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PROGRESS TOWARDS SOFT X-RAY BEAM POSITION MONITOR DEVELOPMENT*

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Abstract

X-ray beam position monitors (BPMs) are instrumental for storage ring light sources, where they reliably provide positional measurements of high-power beams in hard X-ray beamlines. However, despite a growing need, coming especially from coherent soft X-ray beamlines, non-invasive soft X-ray BPMs have not been demonstrated yet. In this paper we report on our efforts to develop a non-invasive soft X-ray BPM with micron-scale resolution for high-power white beams. In our approach, multi-pixel GaAs detector arrays are placed into the beam halo and beam position is inferred from the pixel photocurrents. Presently, the first detector array prototypes have been manufactured for low-power beam tests. The mechanical design of a BPM test-stand, which will be installed in the 23-ID canted soft X-ray undulator beamline at NSLS-II, is largely completed. In addition, we are developing new algorithms of beam position calculation which take full advantage of extended multi-pixel detector arrays. In this paper we will review our design choices and discuss recent progress.

INTRODUCTION

In our soft X-ray BPM (sXBPM) design we directly sense the intensity of the outer portions of the X-ray beam with custom-made semiconductor detector arrays and then determine X-ray beam position from pixel photocurrents, see Fig. 1. Some challenges with this approach are that the device must withstand high power, operate in UHV, and preserve X-ray beam coherence. Other challenges, also applicable to conventional photoemission type XBPM designs [1, 2], include: 1) systematic errors due to widely varying beam profile with changes of ID gap and, for elliptically-polarized undulators, phase; and 2) contamination of insertion device (ID) radiation with "stray radiation" coming from the closest dipole and other magnets [3]. We believe these challenges could be eventually overcome, and that our multi-pixel detector array approach could be very effective in dealing with challenges 1) and 2) above.

However, because this device has never been demonstrated, we are taking a graded approach in our 3-year R&D program. Our 1st goal is to design, fabricate and demonstrate suitable performance of the detector arrays. Tests are performed with high-power lasers and other sources (visible and IR) and then at the TARDIS endstation of the 23-ID-1 (CSX) beamline at NSLS-II (soft X-ray).

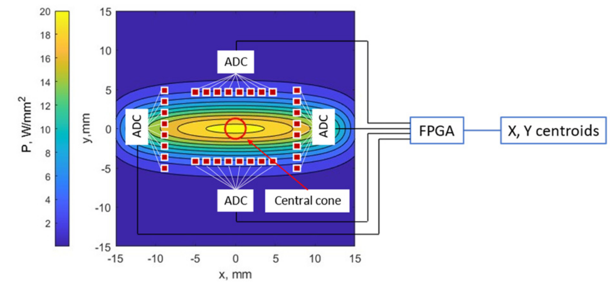

Figure 1: sXBPM concept.

Our 2nd goal is to design, fabricate, and install the sXBPM into the 23-ID first optics enclosure (FOE), 26 m downstream of the CSX ID (EPU49, $L = 2$ m), where the sXBPM detectors can be positioned to intercept the outer portions of white soft X-ray beam. Figure 1 shows maximum expected power density at the sXBPM location at $K = K_{max} = 3.458$, $E_1 = 250$ eV, linear horizontal polarization. When the ID is tuned to higher photon energy, the maximum power density and the beam width go down approximately proportional to K.

Our final goal is to demonstrate micron-scale positional resolution of the sXBPM, at the sampling rate of 10 Hz or higher.

To install the sXBPM into an operating beamline our design must guarantee no interference with beamline operations under all possible scenarios. Therefore, the detectors are placed on manipulator blades, which could be completely removed from the beam. Movable blades also give the advantage of detector placement tailored to the beam profile at a given undulator gap and phase (see i.e. [4]), however whether this is a must-have feature for the future sXBPM designs is still an open research topic.

Many wide-gap semiconductors, including CdTe, SiC, GaN and diamond, were explored for this application, and GaAs was selected due to its reproducibility, reliability and robustness for high-yield manufacturing and mature processing technology. GaAs/AlGaAs-based optoelectronic devices manufactured from wafers grown by Molecular Beam Epitaxy (MBE) are well known for long-term operation in extreme environments with high optical power, current densities and temperatures, for instance in high-power diode lasers. Reliable operation of GaAs/AlGaAs photodiodes and photodiode arrays have been demonstrated in many applications, some of which also require superior radiation resistance, including space satellite power generation.

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PROGRESS TO-DATE

Beam Physics and Algorithm Development

We spent significant effort on beam physics modelling, synchrotron radiation calculations (analytically and with codes such as SRW [5] and SPECTRA [6]), and the development of optimal algorithms to calculate the X-ray beam position from the individual detector pixel signals, to be reported separately. These studies were mainly performed to 1) guide the mechanical design of the sXBPM for the expected power distributions, required tolerances, optimized device geometry, required travel ranges, final device location, etc.; 2) guide the semiconductor detector array design with regards to optimal pixel geometry, expected power levels, optimal detector bandwidth, etc.; 3) explore and demonstrate the advantages of multi-pixel detector arrays for the XBPM application.

Key results to-date are as follows. Optimal detector placement for various undulator tuning parameters has been determined. Tolerances for the detector positioning were established. Effects of the individual pixel size and overall detector array area were quantified. Effects of the detector spectral bandwidth were investigated. It was shown that multi-pixel arrays can take advantage of more advanced position calculation algorithms than the Difference-over-Sum used in conventional BPMs. Finally, we showed through modelling that multi-pixel arrays could achieve superior performance with regards to discriminating against stray radiation, coming mainly from the downstream dipole.

Figure 2 illustrates our basic approach to the optimal placement of the photodiode arrays. We introduce four objective functions (separately for the horizontal and vertical beam motion, and for two detector array directions),

$$B(x,y) = \log_2 \frac{|\Delta P(x,y)|}{P_{max}}, \qquad (1)$$

where $P(x,y)$ is the undulator radiation power density at the sXBPM location, $\Delta P(x,y)$ is its change due 1 micron beam displacement in the corresponding direction, and P_{max} is the maximum of $P(x,y)$ with respect to x or y, for the horizontal or vertical array orientation, respectively. $B(x,y)$ at each of the pixels gives the minimum number of ADC bits required to achieve 1 micron resolution. Optimal placement is achieved by maximizing the integrated value of B across the array. The examples from Fig. 2 show that 20-bit ADC is sufficient to determine the horizontal position from the arrays placed as shown, because all (left figure) or most of the pixels (right) have $|B(x,y)| < 20$. Similar conclusions can be made for vertical beam motion.

Other array placement constraints come from the need to preserve user beam coherence, which requires staying away from the undulator radiation central cone, see Fig. 1. Finally, specific to our sXBPM location, additional constrains are due to the upstream X-ray beam apertures.

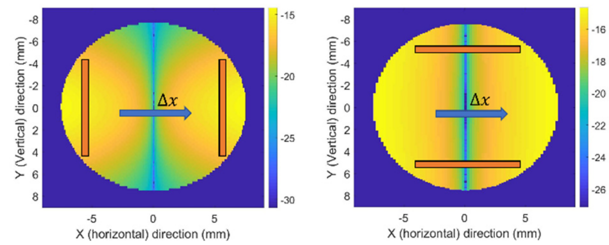

Figure 2: $B(x,y)$ plotted for K = 3.458, linear horizontal polarization; circular shape is due to the upstream mask.

Mechanical Design

The sXBPM contains four water-cooled blade assemblies, each of which will have a GaAs detector assembly mounted within it, that can be inserted into the outer portion of the undulator beam with sub-micron accuracy and resolution. The primary challenges in the design of the sXBPM include: 1) mechanical stability of the assembly, 2) management of the heat load from the X-ray beam, 3) compactness to fit within 23-ID FOE, and 4) accessibility for modifications. At present, the mechanical design is nearly complete, the final sXBPM location is fixed, the interference with existing beamline components is resolved. We are presently ordering various components including linear motion assemblies, gate valves, etc. Some of the components, e.g., high-stability Invar support and chamber clamps for the entire assembly will be fabricated by BNL central shops. The sXBPM assembly is to be performed at NSLS-II.

Figure 3 illustrates some features of the mechanical design. On left, four copper manipulator blades are visible through the central cross, which has 4” ID flanges. Detector heat shields are shown in blue. The overall weight of the assembly is about 220 kg. Electrical and water connections are not shown. The right figure shows the tip of the manipulator blade. Perforated heat shields allow a small fraction of the X-ray to reach the photodiode (PD) detector array. At the moment we are planning to place an ADC right next to the array (i.e. in UHV), although out-of-vacuum placement is also being considered as a back-up.

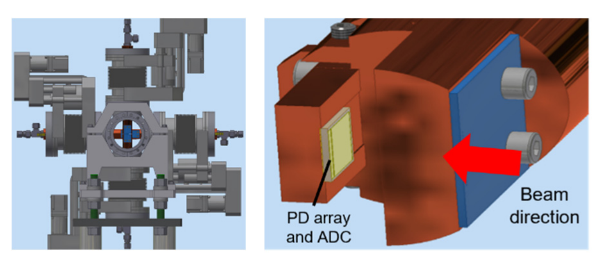

Figure 3: (left) sXBPM cross-section, (right) close-up of the tip of the manipulator blade.

Photodiode Design, Fabrication, and Testing

Our first-year activities consisted of the following: design and performance modelling of shallow P-N junction GaAs detectors, fabrication of small pixel photodiode arrays and array responsivity measurements with laser and broad-band light sources.

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The calibration layers and two photodiode wafers with different p-doping in the top absorbing layer were grown by solid-source MBE. The device wafers were processed into 32- and 64-pixel photodiode arrays with mesa sizes from 5×12 to 70×100 μm^2 and optical window sizes from 2×6 to 50×60 μm^2. Silicon nitride was used for isolation and sidewall passivation. Metallization of p-side was made by e-beam deposition of Ti/Pt/Au followed by metal lift-off. The wafers were lapped and polished down to 200 μm thickness. The Ohmic contact on n-side was made by e-beam deposition and annealing of Ni/Au/Ge/Ni/Au followed by deposition of Ti/Pt/Au metals. The wafers were cleaved into bars and mounted with indium on 32-lead ceramic carriers for characterization with high power Ar-ion and He-Ne lasers.

Extensive electrical and optical characterization of the photodiodes was performed. This included I-V curves for the devices with variations in the metal contact annealing regime for minimization of the contact resistance and responsivity measurements at laser wavelengths of 514 and 632 nm with the absorption depths of 0.1 and 0.25 μm, respectively. The linearity of the photocurrent vs. incident power density up to 120 W/cm^2 was verified with an Ar-ion laser. The extension of the depletion region of the P-N junction with reverse bias was used to assess the thickness of the depleted surface layer. The responsivity spectrum was measured with FTIR to determine the hole diffusion length for modelling of the detector responsivity in the hard X-ray spectral range. The experimental data are being thoroughly analyzed in preparation for publications.

Ten arrays with different pixel dimensions, p-doping levels, and annealing regimes have been packaged, cleaned for high vacuum, and shipped to BNL for measurements of responsivity spectra in the soft X-ray range at NSLS-II, described below. A schematic of the device cross-section and a photo of one of the arrays are shown in Fig. 4.

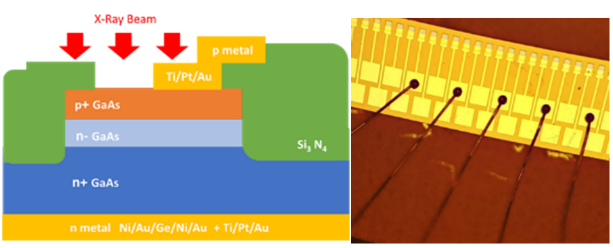

Figure 4: Photodiode array for CSX TARDIS experiment. (left) schematic cross-section; (right) 64-pixel array with 70×100 μm^2 mesa size and wire bonds to contact pads.

Preparations for Soft X-ray Tests

Having extensively tested the first prototype arrays with high-power laser light, we are now proceeding with soft X-ray tests, mainly to characterize the spectral sensitivity of several detector design prototypes. These studies are performed at the TARDIS endstation of CSX beamline, which can provide monochromatic X-rays in the range of 0.25-2 keV. These studies are significantly different from the typical user experiments routinely performed at the beamline, chiefly because numerous signal cables (one for each pixel) need to be brought out of the vacuum chamber. To address this, a special vacuum flange, retrofitted with electrical connections, was customized to include the detector mounting plate (Fig. 5, left). This flange was then mounted on the TARDIS chamber of the CSX beamline (Fig. 5, right), replacing an existing Pyrex glass viewport.

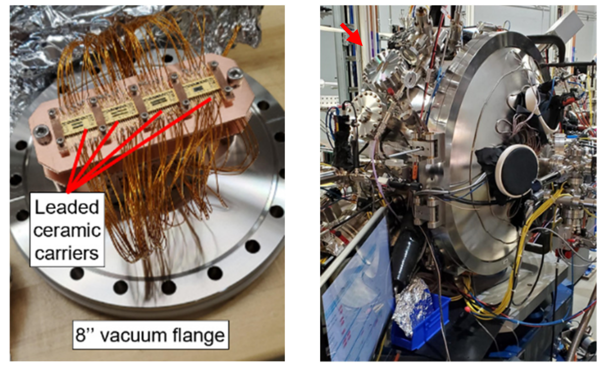

Figure 5: Customized vacuum flange with GaAs detector arrays (on leaded ceramic carriers) before (left) and after (right, arrow) mounting on the CSX TARDIS chamber.

SUMMARY

Our R&D program aims to demonstrate a novel XBPM (sXBPM) targeted for white beams in coherent soft X-ray beamlines. The device is to be installed and tested at the 23-ID canted undulator beamline at NSLS-II. About one year into the program, the mechanical design for the sXBPM is largely complete; procurement of the components is underway. Separately, the first GaAs detector arrays have been fabricated and characterized with an Ar-ion laser and are being tested with soft X-ray at the CSX endstation. Simulations are underway to develop algorithms for beam position calculations tailored to multi-pixel detector arrays, which would provide the best resolution and lowest systematic error due to changes in undulator tuning and due to stray light contamination.

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REFERENCES

[1] E. D. Johnson and T. Oversluizen, "Compact high flux photon beam position monitor", *Rev. Sci. Instrum.*, vol. 60, no. 7, pp. 1947-1950, 1989. doi:10.1063/1.1140896

[2] D. Shu, B. Rodricks, J. Barraza, T. Sanchez, and T. M. Kuzay, "The APS X-ray undulator photon beam position monitor and tests at CHESS and NSLS", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 319, no. 1–3, pp. 56–62, 1992. doi:10.1016/0168-9002(92)90531-8

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB121

[3] G. Decker and O. Singh, "Method for reducing x-ray background signals from insertion device x-ray beam position monitors", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 2, no. 11, p. 112801, 1999. doi:10.1103/PHYSREVSTAB.2.112801

[4] H. Aoyagi, T. Kudo, and H. Kitamura, "Blade-type X-ray beam position monitors for SPring-8 undulator beamlines", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 467, pp. 252-255, 2001. doi:10.1016/S0168-9002(01)00292-3

[5] O. Chubar and P. Elleaume, "Accurate and Efficient Computation of Synchrotron Radiation in the Near Field Region", in *Proc. 6th European Particle Accelerator Conf. (EPAC'98)*, Stockholm, Sweden, Jun. 1998, paper THP01G, pp. 1177-1179.

[6] T. Tanaka and H. Kitamura, "SPECTRA: a synchrotron radiation calculation code", *J. Synchrotron Radiat.*, vol. 8, no. 6, pp. 1221-1228, 2001. doi:10.1107/S090904950101425X