DIAMOND-BASED PHOTON BPMS FOR FAST ELECTRON-BEAM DIAGNOSTICS IN SYNCHROTRON RADIATION SOURCES

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Abstract

Electron-beam stability is amongst the primary concerns in current Synchrotron Radiation (SR) sources; in particular, in third-generation SR facilities high-brightness beamlines using undulator radiation are extremely sensitive to electron-beam oscillations. Orbit stabilization has been intensively addressed in the past years and many SR machines have been equipped with a Fast Orbit Feedback (FOFB) based on electron Beam-Position Monitors (eBPMs).

On the other hand, photon Beam-Position Monitors (pBPMs), besides providing beamline users with crucial calibration data, are also a useful tool for keeping the electron beam under control, by monitoring position and intensity of the delivered radiation. The machine control system can take advantage of this information in order to improve the stability of the electron-beam.

A diagnostic beamline, utilizing a couple of fast pBPMs based on single-crystal CVD diamond detectors, has been built and inserted into the central dead-end outlet of one of Elettra's bending-magnets. Tests have been carried out both during normal machine operations and by deliberately moving the orbit during dedicated shifts. Owing to the outstanding properties of diamond in terms of speed and radiation hardness, the results show how the aforementioned system allows the beam position to be monitored with sub-micrometric precision at the demanding readout rates required by the FOFB. The radiation hardness of the sensors allows the operation over extended periods of time without special maintenance.

Therefore, this system is particularly suited for storage-ring sections lacking in electron-beam monitoring and the tested diagnostic line represents a demonstrator for future implementation of pBPMs at several bending-magnet front ends of Elettra.

INTRODUCTION

In modern SR facilities electron-beam monitoring and stabilization are amongst the primary concerns. In particular, the high-brightness beamlines using undulator radiation are the most sensitive to electron-beam oscillations occurring in 3rd-generation light sources [1]. Therefore, such machines are equipped with specific control systems, like the FOFB, based on the measurements of the eBPMs implemented along their storage rings [2].

Despite such stabilization measures and owing to a number of instability sources, the resulting photon beam can exhibit residual fluctuations in terms of both position and intensity. These phenomena can be detected by utilizing pBPMs, which are capable of simultaneously estimating the intensity and the position of the emitted beam passing through. Fast pBPMs inserted in beamlines are well-suited for either *a posteriori* data calibration or real-time adjustment in beamline experiments [3]. Nevertheless, the information provided by such detectors is useful for the electron-beam diagnostics and it can be integrated into the FOFB [4]. In particular, if pBPMs are installed upstream from the beamline optics, their measurements are directly related to the status of the electron beam as they are not affected by any instability imputable to optical elements (such as mirrors, monochromators, etc.).

Amongst the available technologies for the production of fast and semitransparent *in situ* pBPMs, diamond grown by Chemical Vapour Deposition (CVD) is one of the most suitable materials owing to its outstanding physical properties. Because of its high bond energy it can withstand the high dose rates occurring in 3rd- and 4th-generation SR sources and its low atomic number renders it semitransparent to X-rays. Besides, due to its high energy gap, intrinsic diamond is an insulator with low thermal noise at room temperature, while its high electron and hole mobility allows charge to be collected faster than in many other active materials [5, 6].

With the aim to provide Elettra's future FOFB with additional information stemming from state-of-the-art diamond pBPMs, a diagnostic beamline has been built at the central outlet of one of Elettra's bending magnets. The present document reports on the main features of the implemented line, its monitoring performances and its long-term reliability.

DIAGNOSTIC BEAMLINE

At Elettra, each bending magnet was originally designed with a three-way radiation pipe. The lateral outlets became then the anchoring points for the implemented user beamlines, while the central ones remained unused. The presented diagnostic line has been built at one of those central dead-end outlets in order to continuously monitor the photon beam without interfering with normal beamline operations. This prototype has been completely accommodated inside the shielding wall of the storage ring, between the pipes of the 10.1L and 10.1R beamlines, as shown in Fig. 1. This solution has imposed stringent space constraints, which have been met due to the compact size of the diamond pBPMs.

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This diagnostic line features an overall length of about 5 m and it is hooked up to the main shutter of front end 10.1, through a 2-mm-thick water-cooled aluminium window located approximately 4 m downstream from the source point. Due to its geometry, the window accepts (horizontally) about 1 mrad of the beam cone. Moreover, it separates the UHV of the storage ring from the vacuum of this demonstrator line and it serves as X-ray filter to reduce the heat load on the CVD detectors.

Half meter downstream from the Al window, a remotely controlled beam shutter is situated in order to block the beam whenever it is required. Other 80 cm further downstream, the line incorporates a motorized slit system, which allows the beam to be shaped and cleaned in horizontal and vertical direction, respectively. The upstream pBPM (D1) is placed 1.3 m upstream from the slits (i.e. 6.6 m from the source), followed by the downstream pBPM, which is 2.4 m apart from it (i.e. 9 m from the source).

In particular, with such arrangement the system can work in a *camera obscura* geometry, which has been adopted, in order to circumvent the complications caused by the wide horizontal emission angle of the bending magnet. During normal operations, both apertures are narrowed; thus, the slit system acts as a pinhole and D1 is not strictly necessary for the position monitoring. However, the vertical slits can be opened completely, allowing the beam through for its entire vertical size. In such case, the position information of D1 is required in combination with that of D2 to estimate the vertical position of the source.

Outside the shielding wall, a PC-based control system (DAQ) allows acquiring and processing of pBPM data for testing and beam monitoring through a convenient graphical user interface. Furthermore, the DAQ controls motors and biasing modules, allowing for both detector realignment and beam shaping.

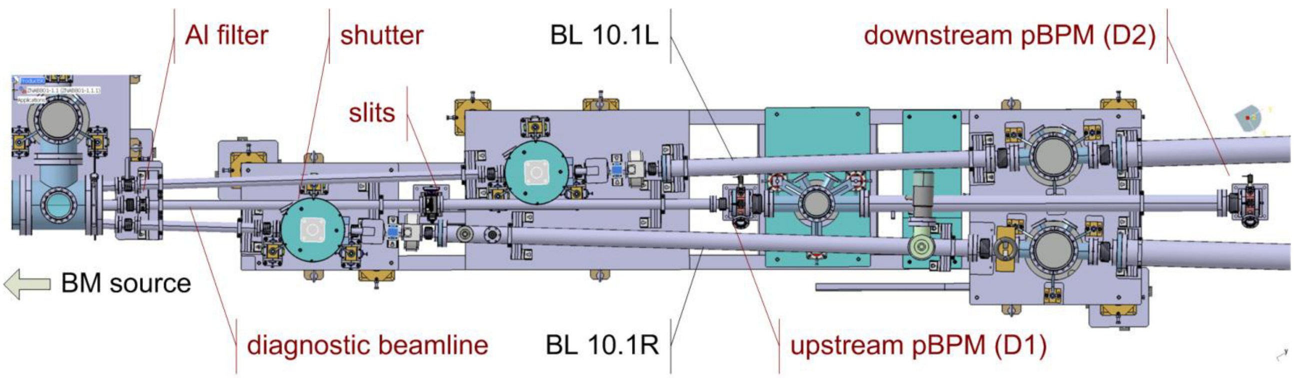

Figure 1: Top view of bending-magnet front end 10.1 at Elettra. The diagnostic beamline is represented by the central pipe between beamlines 10.1L and 10.1R. The main components are labelled in red (upstream to downstream, i.e. left to right): Al filter, beam shutter, motorized slits, upstream pBPM (D1), downstream pBPM (D2).

DIAMOND-BASED PHOTON BPMS

The upstream detector D1 is based on a 50-µm-thick, freestanding, single-crystal CVD diamond. This sensor is a 4.7×4.7 mm^2 die, mechanically grinded and lapped from a 500-µm-thick base material. Front and back surfaces have been coated with 100-nm-thick Al electrodes on top of 100-nm-thick diamond-like-carbon layers. A four-quadrants (*quad*) structure has been created by segmenting the front electrode through a lithographic process, leaving a 100-µm-wide gap between quadrants.

The sensor of the downstream pBPM differs from D1 in terms of thickness and electrode material. It consists of a standard, 500-µm-thick, single-crystal CVD diamond coated with Cr-Au electrodes. It features the same area and *quad* geometry as D1. The lower thickness of D1 reduces its absorption, allowing most of the photons to be transmitted towards D2.

Each of these devices is glued and wire-bonded onto a printed-circuit carrier board and mounted on an X-Y movable stage, which is, in turn, accommodated into a CF-63-flanged, UHV-compatible detector chamber. These carrier boards are electrically connected via BNC and SMA feedthroughs for biasing and readout, respectively. In order to acquire the photo-generated currents, these readouts are then fed into AH501B picoammeters[1]. While these instruments allow the signals to be sampled at a maximum rate of 6.5 kHz, the diamond pBPMs described above can detect incoming photons with much higher time resolutions; they are capable of monitoring SR beams on a bunch-by-bunch basis, even at a 500-MHz repetition rate [7].

PERFORMANCES

In order to evaluate the position-encoding capabilities of the system, some preliminary characterizations have been carried out. The slit aperture has been fixed to 300×300 µm^2; as mentioned, with such setup the system works in a *camera obscura* configuration both horizontally and vertically. Mesh and linear scans of the detectors have been performed during normal machine

1http://iloweb.elettra.eu/index.php?page=_layout_prodotto&id=141&lang=en

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operations.

D2 has been moved with respect to the stationary photon beam by utilizing the stepper motors coming with the detector chamber. At a sampling rate of 10 Hz the pBPM has estimated the relative beam displacement (with *difference-over-sum* method) with a precision of 124 nm. As shown in Fig. 2, the linear range extends for approximately 400 µm.

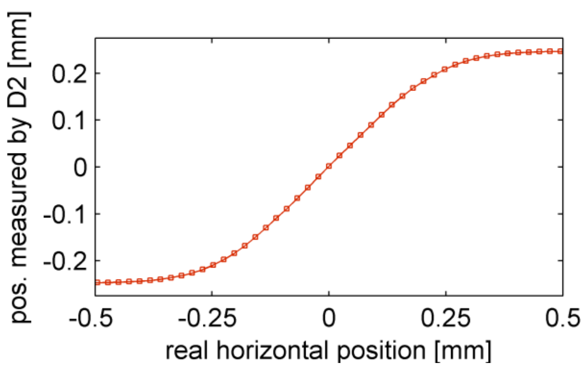

Figure 2: Horizontal position estimated by D2 during a horizontal translation of its movable stage.

In this case, to a first approximation, the 10-kHz precision can be estimated in 3.9 µm. As a matter of comparison, with a 10-Hz acquisition rate, a precision of 72 nm is theoretically expected in such flux conditions. However, it must be pointed out that the acquired data are dominated by systematic errors such as stepping precision, slow beam movements, etc.

Analogous linear scans have been performed during dedicated shifts by deliberately moving the electron beam while keeping the detectors in position (horizontal case shown in Fig. 3). In this case, the position estimated by D2 has shown a similar trend, except for a quasi-periodic deviation from the linear interpolation. When applying an unsharp filter in the linear part of the curve confined by the red vertical lines, an undulation with a period of about 260 µm and an amplitude of about 15 µm becomes prominent. In principle the unsharp filter (measured values minus the line-fit values) reveals the deviation of the electron beam position from the photon beam position. Interestingly, this deviation follows in sufficient approximation a Sinc function which is the Fourier transform of a box function of width B, with a zero crossing at about $2B$ = 60 µm. Eventually this is not surprising since the beam position was sampled through the pinhole with a step width B of exactly 30 µm. In this configuration, according to the Nyquist sampling theorem, the maximum resolvable spatial frequency is 60 µm. Since in such bending-magnet section the electron-beam position is not directly measurable with the eBPMs, it is estimated through a non-linear fit on the simulated optics. Therefore, this result justifies the hypothesis that the interpolation algorithm of the eBPMs introduces such undulation.

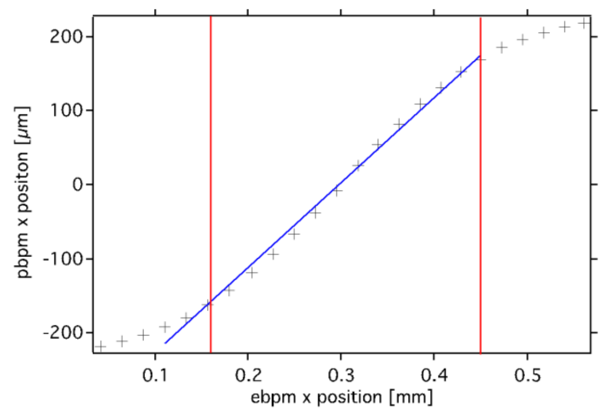

Figure 3: Horizontal position estimated by D2 versus eBPM estimation during deliberate motion of the electron beam. The crosses represent the measured data, the blue line is a linear fit within the linear range (delimited by by red lines).

It is worth mentioning that, due to the small vertical emission angle (about 100 µrad at 2 GeV), the slit aperture cuts specific portions out of the Gaussian vertical beam profile. This turns into a significant flux decrease for wide vertical beam movements and, as a consequence, a reduction in precision. In future, the vertical aperture is likely to be increased in order to avoid these effects; as explained above, in such case the vertical position has to be estimated by the combined readings of D1 and D2.

Test at a 6.5-kHz sampling rate have also been carried out during normal machine operations (2 GeV, 300 mA). A typical trace of the vertical position estimated by D2 is reported in Fig. 4 and its Fast Fourier Transform (FFT) is shown in Fig 5.

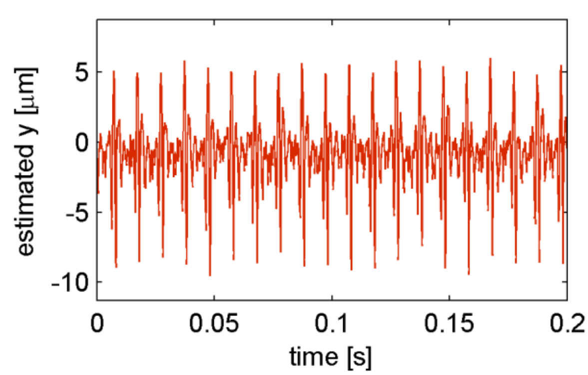

Figure 4: Vertical position estimated by D2 at a sampling rate of 6.5 kHz.

A periodic pattern with a σ_{RMS} of about 2 µm is prominent and superimposed with a stochastic uncertainty of about 500 nm, which can be considered as the resolution limit for the system at the aforementioned acquisition rate and photon flux. The FFT reveals a number of systematic components contributing to such fluctuations. In particular, significant contributions at 17 Hz and 23.5 Hz (imputable to water cooling) are visible;

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besides this, 100-Hz fluctuations and harmonics are prominent (noise from correctors).

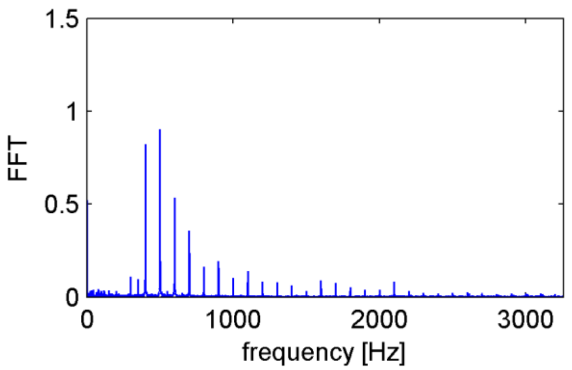

Figure 5: FFT magnitude of vertical position estimated by D2 at a sampling rate of 6.5 kHz.

For what concerns intensity monitoring, the photon flux can be directly estimated through the sum of the acquired photo-currents. With a machine current of 300 mA this gives 20 nA and 0.19 μA for D1 and D2, respectively, with a precision better than 1%. Since only sparse data on radiation damage of this kind of CVDs caused by long-term exposure with x-rays is available in literature, the demonstrator was operated continuously over a period of 9 months. The total current remained reasonably constant over the span of time with respect to a given machine energy (Fig. 6); this is an important point with a view to future applications of CVDs in FOFB systems.

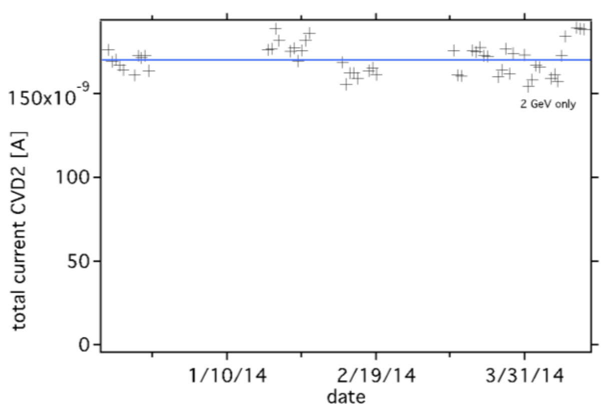

Figure 6: Long-term stability of the intensity monitoring of D2 for normal machine operations at 2 GeV (measured data reported as crosses).

CONCLUSIONS

In its first 9 months of operation the diagnostic-line demonstrator has turned out to be a reliable instrument, allowing for surveillance of bending-magnet radiation with high relative intensity resolution (better 1%) and high position resolution (better than 1 μm) at a maximum frame rate of 6.5 kHz. In order to include these diamond-based pBPMs in a FOFB system, the maximum frame rate should be increased to 10 kHz; this requires some refinements on the readout electronics, which can be implemented without major problems.

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