THE USE OF SINGLE-CRYSTAL CVD DIAMOND AS A POSITION SENSITIVE X-RAY DETECTOR

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Abstract

Synchrotron light sources generate intense beams of X-ray light for beamline experiments, and the stability of these X-ray beams has a large impact on the quality of the experiments that can be performed. User experiments increasingly utilise micro-focus techniques, focusing the X-ray beam size to below 10 microns at the sample point, with beamline detectors operating at kHz bandwidths. Thus, there is a demand for non-invasive diagnostic techniques that can reliably monitor the X-ray beam position with sub-micron accuracy in order to characterise X-ray beam motion, at corresponding kHz bandwidths. Reported in this paper are measurements from single-crystal CVD diamond detectors, and a comparison with the previous-generation of polycrystalline CVD diamond detectors is offered. Single-crystal diamond is shown to offer superior uniformity of response to incident X-rays, and excellent intensity and position sensitivity. Measurements from single-crystal diamond detectors installed at Diamond Light Source are presented, and their use in feedback routines in order to stabilise the X-ray beam at the sample point is discussed.

INTRODUCTION

Diamond radiation detectors typically utilise diamond films or plates, some 50 μm thick. Electrodes are deposited on opposite surfaces of the plate (the “front” and “back” of the device), with wire-bonded connections to a PCB frame or holder for the diamond. Standard lithography techniques allow the size and shape of the electrodes to be controlled: dots, quadrants, strips, and pixels can all be realised on the diamond surface. Figure 1 shows a typical arrangement.

Sufficiently energetic incident radiation absorbed by carbon atoms promote electrons from the valence band into the conduction band, forming electron hole pairs. Under the influence of a bias voltage these charge carriers travel to one of the electrodes, where this current can be amplified and measured.

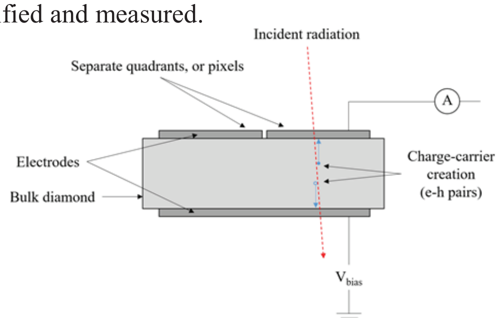

Figure 1: A schematic layout of a diamond X-ray detector

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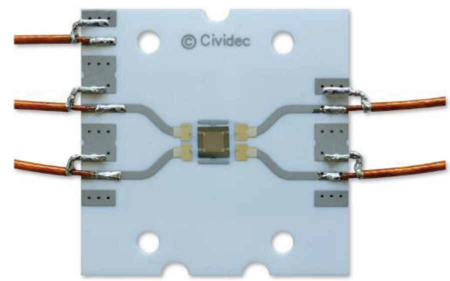

Figure 2: A photograph of the single-crystal diamond detector tested at DLS. The detector is a 4.5 mm x 4.5 mm square diamond in the centre of the image, and is mounted on a ceramic PCB.

Experiments carried out at Diamond Light Source Ltd. (DLS) have been performed to evaluate the performance single-crystal diamond X-ray detectors. Maintaining the spatial stability of the X-ray beam relative to the sample point for the duration of user data collection is vitally important for synchrotron beamlines. Sub-micrometer beamsizes at the sample point are increasing common, and the typically required beam stability is some 10% of beamsize [1]. Reliable X-ray diagnostics are essential during beamline commissioning, during routine “start-up”, and during data collection itself as, increasingly, beamline detectors at DLS operate in the kHz regime. Single-crystal diamond detectors offer the ability to make correspondingly high precision position measurements at these bandwidths.

Results presented in this paper are from quadrant detectors, with four square electrodes (metallised “quadrants”, or “pads” on the surface of the diamond, less than 100 nm thick) deposited onto one face of the diamond, and a single electrode deposited onto the opposite face of the diamond. These sensors can be used to provide both spatial and intensity measurements. Commonly, this type of detector is referred to as an X-ray Beam Position Monitor (XBPM).

SIGNAL LINEARITY VS INCIDENT FLUX

The signal produced by diamond detectors is typically a current of a few nanoamps to microamps. The signal produced (i.e. the number of charge carriers created in the bulk diamond) is directly proportional to the number of absorbed photons, and thus proportional to the incident light. Signal-crystal diamond has been shown to exhibit a linear signal response to incident flux over many orders of magnitude.

The I04 beamline at DLS has the ability to attenuate the incident light using a series of calibrated absorption materials, inserted into the X-ray beam path. In this way, the

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incident flux can be highly controlled, and the flux reaching the detector can be accurately adjusted over several orders of magnitude.

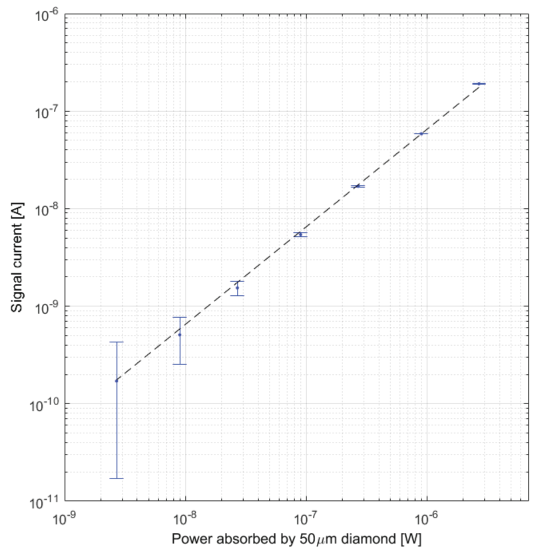

Figure 3: The linearity of signal response from a 50μm thick single-crystal diamond detector.

Figure 3 shows the linearity of the detector to incident flux ("absorbed power") for incident light at 12.7 keV. The amount of incident flux (determined by the absorption materials inserted into the beam path) is independently established using a calibrated diode. Measured noise on the signal is as low as 0.52% of the detected signal at 1 kHz bandwidth.

SIGNAL UNIFORMITY ACROSS THE DETECTOR FACE

Polycrystalline diamond can be used as a detector of ionizing radiation, however the resolution of the sensor is limited by the size of the crystal grains, and single-crystal diamond is known to produce a superior detector [2, 3]. In order to measure the uniformity of a diamond detector a focussed X-ray beam is used to illuminate the sensor surface and the resulting signal currents are measured. A calibrated diode is mounted behind the detector in order to provide an independent measure of the incident beam intensity (referred to as an "*i0*" measurement). The diamond detector is mounted on a precision motion stage, capable of sub-micron movements in the horizontal and vertical direction. The signals from each of the four detector channels are recorded as a 2D raster scan of the detector through the incident beam is performed. As a raster scan of this nature takes some considerable time (some ~30 minutes) the measured signal from the diamond detector quadrants must be normalised to the *i0* measurement in order to remove the effects of top-up and other variations in incident beam intensity over this period.

The results of such a scan using a 25 µm (RMS) Gaussian beam of 12.7 keV photons are shown in Figure 4, where the sum of the signal currents from each of the four quadrants is presented.

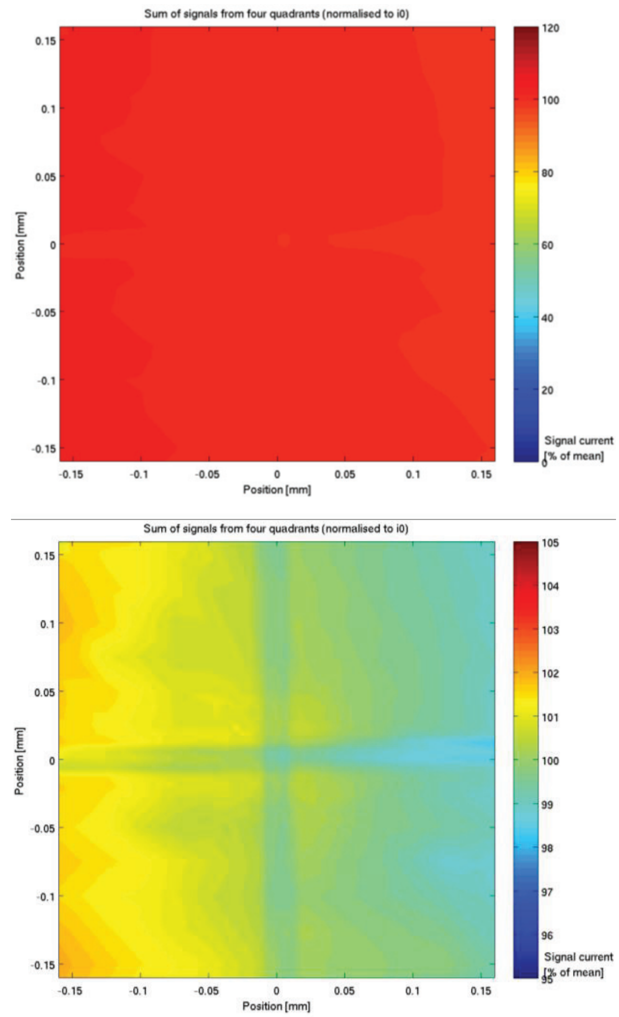

Figure 4: (Top) The measured uniformity of response to incident X-rays over the position-sensitive region at the centre of the detector. The signal current from all four quadrants is summed and displayed. (Bottom) The same measured signal, scaled in order to small changes in sensitivity over the surface of the detector.

These results show a uniform response to signal to within a few percent. There is however a measurable change in the measured signal between the left and the right of the detector (as viewed in this plot). This is due to the polishing of the diamond resulting in a wedge shape. Where the diamond is thickest (at the left of the image) it absorbs more of the incident light and thus a higher signal current is produced.

The gap between the quadrants is visible on the uniformity plot, seen as a "cross" on the image. The thickness of this cross in the plot is a convolution of the size of the insulating gap between neighbouring quadrants, 2 µm, and the incident X-ray beam size, 25 µm.

That the measured signal current appears weaker in this gap region is due to an artefact with the *i0* normalisation.

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The metallised electrodes, despite being less than 100 nm thick, absorb a portion of the incident light. However, there Figure 5 show the individual measured signal currents from each of the four quadrants (labelled A, B, C, and D) as the X-ray beam is moved across the face of the detector shown in Figure 4.

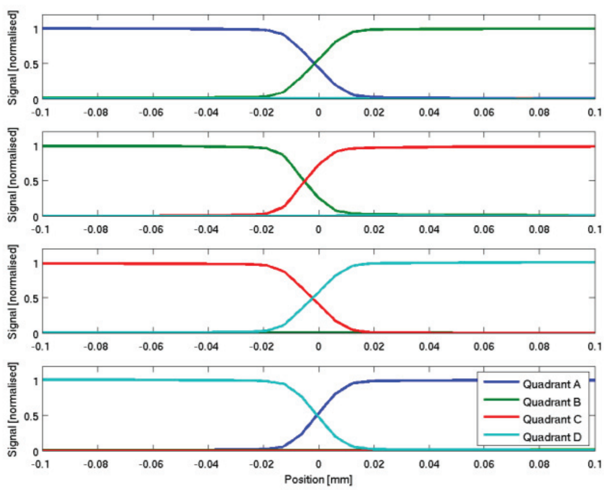

Figure 5: The results of 1D scans of the X-ray beam moving across the face of the detector is shown, demonstrating the uniformity of the signal currents seen as the beam passes from one quadrant into the neighbouring quadrants. The top plot shows the signal seen as the beam moves from quadrant A into quadrant B; the second shows the beam moving from quadrant B into quadrant C; and so on.

The measured signal currents from four 1D scans are presented. Each scan is 200 μm long scan as the X-ray beam passes from one quadrant into the next. Quadrant A is located in the top left of the detector shown in Figures 2 and 4; quadrant B is top right; and naming continues in a clockwise direction. The top plot of Figure 5 shows the signals measured during a scan starting at coordinate (X = -0.1 mm, Y = 0.1 mm) and moving horizontally to (X = 0.1 mm, Y = 0.1 mm); the second plot shows the results from a scan starting at (X = 0.1 mm, Y = 0.1 mm) and moving vertically to (X = 0.1 mm, Y = -0.1 mm); and so on.

THE EFFECTS OF CHANGING BIAS VOLTAGE

The bias voltage that is applied to the detector has an impact on the velocity at which the charge carriers will travel through the bulk diamond. This has previously been examined elsewhere [4], and it is recognised that the sensitivity of single-crystal diamond detectors can be influenced by the magnitude of the bias used.

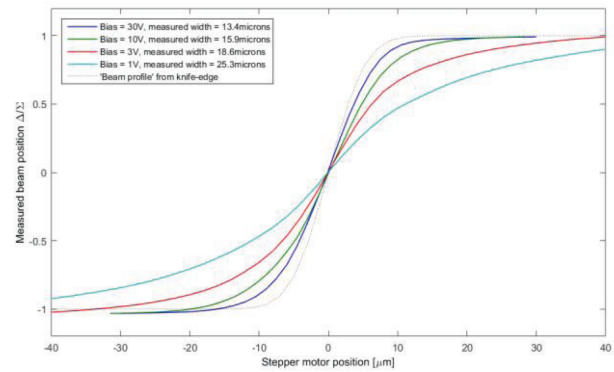

Figure 6: The recorded 1D X-ray beam spatial profile using a single-crystal diamond detector with different bias voltages applied.

Figure 6 shows the measured beam position (calculated as the difference of quadrants located on opposite sides of the device divided by the sum of all four quadrants, Δ/Σ) during a scan of the detector across the incident X-ray beam, for various bias voltages on the I24 beamline at DLS. The beam size is independently measured using a knife-edge scan to be 10.0 μm (RMS) in size. The incident light is 12.7 keV photons, and the flux is measured to be 2.5e9 photons / s.

It is seen that the apparent X-ray beam profile is dependent on the bias voltage used. It is hypothesized that at higher bias voltages the velocity of the charge carriers is greater, and so there is less time for diffusion of the charge carries through the material to occur before they eventually reach the electrode. Thus, at higher bias voltages the measured profile from the detector signal currents more closely matches the “real” X-ray beam profile obtained from a traditional knife-edge measurement.

RF READOUT AT 2 GHZ

A CIVIDEC 2 GHz Broadband Amplifier was used for RF readout of the single-crystal diamond detector in order to make observations of the bunch train at DLS. The ring mode used was so-called “hybrid mode”, consisting of a train with 686 1 nC electron bunches, and a single 1 nC “hybrid bunch” in the remaining gap. Figure 7 shows the measured signals, recorded by a 13 GHz oscilloscope. The repeating train itself (top), as well as the 2 ns bunch separation and single bunch (middle and bottom) are easily distinguishable. It should be noted that the actual measured synchrotron bunch length measured at Diamond Light Source was ~20 ps (as recorded by streak camera measurement), meaning that these measurements are many orders of magnitude away from being able to resolving the actual DLS bunch length itself, however they are encouraging in that they offer the potential to distinguish individual bunches. This provides the possibility to develop bunch-by-bunch beam position and intensity measurements in the future.

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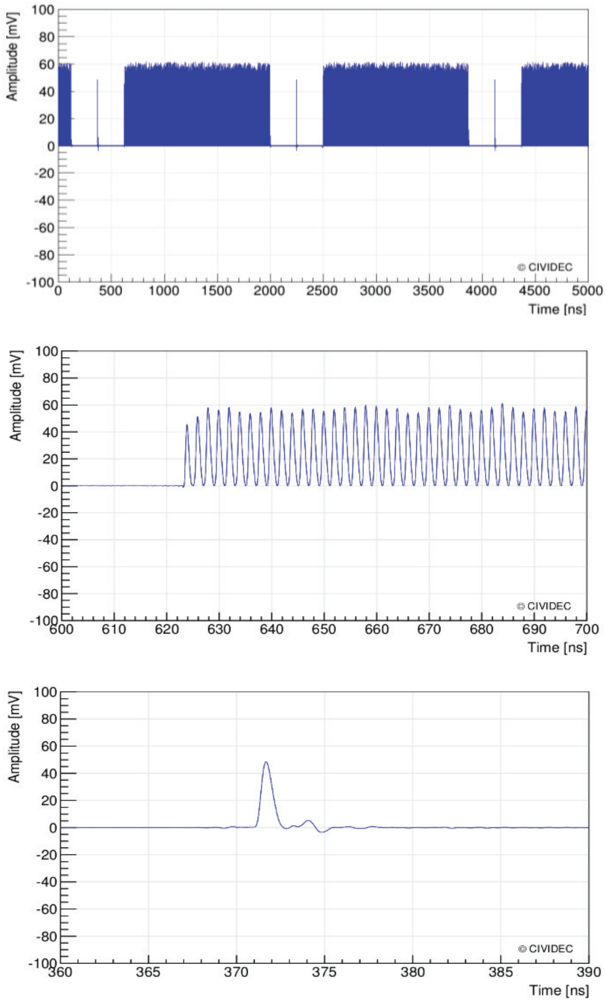

Figure 7: Measurements of the bunch train at DLS. (Top) the repeating bunch train with a single "hybrid bunch" in the gap is seen. (Middle) The 2 ns bunch structure can be resolved. (Bottom) The single 1 nC "hybrid bunch" can be observed.

CONCLUSIONS

Single-crystal diamond X-ray beam position monitors are shown to perform excellently as a non-destructive monitor for synchrotron X-ray beamlines. The transparency of single-crystal diamond makes it a suitable detector material for beamlines operating above 4 keV photon energy.

Accurate and repeatable beam intensity measurements at kHz bandwidths are obtained as long as care is taken that the incident X-ray beam is positioned at the centre of the four quadrants so that the effects of a slight "wedge" of the diamond plate can be mitigated. The RMS noise observed on such intensity measurements has been shown to be as low as 0.52% of the observed signal at 1 kHz bandwidth. The corresponding position measurement resolution is estimated to better than 1% of the beamsize. This corroborates data published elsewhere, demonstrating better than 1% of beamsize position noise at kHz bandwidths, even during unusually low flux measurement conditions, and it has previously been shown that, particularly for low-flux conditions, single-crystal diamond offers offer superior performance when compared to other X-ray diagnostics [3]. The results published in this paper offer further evidence of the advantages of these diamond detectors.

The first permanent beamline installations of single-crystal diamond radiation detectors at DLS occurred early in 2016, and further single-crystal diamond XBPMs are due to be installed imminently. Early results in using these XBPMs as part of routine beamline commissioning and "start-up" have been extremely encouraging, and simple feedback routines in order to maintain a beam position at the sample point have been developed and employed.

The challenge remains to develop technologies that would allow non-destructive X-ray beam monitoring below 4 keV photon energies, where even 50 µm thick plates of diamond absorb too many user photons. Refinements to traditional mechanical polishing techniques allow for plates down to some 10 µm – 20 µm thick to help alleviate this problem. Elsewhere, novel techniques have been explored offering the potential for diamond membranes just a few µm thick [5]. Such very thin devices may also offer additional advantages for XFEL machines with higher photon fluxes and higher power densities.

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