandwidth range is shown and discussed in Fig. 11. A residual noise component for the duo-lateral cathode and tetra-lateral anode currents at $50\,\text{Hz}$ can be partially attributed to seismic pickup, since the vertical direction of the detector mount was more sensitive to vibrations than the horizontal direction. The distinction between seismics and electrical pickup as noise floor contributors could be made by a more elaborately damped setup which is currently being devised for subsequent measurements.

Following Eq. (8), the observed noise performance of the duo-lateral detector at $1\,\text{kHz}$ corresponds to a position resolution of $350\,\text{nm}$ for the cathode and $150\,\text{nm}$ for the anode side, with the tetra-lateral detector comparable to the duo-lateral anode side. At lower sampling rates of $10\,\text{Hz}$, the resolution dramatically improves to values of $<50\,\text{nm}$ for the duo-lateral cathode and $<30\,\text{nm}$ for the anode side, again with the tetra-lateral detector comparable to the duo-lateral anode side.

The achievable position resolution can be demonstrated by moving the detector stepwise and recording the difference in the position signal. The effected vertical step width was measured concurrently by an optical encoder with $10\,\text{nm}$ resolution. In Fig. 12, steps of $700\,\text{nm}$ in vertical direction were recorded at bandwidths of $10\,\text{Hz}$ and $1\,\text{kHz}$.

To probe the overall frequency sensitivity of the combined system of PSD-XBPM and current amplifier, the setup was acoustically excited at selected frequencies. The peak amplitude of the excitation frequency was then recorded by the spectrum analyzer. As can be inferred from Fig. 13, the frequency response of the detection system drops off strongly between 2 and $10\,\text{kHz}$, with the $-3\,\text{dB}$ level between 3 and $4\,\text{kHz}$. With the detector capacitances in the

FIG. 11. Signal-to-noise ratio (S/N) comparison of a $3 \times 3\,\text{mm}^2$ duo-lateral (DL, Serial No. 2513-15B) and a $5 \times 5\,\text{mm}^2$ tetra-lateral detector (TL, Serial No. 2513-16) for different bandwidths. Up to a detection bandwidth of $10\,\text{kHz}$, the S/N exceeds a factor of $2 \times 10^3$, corresponding to submicron resolution.

FIG. 12. (Color online) Translation stage steps of a $5 \times 5\,\text{mm}^2$ tetra-lateral detector at bandwidths of $10\,\text{Hz}$ and $1\,\text{kHz}$. Both steps cover a width of $700\,\text{nm}$.

FIG. 13. Detection of selectively excited vibrations. The normalized amplitude of the excitation frequency as detected via the cathode and anode currents of a $3 \times 3\,\text{mm}^2$ duo-lateral detector is plotted vs the excitation frequency. The $-3\,\text{dB}$ level is indicated with a dashed line.
100 pF range and the interelectrode resistances given in Table I, this passband behavior is expected.

F. Feedback capability

A feedback system based on the detector signals of a $3 \times 3$ mm$^2$ duo-lateral detector (Serial No. 2513-1D) and the piezoactuator of a monochromator crystal has already been successfully commissioned. Here, the anode-side difference-over-sum signal was employed in a slow proportional-integral-derivative (PID)-feedback loop to stabilize beam drifts during energy sweeps. The piezoactuator voltage for the roll movement of the second crystal of the double crystal monochromator was controlled to lock the beam to the center of the PSD detector 6.5 m downstream of the monochromator with a precision of $<1/100$ FWHM beamsize as depicted in Fig. 14.

G. Discussion

The presented results confirm the properties usually observed for bulk duo- and tetra-lateral designs. The tetralateral detector has a higher relative position resolution due to its higher S/N values over the full observed bandwidth range. The duo-lateral detectors feature a small absolute position detection error due to their inherent decoupling of the orthogonal spatial directions. Both properties—high relative position resolution and small absolute position detection error—are of different importance depending on their field of operation. For fast beam stabilization schemes, the high relative position resolution of the tetralateral design is the most important. For particle detection applications, on the other hand, the small absolute position detection error of the duo-lateral design is the major advantage.

The tetra-lateral prototype (Serial No. 2513-16) tested in the present work offers room for improvement in several points. First, the pin cushion effect can be strongly reduced by the introduction of a so-called infinity-plane implant with low resistivity surrounding the active area. Second, tetralateral detectors require a less complicated production procedure, with essentially only an implantation and a metallizing step required for the cathode side. Therefore, a further reduction in detector thickness to values of 3 µm or thinner should be feasible, with an accompanying increase in detector transmission. Moreover, an additional high-dose implant on the cathode side to lower the sheet resistance can reduce the leakage currents. This would give room to improve their already impressive position resolution as exemplified in Fig. 15 even further. A new batch of detectors to exploit these advantages is planned to be fabricated and tested in the near future.

Most obviously, in the cases where only one spatial direction is of interest to the application, a one-dimensional lateral diode design should be chosen, limiting the required electrode connections to two anodes and one countercathode. From the above discussion, this device would inherit all advantages of the tetra-lateral design (noise performance, resolution, ease of fabrication) without the pin cushion effect, while still providing a large active detector area.

Irrespective of which of the PSD designs is chosen, the presented results show that a transmissive XBPM based on a thinned PSD has several attractive features that set it apart from other design approaches.

First and foremost, its large active area with submicron resolution is rivalled only by some position sensitive ion-chamber designs and chemical-vapor deposition (CVD) diamond photocurrent pixel detectors. In contrast to ion chambers, the PSD detector does not require much space along the x-ray beam direction. A comparable economy of space requirements is provided by transmissive CVD diamond quadrant photocurrent pixel monitor devices. Another feature of the PSD design is its high photon efficiency, providing a high S/N ratio. It therefore has a high position resolution already in medium-to-low photon flux conditions in which, e.g., fluorescence backscattering quadrant-diode monitors do not provide sufficiently large signal currents. The cross-talk issue of any quadrant-readout-based design is specifically avoided by duo-lateral PSDs, a feature that only the photocurrent pixel detector and other imaging XBPMs (e.g., Refs. 28 and 29) can provide. Duo-lateral PSDs also allow the determination of the true center-of-mass position of the beam, a property only shared by true...
imaging monitors. Any device with cross-talk between the orthogonal spatial directions is limited in this regard, as are detectors with pixel dimensions of comparable size to the beam. Detectors that sample the fringes of the beam cross section, such as annular detectors, or blade designs, are particularly suited for much higher photon flux conditions than PSDs, but detect beam movements without determining the true center-of-mass position.

A further advantage inherent in the PSD design setting it apart from most other physical effects exploited in beam monitoring devices is its operation both under x-ray and visible light irradiation. Precision instruments not easily available in a beamline can thus be employed to evaluate the detectors. In addition, commissioning of control systems and feedback schemes is possible without actually running the devices in the beamline.

Last but not least, its high position resolution even at fast sampling rates in the kiloHertz regime completes the PSD’s feature set.

IV. CONCLUSION

In conclusion, the first transmissive PSD-XBPMs have already proven their potential for a generic solution for beam monitoring and for their use in feedback schemes for crystal monochromator beamlines. With their submicron position resolution at kiloHertz detection bandwidths and a peak resolution of several 10 nm at 10 Hz over a several millimeter sized active area, they are prime candidates for inclusion in fast and high-resolution feedback stabilization schemes.

The comparison of the duo-lateral and tetra-lateral detector designs yields favorite application scenarios for either principle. The extension of the tetra-lateral design to a pin cushion-corrected version in a dedicated production process could further increase the attractiveness of this design approach.

With the detectors now permanently included in BESSY beamlines BL14.1 and KMC-1, a thorough assessment of the long-term stability of the detectors is underway. Further results on the performance of the larger (10 × 10 mm²) and smaller (1 × 1 mm²) detectors both from measurements at BESSY and from the PSD development project partners should become available soon.

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