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Characterisation of CVD Diamond devices as XBPMs at SOLEIL

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Abstract. Single crystal CVD diamonds have been developed for use as XBPMs on the beamlines of the French synchrotron SOLEIL. These devices have been calibrated and characterized directly on the beamline following an elaborate protocol. An example is given for an XBPM installed on PROXIMA 2. This device has shown a charge collection efficiency of 100% for only 0.2V/ μm with total signal-to-noise ratio better than 10^5 . A complete 2D scan gives the homogeneity of the scale factors over the active surface with a very low error corresponding to 0.6 μm (beam off-center and maximum calibration error). The current sensitivity measurement shows a fluctuation less than 0.02% and the responsivity is calculated to measure the incident flux. And finally, the spatial resolution for these XBPMs is better than 1 μm rms at 1kHz and 100 nm rms at 5 Hz.

1. Introduction

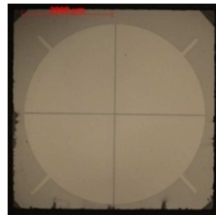
Beamlines at synchrotron facilities need X-ray Beam Position Monitors (XBPM) to be robust, transparent and very sensitive to precisely monitor and regulate the intensity and position of the X-ray beam. The incident X-ray stability is critical to the success of an experiment, either because of micro focusing, or for data normalization. For example, the PROXIMA 2A (PX2-A) beamline will be dedicated to micro-crystallographic experiments on crystals of biological macromolecules. It will provide a beam size of 5 μm $\times$ 3.5 μm for diffraction experiments on micro-crystals below 10 μm in size, and to succeed, this beamline must provide a stable position of the beam (50 nm rms) over a wide time range: from a few ms to several minutes. However, XBPMs currently available and in use – such as devices employing fluorescence from a thin foil associated with four photodiodes [1] or very thin silicon photodiodes [2] – are not sensitive enough, nor robust enough, nor sufficiently transparent to achieve the required performance. Furthermore, such devices are typically accurate to within a few microns at 100 Hz or degrade rapidly under the flux of X-rays.

Single crystal CVD (scCVD) diamonds have generated much interest as X-ray monitors [3] at many synchrotron facilities because of their robust properties, low X-ray absorption and their high sensitivity. Here, we characterise the performance of such XBPMs manufactured from scCVD diamonds.

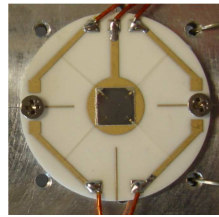
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2. Experimental Setup

Several XBPMs have been made from single crystal CVD diamond of “detector grade” with dimensions of 4.5mm × 4.5mm and 50μm thick (ElementSix). In collaboration the CEA Diamond laboratory (Saclay, France), we fabricated a series of classical four-quadrant detectors with 200nm Al electrodes using a standard photolithographic technique with an inter-electrode gap of 20μm. These detectors were mounted and wire-bonded onto a PCB board and installed in a vacuum chamber.



(a)



(b)

Figure 1. (a) Diamond with four electrodes
(b) XBPM mounted on PCB board.

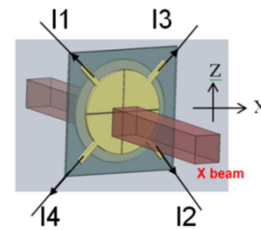


Figure 2. Representation of XBPM as installed on PX2 (2mm (H) x 1mm (V))

An XBPM has been installed on the PROXIMA 2 beamline downstream of the channel-cut crystal monochromator. The measurements of characterisation protocol employed a large unfocussed beam of 2 mm × 1 mm (which was reduced in size with slits for more precise scans) at an energy of 12.65keV ($\sim 3 \times 10^{12}$ ph/s at 400mA storage ring intensity).

The XBPM and its vacuum chamber were mounted on an XZ translation stage (0.1μm resolution) as shown on figure 2. The four electrodes were connected to a four-channel current-to-voltage amplifier (LOCuM-4, by ENZ www.enz-de.de) and the voltages were digitized by an ADC (Adlink 2010). Although the voltage polarization was optimized with a variable source voltage, a simple 9V battery was used and provided lower noise.

The position of the beam is reconstructed in the two directions by a simple centre of gravity algorithm:

$$X(mm) = \frac{(I1 + I4) - (I2 + I3)}{I0} / Kx - OffsetX \quad \& \quad Z(mm) = \frac{(I3 + I1) - (I4 + I2)}{I0} / Kz - OffsetZ \quad (1)$$

with I_i the four electrodes currents, I_0 the sum of four currents, the K_x and K_z the scale factors (mm^{-1} , obtained after calibration) corresponding to the displacement X and Z , $OffsetX$ and $OffsetZ$ the beam position offsets (mm) relative to the four-quadrant centre. The difference over the sum of the currents varies from -1 to 1, the linearity and the slope of this calculation depends on the incident beam size.

3. Experimental Results

3.1. XBPM total current versus polarization voltage & noise current

The diamond was irradiated with synchrotron X-rays on the PX2-A beamline ($E=12.65keV$), and the current of each electrode was measured as a function of the polarization voltage. A full charge collection was obtained for only 0.2V/μm with a total current of 6.1μA. Previously, a similar measurement had been done without X-rays to check the electrical connections and to measure the leakage current of the XBPM. The ratio of X-ray beam induced current (XBIC) and leakage current was better than 10^5 . The noise for each electrode was measured with and without X-rays in measurement conditions (i.e current-to-voltage gain = $10^6V/A$, ADC sampling frequency=500kHz, integration time 100ms). The S/N ratio ($I_i/\sigma I_i$) measured was better than 2×10^5 , and thus the limit of the spatial resolution was determined to be 10nm rms as estimated by simple error propagation (with the scale factors $K_x=K_z=1 mm^{-1}$).

1.2. XBPM Calibration

The horizontal and vertical calibration curves have been determined by displacing the XBPM (pre-aligned in the beam) whilst recording the four currents for all positions. The difference over the sum (Equation 1) versus position is fitted with a linear function (Figure 3) for horizontal and vertical scans. The fitting leads to scale factors of $K_x=1.05\text{mm}^{-1}$ and $K_z=1.95\text{mm}^{-1}$. The difference between the two directions comes from the respective size of the beam (larger in Z)

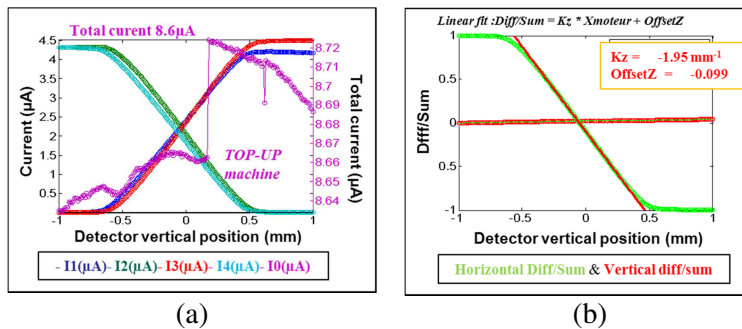


Figure 3. (a) Electrode and total currents vs. one vertical XBPM displacement. (b) Difference over the sum of currents vs. one vertical XBPM displacement.

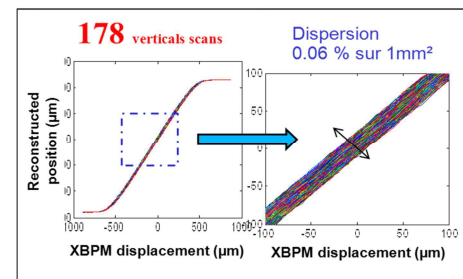


Figure 4. Superposition of 178 reconstructed position scans.

The spatial homogeneity of the XBPM calibration has been confirmed with a fine 2D (10μm steps) scan over the active surface. The excellent superposition of 178 reconstructed position scans (Figure 4(a)) shows the efficiency of the calibration in reconstructing the position over a large active area. Finally, this calibration gives the mean of the scale factor with a small dispersion $\sigma(K_z)=1.2\mu\text{m}^{-1}$. The maximum relative reconstructed position error, when a scale factor of $K_z + 2\sigma K_z$ is applied, is 0.6μm at the edge of active area.

1.3. XBPM Intensity monitoring

The homogeneity of the beam intensity measurement can be determined with the same 2D scan. The plot in Figure 5 gives an image of the total current (I0) for all positions of the XBPM. We measured a variation of 30nA rms over 1mm² corresponding to 0.35%. This device can therefore be used as an excellent intensity monitor.

The sensitivity of this monitoring is illustrated by following the current fluctuation in the time. Figure 6 displays this with a time scan acquisition of the X-rays in Top-Up mode (0.5% re-injection every 4 minutes) and yields a standard deviation for the total current of 1nA rms (0.02%).

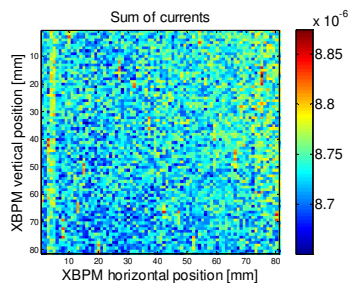


Figure 5. Image of homogeneity of I0 on the center of active area

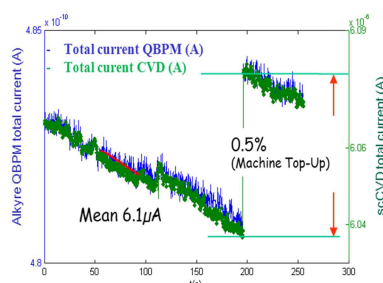


Figure 6. Time scan with visualisation of the top-up machine

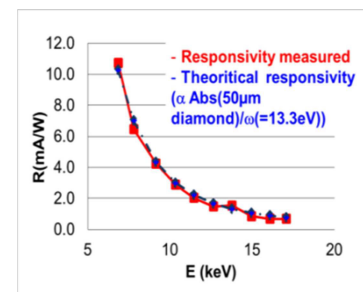


Figure 7. Responsivity of the scCVD diamond XBPM versus energy

The responsivity of the XBPM is measured to use it as an absolute photodetector [4]. The XBPM was irradiated at different energies (5-17keV). The XBPM total current recorded for each energy was compared with the theoretical incident flux calculated from the calibrated silicon photodiode current situated downstream. The responsivity as a function of energy is shown in Figure 7 and compares well with the theoretical responsivity which depends on the absorption of diamond (with the charge collection efficiency parameter set to 100% and $\omega=13.3\text{eV}$ of average energy to create e-h pair).

1.4. XBPM spatial resolution

The spatial resolution has been measured for different bandwidths in identical conditions. The XBPM and the beam are fixed and the voltage to current gain was set at 10^6V/A (bandwidth of 2.5kHz). Figure 8 shows the reconstructed position for small displacement of $5\mu\text{m}$ and $1\mu\text{m}$ for an ADC integration time of 100ms and 1ms. Figure 9 shows the variations (standard deviations) of the reconstructed positions in both directions as a function of the bandwidth. The difference is due to the beam size.

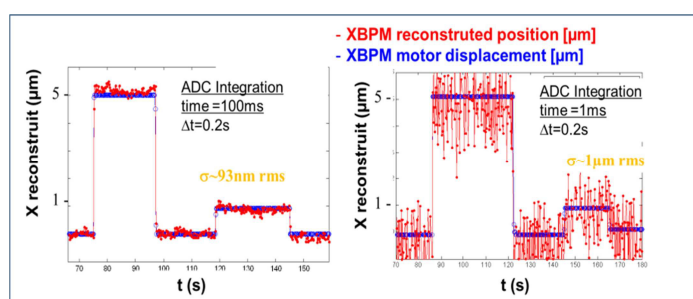


Figure 8. Time scan with small XBPM displacement with ADC integration time of 100ms and 1ms

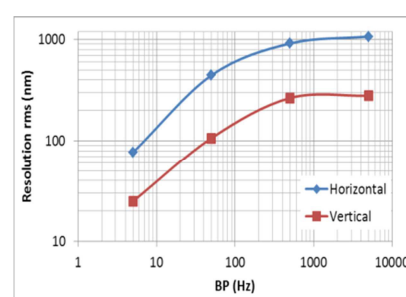


Figure 9. Standard deviation of reconstructed position measured versus the bandwidth

4. Conclusion

We have manufactured and demonstrated the performances of scCVD diamond XBPM with a resolution better than $1\mu\text{m}$ rms at 1 kHz acquisition and 100 nm rms at 5 Hz. The sensitivity for photon flux monitoring is better than 0.02%. The test protocol elaborated here have been used for several types of XBPMs (CVD diamond, silicon PSD photodiodes, fluorescence foil + photodiodes), and it is continually optimized. Ten CVD diamond XBPM of different geometries will be installed at SOLEIL on the PX2 and SIRIUS beamlines. A new prototype for pink beam on the NANOSCOPIUM beamline, and a very thin polycrystalline prototype ($3\mu\text{m}$ thickness) for tender X-rays on SIRIUS are currently developed.

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