DIAMOND X-RAY BEAM POSITION MONITORS*

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Abstract

Modern Synchrotrons are capable of significant per-pulse x-ray flux, and time resolved pulse-probe experiments have become feasible. These experiments provide unique demands on x-ray monitors, as the beam position, flux and arrival time all potentially need to be recorded for each x-ray pulse. Further, monitoring of white x-ray beam position and flux upstream of beamline optics is desirable as a diagnostic of the electron source and insertion device alignment. We report on diamond quadrant monitors which provide beam diagnostics for a variety of applications, for both white and monochromatic beams. These devices have a position resolution of 25 nm for a stable beam, are linear in flux over at least 11 orders of magnitude, and can resolve beam motion shot-by-shot at repetition rates up to 6.5 MHz.

INTRODUCTION

As x-ray beams from modern lightsources become more intense, with smaller spots and shorter pulse durations, new solutions for beam monitoring are needed. Diamond has great potential as a transmission material for x-rays, as it has a low atomic number, a high thermal conductivity and a high mechanical strength (allowing very thin free standing structures). The electronic features of diamond make it attractive as a photon monitor; it has a high carrier mobility for both electrons and holes and a large, indirect band gap (eliminating the radiative recombination which leads to flux saturation in ion chambers and nearly eliminating leakage). It has a mean ionization energy of 13.3 eV [1], providing 2.5 times the sensitivity of a standard nitrogen-filled ion chamber for the same absorbed power. The high carrier mobility enables monitoring of single x-ray bunches from a pulse train, while the high thermal conductivity and low absorption enable diamond to operate in a beamline front end, with hundreds of watts of incident x-ray power. Diamond monitors are also vacuum-compatible, compact, and could be readily integrated into a beamline window.

DETECTOR DESIGN

We have constructed several types of x-ray monitors based on high purity synthetic diamond. These diamonds are grown by chemical vapor deposition (CVD), and obtained from Diamond Detectors Ltd. The diamonds are screened via x-ray topography [2] to select material that is relative free of threading dislocations to improve the response uniformity of the devices. Oxygen termination is achieved via ozone exposure and metallization for contact creation is performed via sputtering (with masks for quadrant creation when appropriate). The resulting devices can be separated into one of two basic categories: front end (generally white beam), and sample position (often monochromatic) beam monitors.

Flux is determined by measuring the total current passing through the device; in this way the device is similar to a solid state ion chamber. To achieve an absolute calibration, the absorption in the diamond and therefore the spectrum of the absorbed x-rays must be known. Beam position is determined by using a device with an electrode patterned into four quadrants; the current through each quadrant is measured individually. The position is then determined by:

$$Y = G_Y \frac{(A+B)-(C+D)}{A+B+C+D}, \quad X = G_x \frac{(B+D)-(A+C)}{A+B+C+D}$$

where A, B, C and D are the currents through the upper left, upper right, lower left and lower right pads. G is a calibration based on the size of the x-ray beam and is determined by scanning the detector across the beam.

Front End Diagnostics

Diagnostics at a beamline front end are useful both to align insertion devices to the electron beam and to monitor and optimize the downstream alignment of the beamline. In this way, this type of device is useful both to accelerator personnel and beamline users. One such front end device has recently been installed as a fixed component of the NSLS X25 beamline 13.6 m downstream of the undulator for in-line flux and beam position measurement. The beam is relatively large, apertured to a maximal size of 1x6 mm^2, thus the detector was constructed as a set of two 4.7x4.7 mm^2 100 μm thick single crystal plates tiled laterally (fig. 1).

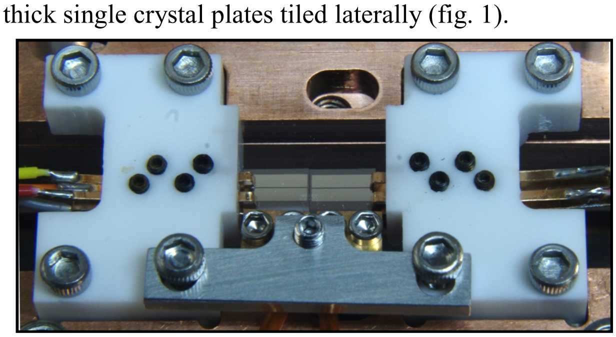

Figure 1: NSLS X25 white beam position monitor (BPM)

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Each plate is metalized on one side with two 4.3x1 mm^2 30 nm thick platinum contacts, vertically separated by a 50 µm "street" as well as a corresponding 4.3x2 mm^2 contact on the opposite side for applying bias to the device. The current from each quadrant is read out by a custom 4-channel current amplifier capable of measuring 1A per channel. This device divides the current by 3000; the reduced current is then read by an Oxford IC Plus Electronics Quad module. The diamond achieves full collection for a bias of 9V (0.09 MV/m field in the diamond). The device was constructed to absorb up to 10 W, corresponding to 700 mA of total current; thus far 300 mA have been measured (100 W of incident beam).

Diagnostics at the Sample Position

Several devices for providing beam monitoring near the sample position have also been constructed. Generally created as a set of four 1.5x1.5 mm^2 30 nm thick platinum pads separated by 50 µm vertical and horizontal "streets" on a 4x4 mm^2 200 µm thick diamond plate (solid 3x3 mm^2 pad on the reverse), this type of detector can be integrated into a PC board to facilitate mounting and signal routing (fig. 2). In addition to flux and position monitoring, these devices are designed to allow temporal profiling of the incident beam. This is accomplished via the use of coaxial signal lines and high-voltage biasing, creating fields in the diamond high enough for full carrier collection on the appropriate timescales. The signal can be taken in current mode or can be routed to an oscilloscope for pulse by pulse measurement.

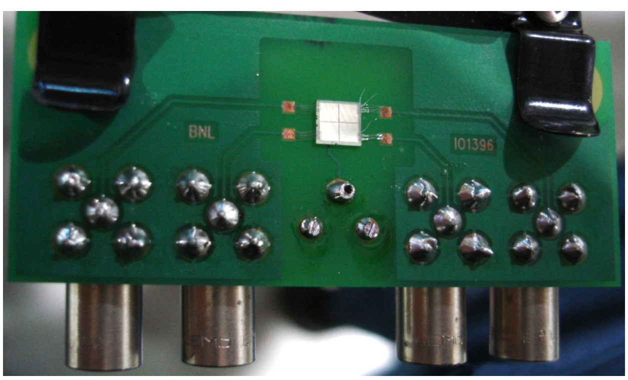

Figure 2: Sample position BPM

RESULTS

Spectral Response and Flux Linearity

Detectors have been calibrated for spectral and flux response, resulting in predictable, reproducible, diode-like response (fig. 3). A simple model of responsivity (S) well describes the response of these devices over the entire range of photon energies investigated:

$$S = \frac{1}{w} e^{-t_{metal}/\lambda_{metal}} \left(1 - e^{-t_{dia}/\lambda_{dia}}\right) CE[v, F]$$

Here, w is the mean ionization energy of diamond (13.25±0.5 eV [1] for these measurements). t_{dia} and t_{metal} are the thickness of the diamond and the metal, and λ_{dia} and λ_{metal} are the photon-energy dependent absorption lengths of the diamond and the metal. CE represents the collection efficiency of the device.

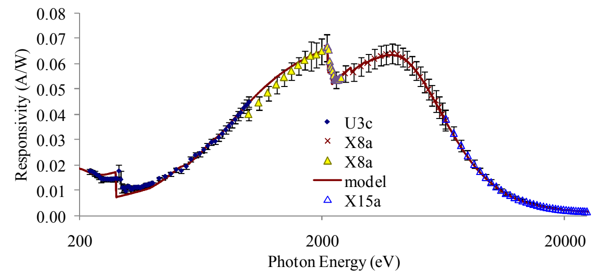

Figure 3: Diamond detector spectral response

Linearity of the response with flux was investigated at both monochromatic and white beam sources to test a wide range of flux values; thus far the devices have proven to be linear in response over eleven orders of magnitude, from 100 pW to 10 W. Data from the higher flux white beam measurements is shown in figure 4 [3].

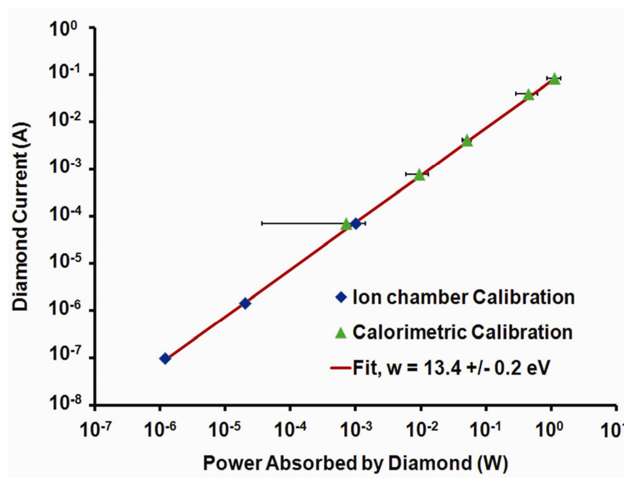

Figure 4: Diamond detector flux linearity

Front End Beam Position Monitoring

A prototype white beam position monitor was installed in the NSLS X25 beamline 13.6 m downstream of the undulator for front end diagnostics. Calibration of the device indicated that it was linear with flux as anticipated; calibration of the positional response is shown in figure 5.

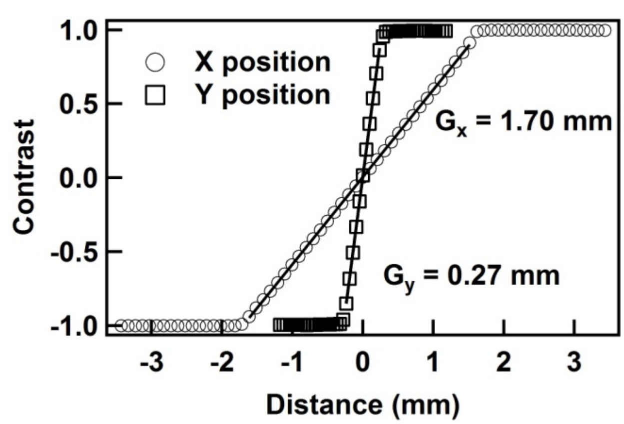

Figure 5: Positional calibration of the X25 BPM

Sensitivity to the beam motion is estimated to be 450 nm in the horizontal and 55 nm in the vertical dimension (fig. 6). This measurement includes all sources of motion affecting the beam and the device and does not indicate the sensitivity limitation of the device itself. The periodicity of the noise likely points to a mechanical vibration in the beamline optics or device mount used for the measurement. The rectangular beam shape (4 mm hor., 1 mm vert.), along with the division of the beam between two separate diamond plates, creates a significant disparity in the sensitivity in each dimension.

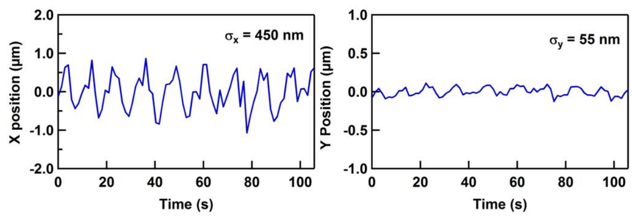

Figure 6. X25 BPM position noise measurement

Interestingly, monitoring of the beam position during a scan of the undulator gap revealed a horizontal beam motion correlating with the change in gap size (fig. 7). This correlation likely indicates a slight misalignment of the insertion device, underscoring the utility of this type of front end monitoring capability.

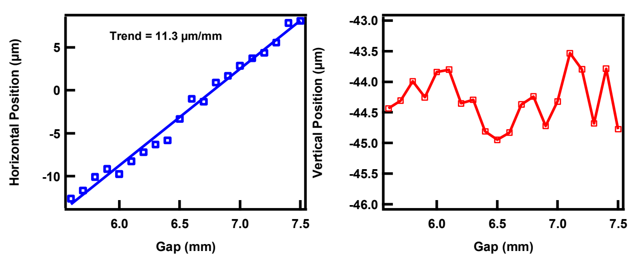

Figure 7: X25 undulator gap scan

Diagnostics at the Sample Position

The detector shown in figure 2 has been used to measure position both in current mode and in pulse mode. The current mode calibration yielded a 1σ position noise of 25 nm (potentially limited by beamline stability) using a 40x40 μm^2 white beam with a power density of ~100 mW/mm^2.

The pulse mode measurement for a single x-ray bunch (using the APS 24 bunch mode at beamline ID-11-D) is shown in figure 8. In this case, the integrated charge on each pad from a single x-ray bunch is used to determine the position. This data is acquired using a fast oscilloscope; in this way the position can be determined for each pulse in the 24 bunch train (6.5 MHz repetition rate). The pulse mode calibration yielded a 1σ position noise of 4.9 μm in the vertical and 100 μm in the horizontal dimension. This experiment, unlike those discussed previously, was performed using the full, unapertured beam (800 μm hor., 40 μm vert.). This allows measurement of the noise associated with beamline optics. The position variation over an hour, tracking the position of just the first pulse from the 24-bunch train, is shown in figure 9, along with the observed correlation between the horizontal and vertical motion. This correlation suggests that a beamline component, likely the x-ray mirror, is misaligned.

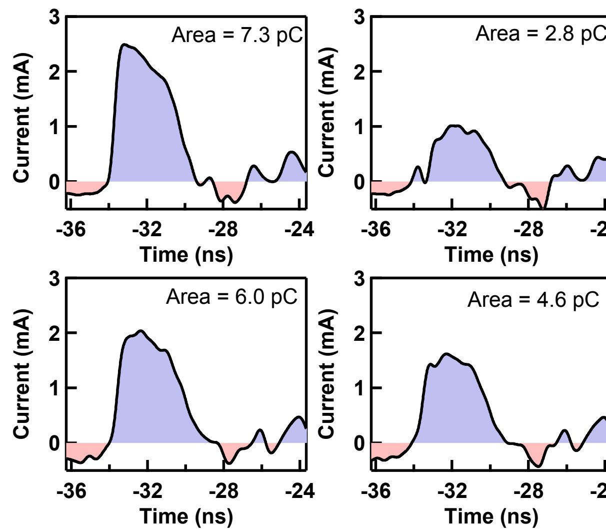

Figure 8: Integrated charge from a single x-ray pulse on the four pads of a quadrant detector

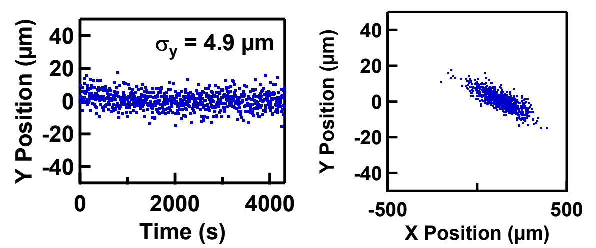

Figure 9: Long term vertical stability (left) and x-y correlation of beam motion (right)

CONCLUSIONS

Diamond-based x-ray beam monitors have been demonstrated for both front end and sample position diagnostics. These devices are capable of simultaneously measuring flux, position and timing. The flux response is linear over eleven orders of magnitude, from the weakest monochromatic beams to high flux white beams. Position sensitivity of 25 nm has been achieved. These devices can monitor the position of individual x-ray bunches from a synchrotron pulse train.

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