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DESIGN OF THE X-RAY BEAM SIZE MONITOR FOR THE ADVANCED PHOTON SOURCE UPGRADE*

K. P. Wootton†, F. K. Anthony, K. Belcher, J. S. Budz, J. Carwardine, W. Cheng, S. Chitra, G. Decker, S. Izzo, S.-H. Lee, J. Lenner, Z. Liu, P. McNamara, H. V. Nguyen, F. Rafael, C. Roehrig, J. Runchey, N. S. Sereno, G. Shen, J. Stevens, B. X. Yang
Argonne National Laboratory, Lemont, IL 60439, USA

Abstract

A beam size monitor provides an intuitive display of the status of the beam profile and motion in an accelerator. In the present work, we outline the design of the X-ray electron beam size monitor for the Advanced Photon Source Upgrade. Components and anticipated performance characteristics of the beam size monitor are outlined.

INTRODUCTION

The electron storage ring for the Advanced Photon Source Upgrade (APS-U) is designed to operate with transverse emittances on the order of 42 pm [1, 2]. The high average brightness X-ray beam presents a number of challenges for measurement and optimisation. In order to quantify the horizontal and vertical emittances, X-ray synchrotron radiation beam size monitors are planned for APS-U [3]. The beamline is illustrated in Fig. 1.

In the present work, we outline the design of the APS-U storage ring electron beam size monitor (BSM) beamline. Performance requirements of the beamline are outlined. The operating principles of the proposed instruments are summarised. Implementation of the beamline subsystems is outlined.

PERFORMANCE REQUIREMENTS

The BSM beamline is a hard X-ray beamline designed to measure the size of the electron beam in the APS-U storage ring. It is specifically optimised to determine the horizontal and vertical emittances of the beam. Functional requirements of emittance measurements are outlined in [1].

The beamline layout and requirements are functionally similar to the DL1A_5 emittance measurement beamlines of the European Synchrotron Radiation Facility Extremely Brilliant Source [4], and the diagnostics beamline of the High Energy Photon Source (HEPS) [5].

The BSM beamline is planned to be used to confirm delivery of the horizontal emittance Key Performance Parameter (KPP) of the APS-U project. During APS-U user operations, the beamline will be used for real-time reporting of the electron beam dimensions.

Physics requirements of the beamline motivate using an AM.1 bending magnet as the source point of bending magnet radiation, at a point in the storage ring lattice where the beam size is dominated by the emittance, and the horizontal dispersion is minimised. Table 1 shows the anticipated electron beam source properties. KPP performance requirements are indicated for comparison. Beam sizes corresponding to the KPPs are calculated for a horizontal emittance of 130 pm rad [1].

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† kwootton@anl.gov

Table 1: Electron Beam Source Properties of the APS-U BSM Beamline Instruments, with the APS-U Storage Ring Operated in Different Modes [6]

Branch	**BL1**	**BL2**	**BL3**	**BL4**	–
Instr.	XBPM	Rel.(x)	Abs.	Rel.(y)	–
Prop.	–	–	–	–	Units
Angle	−0.50	−1.10	−1.70	−2.30	mrad
β_x	1.69	1.65	1.62	1.58	m
β_y	19.8	19.8	19.9	19.9	m
η_x	0.233	0.242	0.263	0.295	mm
Timing mode: $\varepsilon_x = 31.9$ pm rad, $\varepsilon_y = 31.7$ pm rad, $\Delta E/E = 0.156$ %					
σ_{ex}	7.4	7.4	7.3	7.2	µm
σ_{ey}	25.1	25.1	25.1	25.1	µm
Brightness mode: $\varepsilon_x = 42.0$ pm rad, $\varepsilon_y = 4.2$ pm rad, $\Delta E/E = 0.135$ %					
σ_{ex}	8.5	8.4	8.3	8.3	µm
σ_{ey}	9.1	9.1	9.1	9.1	µm
KPP requirements: $\varepsilon_x = 130$ pm rad, $\Delta E/E = 0.135$ %					
σ_{ex}	15.0	14.9	14.7	14.6	µm

The principal physics requirement of the absolute beam size monitor is that the resolution of the instrument (σ_r) not increase the emittance measured by the beam size (σ_e) by more than 10 %. Adding in quadrature, $\sqrt{\sigma_e^2 + \sigma_r^2} < 1.1\sigma_e$, which implies an instrument resolution of ~3 µm [1]. This represents a challenging spatial resolution requirement. A feature of this beamline is the inclusion of a monochromator (and higher harmonic rejector), which are seldom included in emittance diagnostic beamlines [7, 8].

INSTRUMENTS

The principal scientific purpose of the beamline is measurement of the electron beam horizontal and vertical dimensions, both during accelerator commissioning and APS-U operations. The BSM beamline will provide three beam

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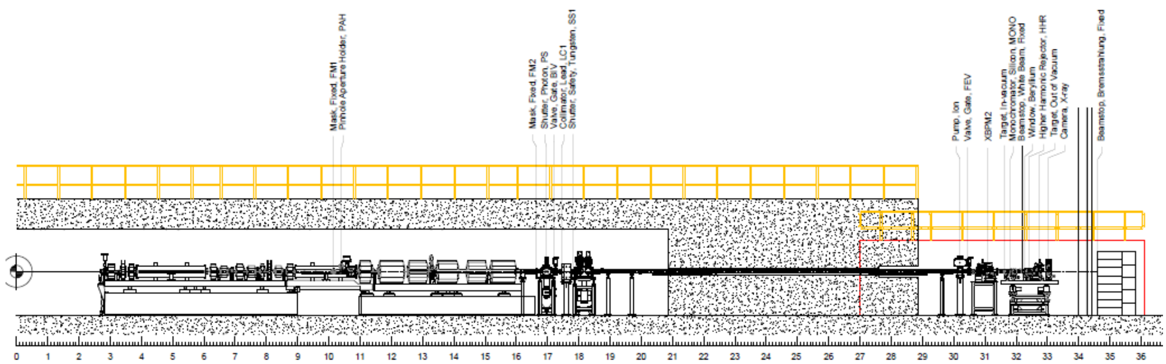

Figure 1: Elevation view of APS-U beam size monitor beamline. Principal beamline components are annotated. The longitudinal coordinate is metres from the centre of the insertion device straight. The bending magnet photon source point is at 3.83 m. The extent of the new BSM beamline enclosure is outlined in red.

size diagnostic instruments: an absolute beam size monitor, and two relative beam size monitors (one for each of the horizontal and vertical planes).

The beamline employs four branch lines, separated horizontally in angle in 0.6 mrad steps. The branch lines are:

1. X-ray beam position monitors (XBPM),
2. Horizontal relative beam size monitor,
3. Absolute beam size monitor,
4. Vertical relative beam size monitor.

The four branch lines are defined by the pinhole aperture holder (PAH). This is illustrated in Fig. 2.

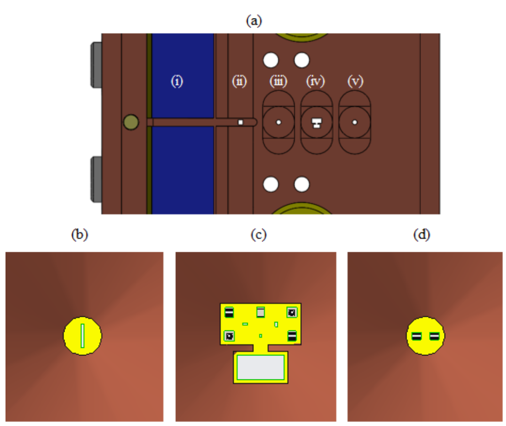

Figure 2: PAH and apertures. (a) Overview of apertures in PAH. (i) XBPM1 electrodes (in blue). (ii) BL1 (beam-defining aperture for XBPM2). (iii) BL2. (iv) BL3. (v) BL4. (b) Enlarged image of BL2 slit defining horizontal relative beam size monitor. (c) Enlarged image of BL3 apertures defining absolute beam size monitor. (d) Enlarged image of BL4 apertures defining vertical relative beam size monitor.

X-ray Beam Position Monitors

XBPMs are used in order to maintain alignment of the photon beam along the beamline. Two monitors are employed inline, for to correct electron beam position and gross angle.

In the beamline front end, XBPM1 has two photocathodes (one above, and one below the orbit plane), to observe beam motion in the vertical plane only. This is warranted since it is observing the fan of bending magnet radiation. A pinhole aperture passing XBPM1 is used to define the photon beam for XBPM2.

In the beamline enclosure, XBPM2 is used to observe beam motion in the horizontal and vertical planes. The white beam bending magnet radiation is incident upon an Yttrium Aluminum Garnet (YAG) scintillator. The scintillation light is split between two optical detectors: a digital camera (for observation at very low electron beam currents), and a diode-based quadrant detector for routine operation.

Using these two XBPMs, the electron beam in the APS-U storage ring can be steered to maintain stable performance of the BSM beamline.

Absolute Beam Size Monitor

The absolute beam size monitor is a hard X-ray (12 keV) pinhole camera. The principal pinhole aperture is square in profile, with an optimised size of $32 \times 32\,\mu\mathrm{m}$ in a $100\,\mu\mathrm{m}$ thickness tungsten foil [6]. In addition to the principal pinhole aperture, other diffraction features are used to provide instrument resolution calibrations.

Both the in-vacuum monochromator and higher harmonic rejector use a Si(111) channel-cut crystal with a vertical 12.7 mm offset between the entrance and exit height of the X-ray beams. The X-ray pinhole camera of the beamline provides a magnification of 3.8 from the electron beam source. The X-ray beam incident upon a YAG is imaged by an optical microscope (magnification ~2), and the image read out by a digital camera.

An in-vacuum knife edge on a motorised translation stage is utilised as a spatial calibration target, immediately upstream of the monochromator.

Relative Beam Size Monitors

Two relative beam size monitor instruments will be provided: one in each of the horizontal and vertical planes [9]. The principal purpose of these instruments is to provide on-

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line readback of the beam size for beam size optimization and control at a rate up to ~10k samples s^{-1}. The layout of components for the horizontal relative BSM are outlined in Fig. 3.

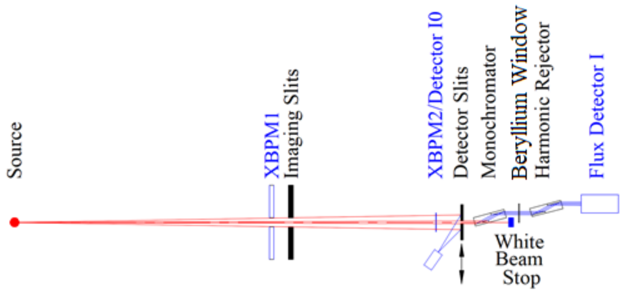

Figure 3: Schematic view of horizontal relative beam size monitor components [6].

The relative beam size monitors are anticipated to provide beam size measurement in two modes.

Intensity Mode The intensity mode of operation is used for relative beam size measurements at up to ~10k samples s^{-1}, significantly faster than imaging detectors of the absolute beam size monitor. Illustrated in Fig. 3, the electron beam source is co-aligned with the imaging slits and the detector slits. The incoming intensity is detected with a diode detector at ($I0$). Subsequently, the X-ray beam passing the detector slit is monochromated and measured using the flux detector (I). As the beam dimension oscillates, the flux passing the second slit changes. This could be utilised for online accelerator optimisation using machine learning [10].

Scanning Mode Additionally, the relative beam size monitor can be utilised for slow (<0.01 Hz) absolute beam size measurements. One-dimensional profiles of the electron beam image can be measured by laterally scanning the position of the detector slits through the X-ray beam. The intensity at each position is measured using the flux detector (I). This may be beneficial during early beamline commissioning, for low stored beam currents.

BEAMLINE COMPONENTS

Mechanical and Vacuum

Mechanical and vacuum components have been engineered according to standard Advanced Photon Source beamline requirements [11].

Beamline Enclosure

The enclosure is a lead-lined bending magnet enclosure for white beam bending magnet radiation [12]. Unlike many beamlines at storage ring light sources, a unique feature of this beamline geometry is the length of the penetration through the circular storage ring shielding wall (~8 m length). While challenging for component layouts, the thickness of shielding in the beam direction is significantly thicker than for a ratchet wall shielding configuration.

Detectors and Controls

Approximate locations of major optical components are summarised in Table 2 below. Component locations are given with respect to the centre of the insertion device straight section.

Table 2: Principal Optical Component Locations along Beamline

Location, z (m)	Component
10.15	First Fixed Mask
10.40	Pinhole Aperture Holder
31.20	Combined XBPM2-Slits-I0 monitor
31.62	Knife edge calibration target
31.91	Monochromator
32.29	Be Window
32.43	Harmonic Rejector
32.56	Slits
33.04	X-ray Camera

Beamline control and data acquisition will be performed using the Experimental Physics and Industrial Control System (EPICS).

Safety Interlocks

For both personnel safety and machine protection, safety interlocks are required for the beamline.

SUMMARY

In the present work, we have summarised design choices for the X-ray BSM beamline instruments for APS-U. Multiple instruments are provided in a compact arrangement, by separating them horizontally in angle. Absolute and relative BSMs will be used to characterize the beam during commissioning and user operations.

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