Single Crystal Diamond Beam Position Monitors with Radiofrequency Electronic Readout

B. Solar[b], H. Graafsma[b], J. Morse[a], M. Salomé[a], G. Potdevin[b], U. Trunk[b]

[a] *Instrument Services and Development Division, European Synchroton Radiation Facility, Grenoble, France*

[b] *Hasylab, Deutsches Elektronen Synchroton, Hamburg, Germany*

Abstract. Over the energy range 5~30 keV a suitably contacted, thin (~100 µm) diamond plate can be operated in situ as a continuous monitor of X-ray beam intensity and position as the diamond absorbs only a small percentage of the incident beam. Single crystal diamond is a completely homogeneous material showing fast (ns), spatially uniform signal response and negligible (<pA) leakage currents [2]. Due to its unsurpassed thermal conductivity, it is the only semiconductor material that can be used in white beams. We report on tests made at ESRF and DESY using diamond beam position monitors of simple quadrant electrode designs with metal contacts, operated using wideband electronic readout corresponding to the RF accelerator frequency. The instrumentation for these monitors must cover a large range of operating conditions: different beam sizes, fluxes, energies and time structure corresponding to the synchrotron fill patterns. Sophisticated new RF sampling electronics can satisfy most requirements: using a modified Libera Brilliance readout system, we measured the center of gravity position of a 25 µm beam at the DORIS III F4 beam line at a rate of 130 Msample/s with narrowband filtering of a few MHz bandwidth. Digitally averaging the signal further provided a spatial resolution ~20 nm rms at 10 Hz.

Keywords: PBPM, Photon Beam Position Monitor, Single Crystal Diamond

INTRODUCTION

DESY and ESRF are collaborating to develop a Photon Beam Position Monitor (PBPM), with a position resolution better than 50 nm. The first systems are for small monochromatic focused beams, close to the sample. Since space around the sample is limited and valued the devices have to be thin and compact. They should absorb only a small fraction of the incident flux, while still giving enough signal in order to be able to measure small beam movements. Single Crystal Diamonds (SCDs) are the best candidates to fulfill these requirements [3]. They are near perfect, very homogeneous, fast, low-Z, and both thermally and mechanically very robust. The ESRF has been working on SCDs for the last few years, and has produced a number of four-quadrant devices used for experiments. Current is generated in the semiconductor material primarily by the photo-electric effect and the sensor operates as a solid state ionization chamber. In the four-quadrant geometry the absorbed high energy photons are converted into corresponding spatially dependent RF signals. These signals are processed by readout electronics into the final beam position information. Instrument characteristics such as precision, resolution, linearity, long term stability and frequency response depends on the quality of the Single Crystal Chemical Vapor Deposition (scCVD) material, sensor geometry, and readout electronics.

SCD SENSOR

The SCD is a semiconductor that is nearly ideal for an X-ray BPM. The e-h pair generation energy is ~13 eV. The low Z gives enough transparency for photons above 5 keV and is optimum for the range between 5-30 keV. The sensor thickness is in practice limited by mechanical properties and the fabrication process from some tens of microns up to approximately 500 microns. The highly homogeneous and pure, electronic grade scCVD material provides long charge carrier life time [1], and biasing with an electric field of 1 V/µm provides fast (~ns), near 100% charge collection. SCD material does not show the spatial artifacts that result from grain boundaries in polycrystalline grades of CVD diamond. Sensors are fabricated from ultrahigh purity (<5 ppb nitrogen) scCVD plates. They are thinned down to an appropriate thickness, polished and screened for defects by cross polarization microscopy and X-ray topography. Sufficiently unform samples are cleaned and metal contacts deposited either using shadow mask or lift-off lithographic techniques. Contacts are typically <100 nm thick and can be directly wirebonded to a ceramic carrier or circuit board. The most simple quadrant motif (Figure 1) has a cross like separation gap and a common backplane: only the backplane is biased and this requires very simple readout electronics. Also available are double side patterned electrodes, giving two orthogonal pairs of electrodes for the differential sensing electronics. In the case of low energy, small (<10 µm) beams, photocharge diffusion dominates the position resolution and thus the sensitivity and region of linearity.

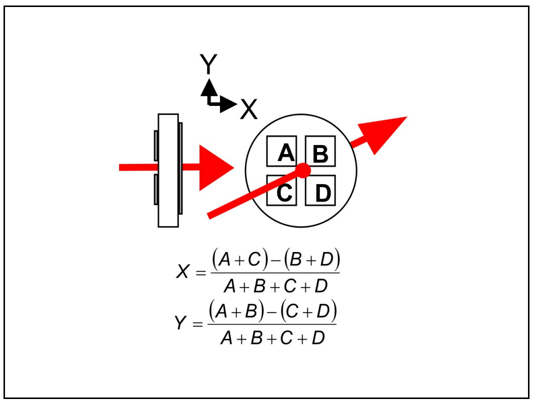

Figure 1: X, Y dependence of the four quadrant detector Electrode motif with bonding pads. The device shown here has additional electrodes (that were grounded for these tests)

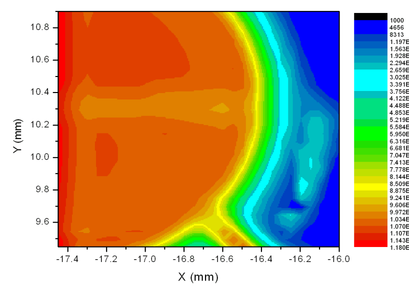

Figure 2: The sum of the normalized response of electrodes A, B, C and D.

The setup was placed on the DORIS III F4 beam line bending magnet white beam source. The raw beam peak energy was at 16 keV but this increased to 25 keV behind the 0.5 mm aluminum filter. Motorized slits of 25x25 µm collimated the beam, and a diamond sensor (4x4x0.38 mm^3) mounted on X-Y scanning table. This sensor had TiW contacts with a 100 µm isolation gap between the quadrants. A calibrated 0.5 mm thick silicon photodiode read-out by an electrometer provided a direct flux measurement. In the first experiment the center of the sensor, over a region of 10x10 µm was scanned (Figure 4) in 0.25 µm steps, while the Figure 7 is presenting the whole sensor scan. Vibrations were in the range of one micron p-p and were filtered up to 5 Hz. Irregularities resulting from the mechanics of the motorized scans (backlash, unaligned axes etc.) were estimated by spiral like and cartesian scans. By removing their contribution and fitting a second degree polynomial linearization a final resolution of 10 nm (Figure 3) RMS was estimated. The same resolution value, which is a convolution of real movements and the electronic 'noise' of the sensor itself, was observed with a long term (several seconds) time trace with the beam position fixed. In this last experiment the response to a mechanical shock introduced three meters away from the hutch was observed (Figure 5). The same data (processed to 130 kHz data rate) gave 300/130/40/20 nm RMS noise corresponding to 50/10/1/0.2 kHz bandwidths. No signal drifts or time response lags were observed during the course of these measurements.

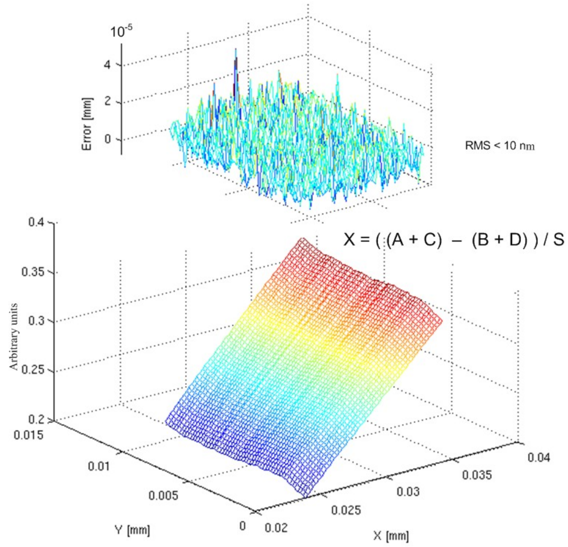

Figure 3: Remaining noise after post-processing (scanner mechanic / linearization)
Figure 4: X position, calculated from raw data

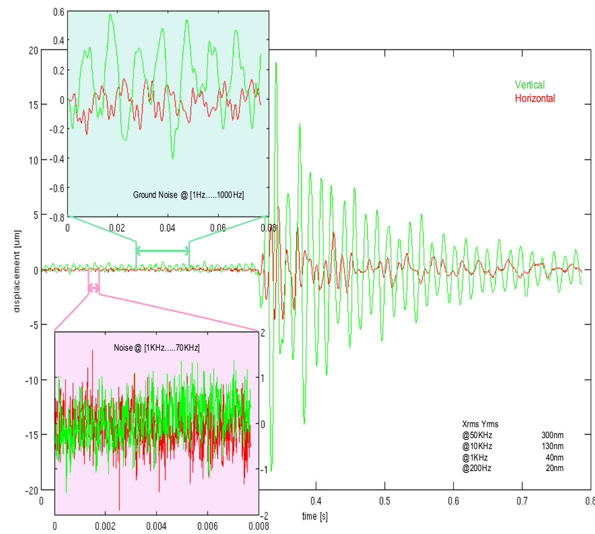

Figure 5: Response to mechanical shock

CONCLUSION

Over the energy range 5~30 keV suitably mounted, thin (~100 µm) diamond plates can be operated in-situ as a continuous monitor of X-ray beam intensity and position as the diamond absorbs only a small percentage of the incident beam. Single crystal diamond is a homogeneous material showing fast, spatially uniform signal response (Figure 2). Tests have been made at ESRF and DESY using diamond beam position monitors of simple quadrant electrode designs with metal contacts, operated using wideband electronic readout corresponding to the synchrotron radiofrequency. The instrumentation for these monitors can cover a large range of operating conditions: different beam sizes, fluxes, energies, and time structure corresponding to the synchrotron fill patterns. Sophisticated new RF sampling electronics can satisfy most requirements using a modified Libera Brilliance readout system. After this proof of concept and fabrication a new series of sensors, the PBPMs, is being prepared for installation on the PETRA III and ESRF beam-lines.

READOUT ELECTRONICS

Charge collected on the electrodes can be measured by integration (e.g. using a straightforward electrometer) or, in the case of a pulsed synchrotron beam, by measuring the voltage of the charge pulses on 50 ohm input impendence at the storage ring radiofrequency (RF). The proportion of voltage between the four electrodes represents the position in the transverse plane and is the same for packet frequency and higher harmonics up to the RF accelerator frequency, which is the most suitable because it covers RF signal extraction for all storage ring fill pattern conditions. The energy distribution depends on the pulse shape. In principle, a higher sensor bias voltage results in faster response time and more energy distributed in the higher harmonics range, but the charge carrier drift velocity in diamond saturates at ~150 µm/ns. A diamond sensor can be described as a current generator with a parallel capacitor. Circuits with inductance and a RF transformer provide better sensor to cable impedance matching (Figure 6). The cable phase matching has due to the small crosstalk (below -60 dB) negligible influence on the instrument precision. An appropriate input band-pass filter and first stage preamplifier gives an optimal combination of noise figure and nonlinear distortion. The rest of the analog readout electronics provides additional signal conditioning incorporating controlled amplification, analog filtering, channel switching and A/D conversion. The first blocks of the digital chain provides the digital part of signal conditioning, filtering, exact amplitude demodulation and low-pass filtering. At this point the output represents the RF amplitude of the corresponding electrode signal. In the final stage the four amplitudes define the photon beam position in the sensor plane. All these requirements fit into the processing scheme of the Libera Brilliance readout system, and only a minor modification of the three stage amplifier in the RF front-end was necessary for our measurements. This system has the important advantage of arbitrary bandwidth with corresponding spatial resolution. At the upper limit it can provide bandwidth near the bunch rate, while processing down-to 10’s of Hz bandwidth can deliver around 10 nm RMS resolution. In practice very wide band readout is not important. The highest bandwidth is expected at synchrotron revolution frequency (for machine studies), while a ~1 kHz bandwidth should be adequate for measuring mechanical vibrations. The lowest bandwidth in the range of 10 Hz is important for photon beam position tuning (i.e. slow feedback systems).

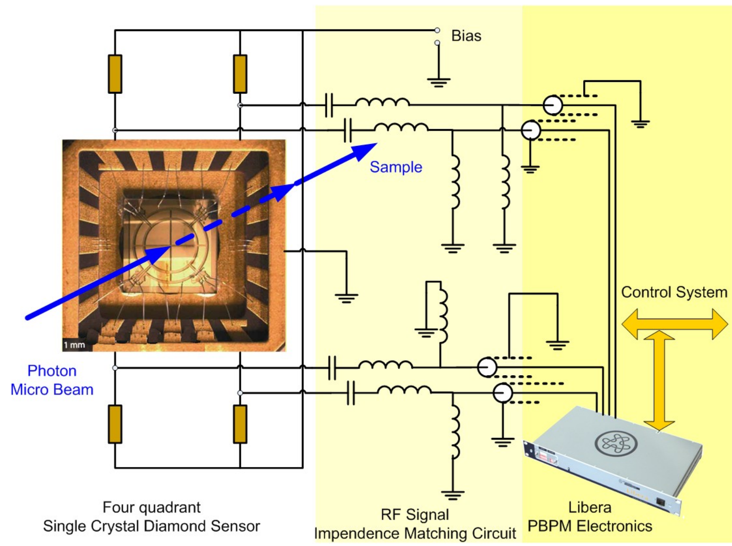

Figure 6: Measuring RF power of sensor response at synchrotron radiofrequency

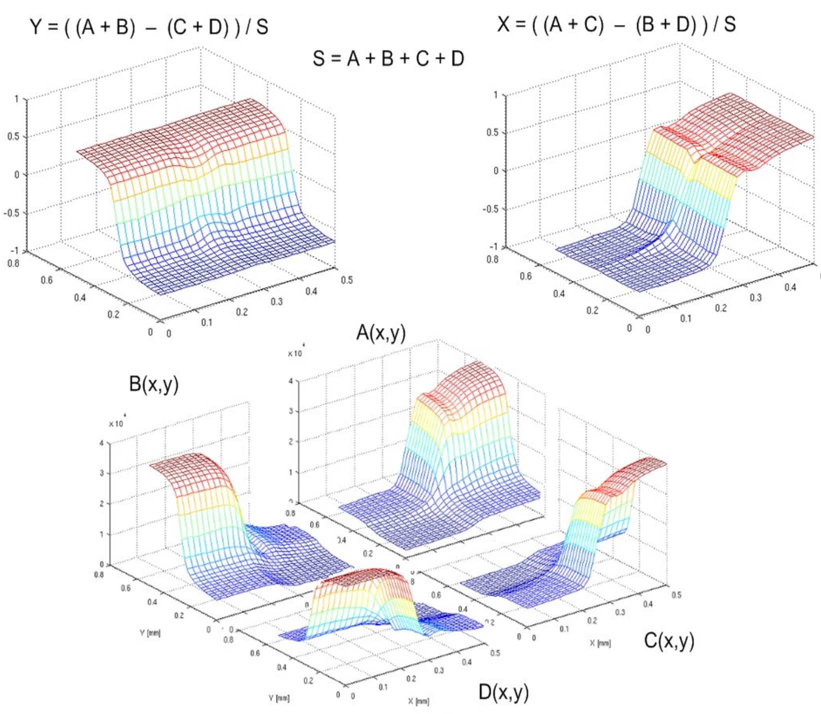

Figure 7: Coarse scan over the 0.5x0.5 mm region

ACKNOWLEDGMENTS

We are grateful to **Prof. Harris Kagan** at **Ohio State University** for the contact deposition and ceramic mounting of the diamond sensors and to **Instrumentation Technologies** for modified **Libera Brilliance** readout electronics used in these tests.

REFERENCES

1. P‘Charge transport properties of single crystal CVD-diamond particle detectors’, M Pomorski, E. Berdermann, W. de Boer, A. Furgeri, C. Sander, J. Morse, Diam. Rel. Mat., 16 (2007)1066.
2. ‘Single crystal CVD Diamond as an X-ray Beam Monitor’, J Morse, M Salomé, E Berdermann, M Pomorski, W Cunningham, J Grant, Diam. Rel. Mat., 16 (2007) 1049–1052
3. ‘Single Crystal CVD Diamond Detectors: Position and Temporal Response Measurements using a Synchrotron Microprobe Beam”, J Morse, M Salomé, E Berdermann, M Pomorski, J Grant, V O’Shea, P Ilinski, Mater.Res. Soc. Symp. Proc. Fall 2007, Vol. 1039-P06-02