Comparison between invasive and non-invasive photon beam monitors in the tender X-ray regime for beamline diagnostics, optimization and feedback

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ABSTRACT

We experimentally evaluate the performance of a novel pixelated diamond sensor for non-invasive X-ray beam monitoring in the tender X-ray regime (6–30 keV). Through simulations and experiments, we assess its precision in measuring beam parameters (flux, position and size) and compare it to a scintillator re-imaging microscope, an established, invasive photon beam diagnostic. Experimental results for the pixelated diamond sensor show a position sensitivity better than 50 μm-rms (on the order of the pixel size), up to >100 Hz feedback rates, and accurate beam size tracking. The pixelated diamond sensor, though less precise than a scintillator reimaging microscope, offers the advantage of being non-invasive and has been successfully integrated into automated alignment routines using EPICS/Bluesky instrument control framework.

Keywords: X-ray, Photon Beam Position Monitor, Diamond Sensor, Diagnostics

1. INTRODUCTION

With the upgrade of synchrotron light sources to diffraction-limited storage rings, new beamlines taking advantage of the increased brightness and coherence will need new photon beam diagnostics in order to ensure optimal performance. A novel pixelated diamond sensor (ClearXCam), developed by Advent Diamond, is designed for non-invasive beam imaging in the tender X-ray regime (6 keV to 30 keV and above), for monitoring, stabilization and continuous correction of the beamline. This study aims to test the precision of the pixelated diamond sensor and compare its performance with traditional diagnostic tools such as a YAG scintillator reimaged with a microscope. Our approach integrates simulations to estimate the expected theoretical performance of the beam imager as a position monitoring device, and experiments conducted at Beamline 5.3.1 at the Advanced Light Source (ALS) to evaluate the actual performance of those diagnostics.

2. SIMULATION OF BEAM POSITION SENSITIVITY

We simulated a beam imaging diagnostics by generating a Gaussian beam of various sizes over a 20 μm grid size, and adding gaussian noise with varying intensity to simulate the effect of shot noise (Figure 1). For each of the simulated images, where $I(x_n)$ is the intensity at position x_n, we estimate the centroid:

$$\hat{x}_m = \sum_n x_n I(x_n) / \sum_n I(x_n) \tag{1}$$

and the beam size:

$$\sigma_x = \sqrt{\left(\sum_n (x_n - \hat{x}_m)^2 \times I(x_n) \right) / \sum_n I(x_n)} \tag{2}$$

and we estimated the average variation over an ensemble of 100 measurements.

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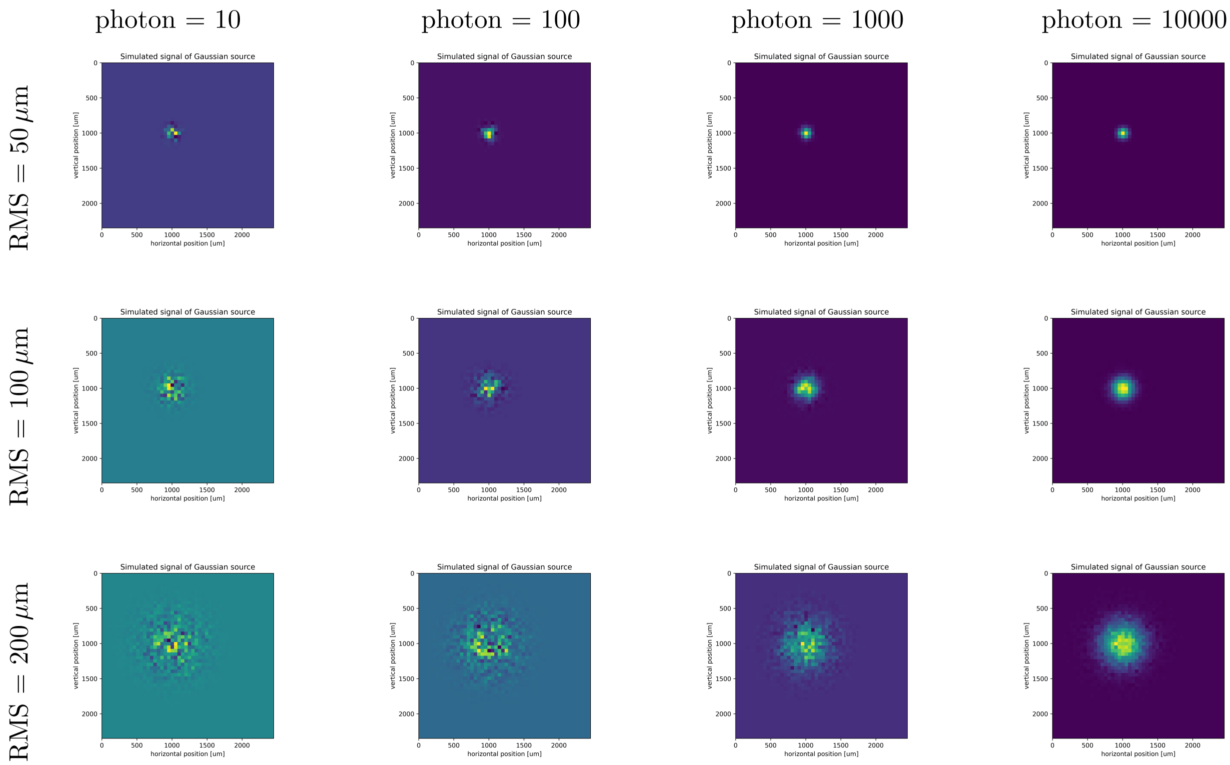

Figure 1. Simulated Gaussian sources with different RMS beam size values and number of photons.

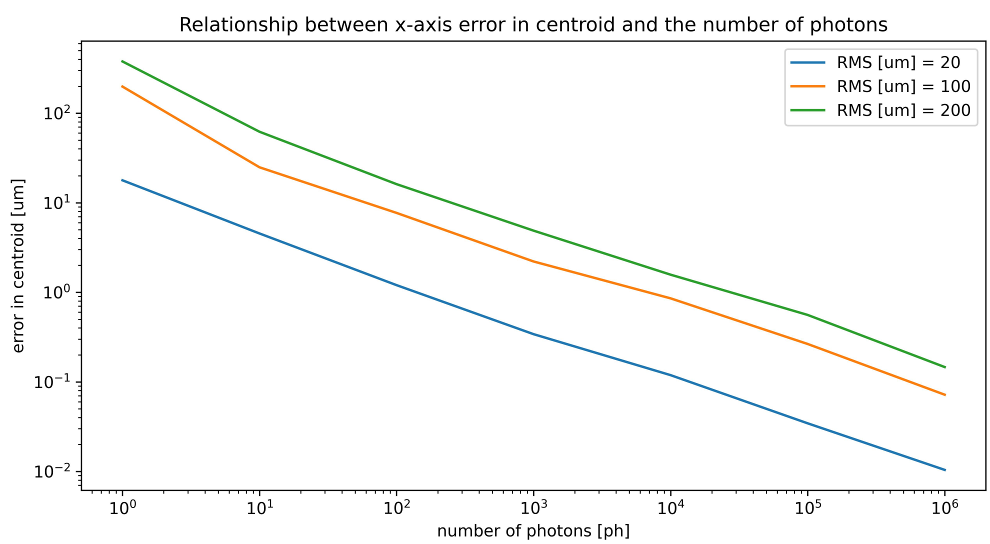

Figure 2. Simulation results: relationship between x-axis error in centroid and number of photons.

We varied total image photon counts from 1 to 10^6 photons, and source sizes from 20 to 200 μm. Figure 2 reveals that the error decreases as exposure increases or the beam size decreases.

Assuming a beam size (RMS) of 100 μm, we determined that 5000 photons are required to achieve a position accuracy better than 1 μm-rms (in the absence of instrument noise).

Bobroff[1] provides a handy estimate of the centroid error for a gaussian beam based on the signal to noise ratio (SNR), the beam size Γ and the number of pixel sampling the beam size N_Γ:

$$(\hat{x} - \hat{x}_m) = \frac{1.8}{\text{SNR}} \sqrt{\frac{1}{N_\Gamma}} \times \Gamma \tag{3}$$

For example, for the sampling of a 100 μm-rms gaussian beam size with 20 μm pixels and collecting only 1000 photons, the expected centroid error would be about 2.5 μm, in agreement with our empirical simulations (considering shot noise only, a coarse estimate is that the SNR is the square root of the number of photons). Generally, for a typical visible light camera with an 8-bit dynamic range (SNR $\approx$ 16) sampling a beam over 5 pixels, it is common to have a centroid error of $1/20^{\text{th}}$ of the effective pixel size when the exposure time is set near the saturation of the camera.

3. EXPERIMENTS

We designed a scintillator re-imaging microscope in order to evaluate the sensitivity of a standard, invasive X-ray beam imager and provide a point of comparison for the pixelated diamond sensor.

3.1 Design of a scintillator re-imaging microscope for X-ray beam imaging

To image the tender X-ray beam, it is possible to use a dedicated X-ray camera with direct CCD detection, but those are bulky (they need to be mounted on a flange), expensive and tend to have relatively large pixel size (typically 15 μm or more) owing to the fact they need a large well depth (>100,000 e-) to provide enough dynamic range for direct detection. Therefore, we designed a relatively compact scintillator re-imaging microscope[2] for X-ray beam imaging and assembled it using off the shelf components (Figure 3).

The scintillator is a YAG:Ce scintillator with 500 μm thickness that converts X-rays into visible photons at around 550 nm wavelength. The objective is a 5× lens with a numerical aperture of 0.14 and a 34 mm working distance (Mitutoyo MY5X-802). We use a Mitutoyo MT-4 tube lens with a 200 mm focal distance to form an image on the sensor of a CMOS camera (a Basler a2A2448-23gcPRO camera based on a Sony IMX-547 sensor with 2448 px × 2048 px, 2.74 μm pixel size, 10 ke- well depth and 3 e- dark noise).

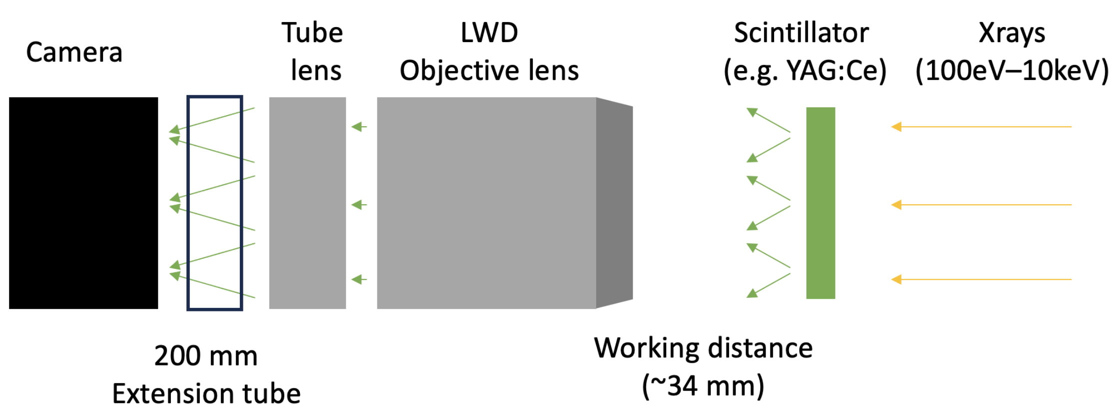

Figure 3. Schematic of a scintillator re-imaging microscope for soft/tender X-ray beam position monitoring.

The effective pixel size of the microscope is 0.548 μm with a 1.34 mm × 1.12 mm field of view and the optical resolution of the microscope is $1.22\lambda/\text{NA} = 4.8$ μm. Assuming a typical yield for the YAG:Ce scintillator of 15 photons/keV, it would generate about 120 visible photons per X-ray photon at 8 keV. The collection efficiency of the objective is $D = -\frac{1}{2}(\cos(\text{NA}) - 1) = 4.9\%$. Taking into account a 65% quantum efficiency of the CMOS sensor, we should be able to collect 4 visible photons per incident X-ray photons, thereby operating in a regime mainly limited by the shot noise of the incident beam without significantly compromising dynamic range.

3.2 Sensitivity measurements of the re-imaging microscope

We installed the scintillator re-imaging microscope at the Advanced Light Source beamline 5.3.1 (operating on a bending magnet) near the focus of the beamline (Figure 4). The beamline has a nominal focus size of 240 μm x 90 μm (HxV, FWHM), though it is a bit larger in practice owing to contamination on the crystal monochromator. We used a monochromatized beam at 8 keV to perform the measurements.

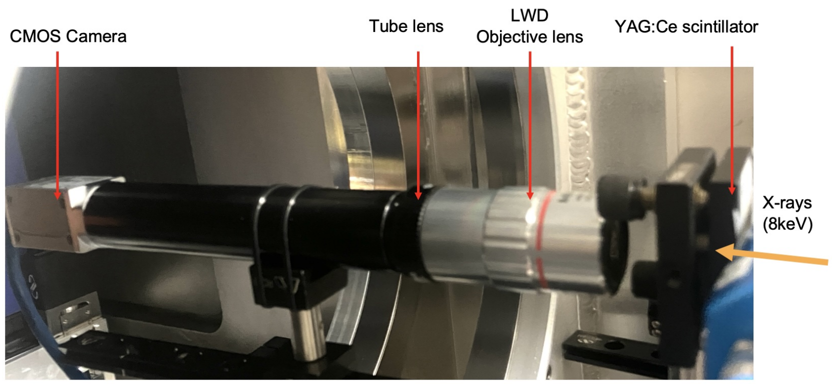

Figure 4. Picture of the scintillator re-imaging microscope at ALS beamline 5.3.1.

We collected data for various exposure time: near detector saturation at 1 s, at 100 ms exposure and 10 ms exposure time (Figure 5). For each exposure, we collected 100 images to build statistics, and for each image we computed the centroid in the horizontal and vertical directions.

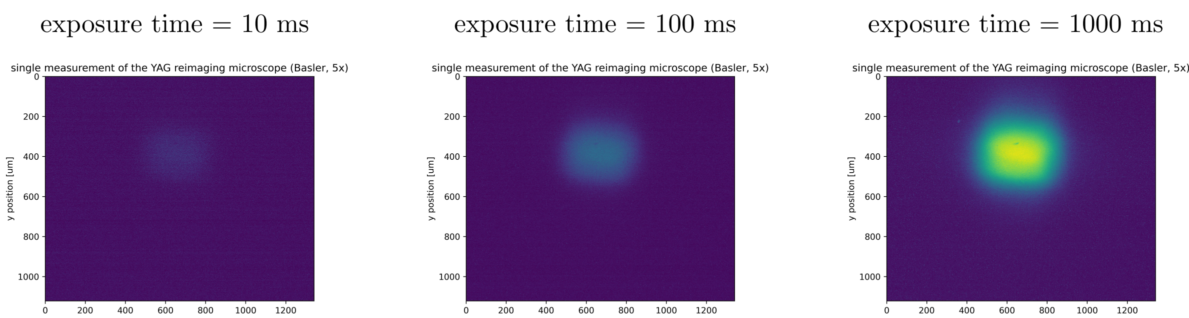

Figure 5. Single measurement with the YAG microscope at ALS beamline 5.3.1 near focus 8 keV operating photon energy for different exposure times. The average horizontal centroid error over 100 measurements is 0.23 μm-rms for 10 ms exposure time, 0.29 μm-rms for 100 ms exposure time and 0.20 μm-rms for 1 s exposure time.

We found that the centroid position error didn't appreciably increase with a decrease of the exposure time, with an average centroid error hovering around 0.25 μm-rms. This shows that the setup is relatively stable and the beam not blurred out by vibrations at frequencies below 100 Hz. A coarse estimate of the number of photons collected at 10 ms is about 10^6, which, according to the expected centroid error from Eq.3, is on the order of 0.05 μm-rms, indicating that the setup is not too far from its physical detection limits despite its relatively crude assembly and uncontrolled environment.

3.3 Pixelated diamond sensor

The ClearXCam[3] pixelated diamond sensor is a commercially available sensor from the company Advent Diamond based on a similar principle developed at NSLS-II.[4] The pixelated diamond sensor has an active area of 2.37 mm $\times$ 2.37 mm, with 48 $\times$ 48 pixels of size 50 μm $\times$ 50 μm. The thickness of the diamond is 50 μm thick and allows for an X-ray transmission of 90% or more above 6 keV. It is a non-invasive photon beam imaging device that can be used to measure the intensity of the beam, but also its position and its size at rates up to 100 Hz.

3.4 Experimental comparison of the pixelated diamond sensor and the scintillator re-imaging microscope

We installed the pixelated diamond sensor at the Advanced Light Source beamline 5.3.1, just in front of the scintillator re-imaging microscope (Figure 6).

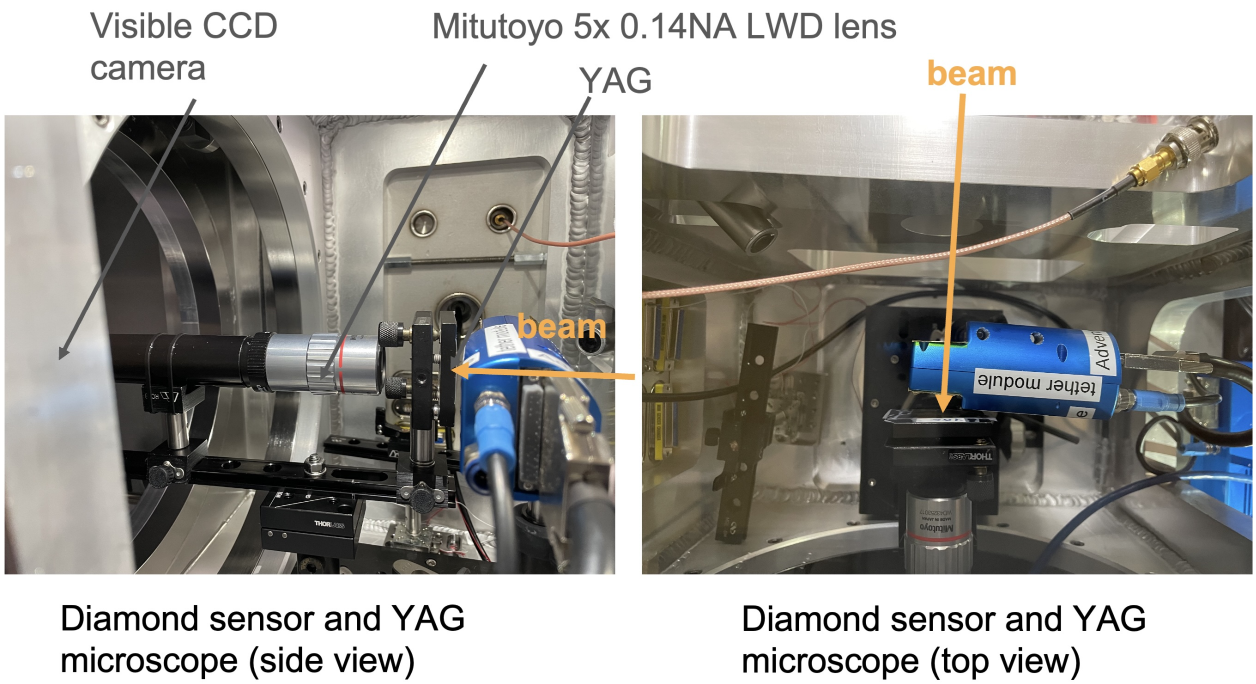

Figure 6. Experimental setup at ALS Beamline 5.3.1.

We collected the data over ethernet using the EPICS controls systems "pvaccess" feature at a rate of 1 Hz, a feature that we previously used to develop automated alignment procedures.[5] We simultaneously collected data with the scintillator re-imaging microscope at 1 s exposure time. We varied the operating photon energy from 6 keV to 9 keV (Figure 7).

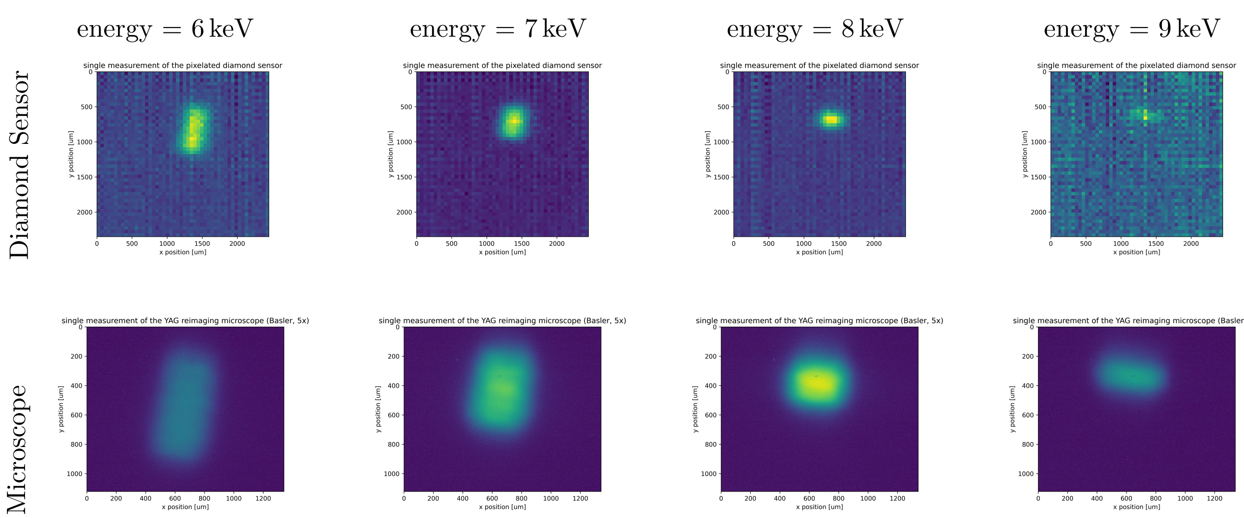

Figure 7. Single measurement of the pixelated diamond sensor and the YAG microscope for different photon energies with 1 s exposure time.

We found that the shape of the beam was qualitatively similar for both sensors and unexpectedly changed while adjusting the channel cut double crystal monochromator (silicon $\langle 111 \rangle$), indicating that the monochromator is severely contaminated and shows that spatial information about the beam is very valuable.

We collected 100 raw images for each photon energy to build statistics and determined the standard deviation between independent determinations of the beam centroid and RMS beam size in both horizontal and vertical directions (Figure 8).

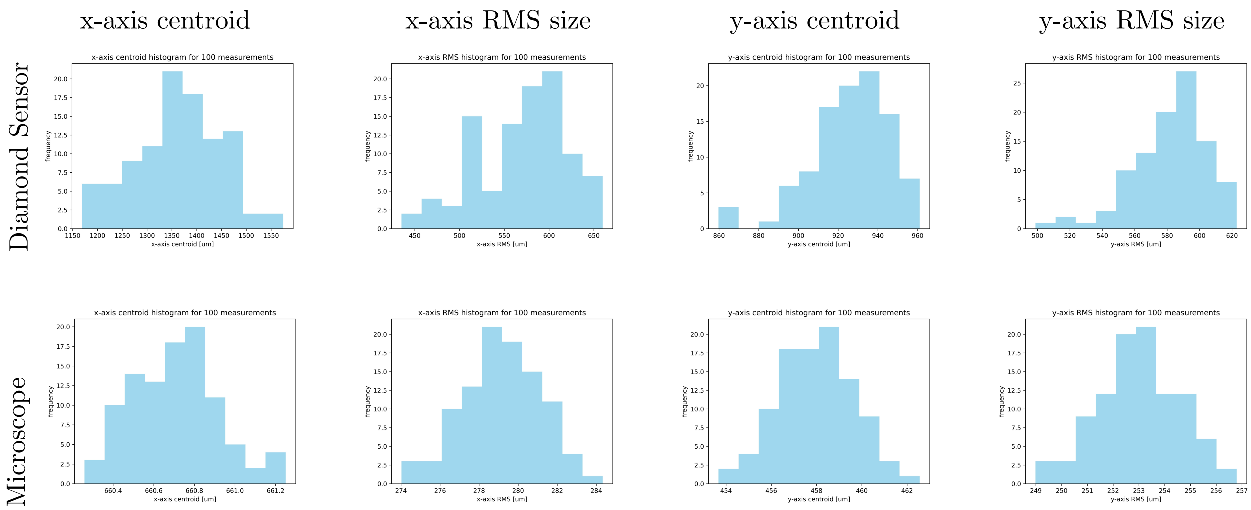

Figure 8. Histograms of the estimated x-axis centroid, RMS beam size and y-axis centroid, RMS beam size for 100 collected images of the pixelated diamond sensor and the YAG microscope at 8 keV.

We found that the pixelated diamond sensor has a centroid sensitivity at 8 keV that is on the order of the pixel size (about 50 μm-rms) in the horizontal direction and 50 μm-rms in the vertical direction (Table 1). This is above the theoretical physical limit evaluated from Eq.3, which is on the order of 0.5 μm-rms. However, the pixelated sensor is not ideal and displays noise and features in the raw images that can be calibrated out and filtered to further increase the precision, a capability provided by the vendor software. Note that the detection efficiency of the pixelated diamond sensor is also much lower than that of the invasive sensor, since it is over 90% transparent to X-rays at 8 keV. The centroid position error for the scintillator re-imaging microscope in the vertical direction is about 1.68 μm-rms, which indicates that the beam is less stable in the vertical direction, probably due to vibrations in the monochromator.

Table 1. Standard deviation of the estimated centroid and RMS computed from 100 images collected at 8 keV.

Device	x-axis (error in μm-rms)		y-axis (error in μm-rms)	
	beam centroid error	beam size error	beam centroid error	beam size error
Diamond Sensor	86.52	49.81	19.59	22.74
Microscope	0.20	1.98	1.68	1.56

4. CONCLUSION

We have evaluated the performance of a typical invasive beam imaging device and a novel non-invasive pixelated diamond sensor that can be monitored during beamline operation. We have evaluated theoretical physical limits for the determination of the beam position and size, and performed measurements with the two devices. We found that the scintillator re-imaging microscope has a precision which is within an order of magnitude of its theoretical limits but is invasive, while the pixelated diamond sensor delivers real-time measurements of beam parameters for photon energies above 6 keV and has a beam position sensitivity on the order of the pixel size (50 μm) which could potentially be improved. It also allows one to detect features in the beam that non-imaging diagnostics would miss, and has proven particularly useful for automated alignment procedures.[5]

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