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## X-Ray Beam Position Monitor Based on a Single Crystal Diamond Performing Bunch by Bunch Detection

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**Abstract.** Diamond is a promising material for the production of semitransparent *in situ* photon beam monitors which can withstand the high dose rates occurring in new generation synchrotron radiation storage rings and in free electron lasers. We report on the development of a 500  $\mu\text{m}$  thick freestanding, single crystal chemical vapor deposited diamond detector with segmented electrodes. Performances in both low and radio frequency beam monitoring are presented as well. By using charge integration techniques at a frame rate of 6.5 kHz in combination with a needle synchrotron radiation beam and mesh scans, the inhomogeneity of the sensor was found to be of the order of 2%; with a measured electronics noise of  $2 \text{ pA} / \sqrt{\text{Hz}}$  a 0.05% relative precision in the intensity measurements (at 1  $\mu\text{A}$ ) and a 0.1  $\mu\text{m}$  resolution in the position encoding have been estimated. Moreover, the high electron-hole mobility of diamond compared with other active materials enables very fast charge collection characterized by rise-times below 1 ns; this allowed us to utilize single pulse integration to simultaneously detect the intensity and the position of each synchrotron radiation photon bunch generated by a bending magnet.

### 1. Introduction

In 3<sup>rd</sup> generation synchrotron radiation (SR) sources, the high brightness beamlines using undulator radiation are the most sensitive to electron beam oscillations. The insertion of photon Beam Position

Monitors (pBPM) is useful in order to provide those systems with important information, such as photon beam position, absolute intensity and temporal structure [1]; furthermore, several beamline experiments require these data to be known in order to give quantitative results [2].

Electron beam position stability has been intensively addressed in the past years by the use of Fast Orbit Feedback (FOFB) based on electron Beam Position Monitors (eBPM) [3]; conversely, beamlines have not been provided so far with a fast local control system based on the information collected by the pBPMs. Those measurements are rarely used to compensate for long term thermal drifts (of the order of minutes) or to adjust experimental data; recently, integration of pBPM information into the FOFB has been proposed [4]. Hence, for both diagnostics and calibration issues, several SR applications require an *in situ* detector showing high transparency, high radiation hardness, fast response and homogeneity.

Because of its extreme physical and electronic properties diamond is the most promising material for the production of semitransparent *in situ* pBPMs [5]: high bond energy allows the use of this material at the high dose rates occurring in new generation SR storage rings; its low atomic number makes it semitransparent under certain conditions (involving both thickness and photon energy); besides, due to its high energy gap, intrinsic diamond is an insulator with low thermal noise at room temperature, while its high electron-hole mobility allows charge to be collected faster than in any other active material.

With these characteristics, diamond might be the only suited material to be utilized as pBPM for X-ray free electron lasers (FEL), which provide very short intense photon pulses with a peak power of some tens of MW.

This paper reports on the development of a pBPM based on a single-crystal chemical vapor deposited (CVD) diamond detector; experimental results are presented to witness the capabilities of this device for both low frequency and *bunch by bunch* beam monitoring.

## 2. Diamond Detector

A single-crystal diamond layer has been grown homoepitaxially by microwave plasma-assisted CVD. After the synthesis, the layer was removed from the substrate by laser cutting and polished on both surfaces, resulting in a 500- $\mu\text{m}$ -thick, freestanding layer with a  $5\times 5\text{ mm}^2$  area. It has been cleaned in class 1000 environment and provided with Cr-Au contacts deposited using standard thermal evaporation techniques; on the front surface two semicircular electrodes with a radius of 1 mm are spaced by 100  $\mu\text{m}$ ; on the rear side, a  $4\times 4\text{ mm}^2$  back-plane electrode has also been deposited.

The diamond sensor was then connected to a gold-plated copper PCB using silver glue and wire bonds (25  $\mu\text{m}$  diameter) respectively for rear and front electrodes.

This detector is meant to be transversally inserted in the monitored beam; for radiations above 8 keV, a minor part of the incident photons is absorbed and electron-hole pairs are generated. When a bias voltage is applied between rear and front electrodes, free charge can be collected; consequently, the measured currents can provide information about beam position and intensity.

## 3. Experimental Setup

The described detector has been tested at the Microfluorescence bending magnet-beamline of the Elettra synchrotron in both *multi-bunch* mode and *single-bunch* mode; in the former, 432 electron bunches are distributed along the ring, spaced by 2 ns; in the latter, a single bunch is filled and accelerated with a revolution period of 864 ns.

After being generated by the accelerator, broad-band radiation (infrared  $\div$  hard X-rays) passes through several absorption stages; since no monochromator has been inserted in the light path, the presented experiments have been performed with a radiation showing a maximum flux at an energy of 20 keV and a spread of about 15 keV. At the end of the evacuated pipes, a double-slit collimator has been used to obtain a needle-beam with adjustable cross section dimensions ranging from 75  $\mu\text{m}$  to 2 mm.

The diamond detector has been mounted on an XY movable stage which is housed in an evacuated chamber provided with stepper motors, bias and signal cables; thus mesh scans of the sensor can be performed.

The diamond has been biased with voltages ranging from 15 V to 500 V and the generated photocurrents have been read by means of two different multi-channel acquisition systems, which work respectively at low and high sampling frequencies. In the first case charge integration and analog to digital conversion (ADC) at 6.5 kHz have been performed, while in the second one the signals are sent to 10 GHz ADCs directly or through radio-frequency pre-amplifiers.

The motor drivers and the acquisition electronics are controlled by a PC, which allows real-time data storage as well.

#### 4. Results

At first the low frequency arrangement has been used to obtain sensitivity maps of the active area of the detector. Utilizing a needle-beam with a section of  $70 \times 350 \mu\text{m}^2$  in combination with the stepper motors, several mesh scans have been acquired; with such measurements the inhomogeneity, defined as the standard deviation from the mean response, in the region of interest (i.e. the central part) has been found to be of the order of 2%.

After that, moving the detector with respect to the beam (motor step of  $10 \mu\text{m}$ ) and collecting with the two front electrodes the photo-charges induced in diamond by electron/hole pair production processes, we can estimate the position of the incident beam (Fig.1). *Difference over sum* of left and right signals has been used to calculate the beam centroid position during horizontal scans (Fig.2).

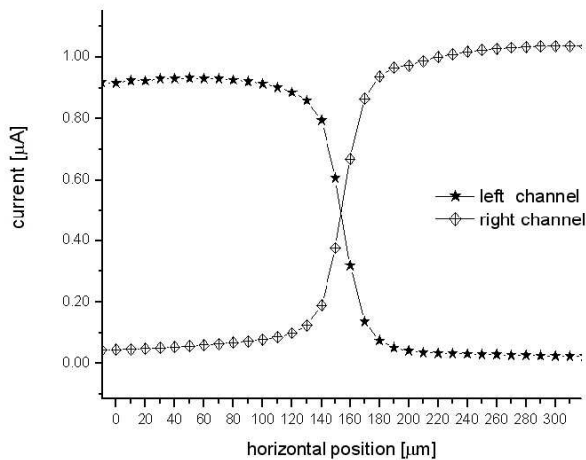


Figure 1. Current acquisition from each channel.

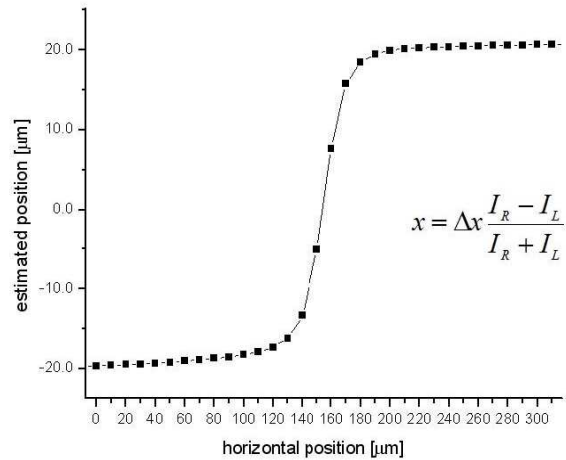


Figure 2. Difference over the sum.

Those results have been compared to the known ground-truth displacements proving the detector to be capable of monitoring position in the central linear region with a precision of 150 nm (estimated using error propagation of standard deviation of the signals).

The high frequency setup has been used to exploit the fast response of the diamond; the monitoring system has been able to detect the signals generated by each photon bunch hitting the sensor in both multi-bunch and single-bunch operating modes.

In the first case, the presented detector has produced waveforms in which the bunches can be clearly distinguished from each other, though they are spaced by 2 ns only; Figure 3 shows a trace acquired during multi-bunch operations with a bias voltage of 300 V and a beam section of  $2 \times 2 \text{ mm}^2$ .

In the second case, single pulses were spaced by 864 ns (i.e. the revolution period); since the machine bunch had a FWHM of about 150 ps, the acquired pulses can also be considered as impulse responses of the whole pBPM. An example of such a response is reported in Fig. 4, denoting rise times below 1 ns. Horizontal linear scans have also been performed in single-bunch mode; using the areas of

the pulses generated by each channel, the beam position has been estimated with a precision of less than 6  $\mu\text{m}$ .

The presented results can be compared with those produced by similar experiments on mono-crystalline [5] and poly-crystalline [6] CVD diamond detectors with regard to low frequency resolution and high frequency response respectively, while single-shot SR characterization has not been reported yet.

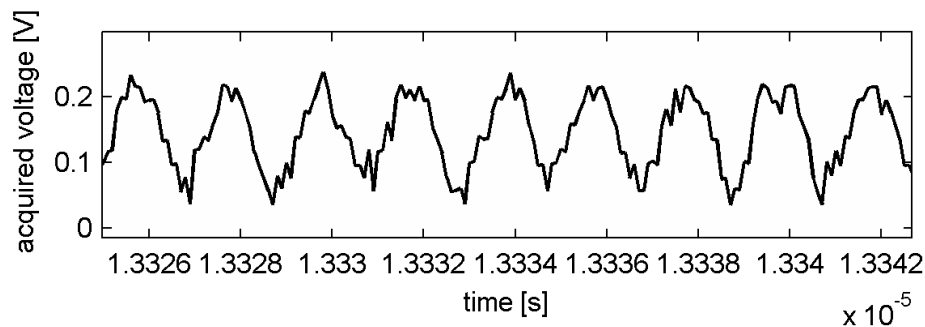


Figure 3. Acquired waveform in multi-bunch mode.

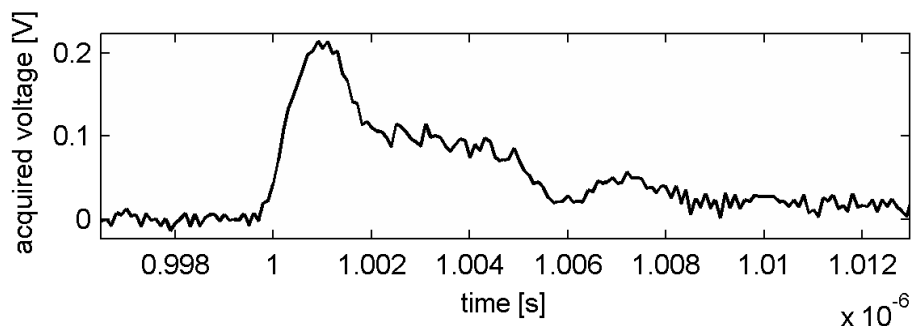


Figure 4. Single-bunch pulse response of the diamond detector.

## 5. Final Remarks

A single-crystal CVD diamond detector has been developed and characterized by means of multi-bunch and single-bunch SRs. The reported performances show that diamond detectors are well suited to be used as pBPMs in synchrotron beamlines; in particular, rise times below 1 ns and resolutions of less than 6  $\mu\text{m}$  allow bunch by bunch position monitoring. Moreover, diamond has proved to be one of the most promising materials to be used as pBPM in FEL applications.

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