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

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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].

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

<table>
<thead>
<tr>
<th>Branch</th>
<th>BL1</th>
<th>BL2</th>
<th>BL3</th>
<th>BL4</th>
<th>–</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instr.</td>
<td>XBPM</td>
<td>Rel.(x)</td>
<td>Abs.</td>
<td>Rel.(y)</td>
<td>–</td>
</tr>
<tr>
<td>Prop.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Units</td>
</tr>
<tr>
<td>Angle</td>
<td>−0.50</td>
<td>−1.10</td>
<td>−1.70</td>
<td>−2.30</td>
<td>mrad</td>
</tr>
<tr>
<td>βx</td>
<td>1.69</td>
<td>1.65</td>
<td>1.62</td>
<td>1.58</td>
<td>m</td>
</tr>
<tr>
<td>βy</td>
<td>19.8</td>
<td>19.8</td>
<td>19.9</td>
<td>19.9</td>
<td>m</td>
</tr>
<tr>
<td>ηx</td>
<td>0.233</td>
<td>0.242</td>
<td>0.263</td>
<td>0.295</td>
<td>mm</td>
</tr>
</tbody>
</table>

Timing mode:

εx = 31.9 pm rad, εy = 31.7 pm rad, ΔE/E = 0.156 %

σex = 7.4 μm

σey = 25.1 μm

Brightness mode:

εx = 42.0 pm rad, εy = 4.2 pm rad, ΔE/E = 0.135 %

σex = 8.5 μm

σey = 9.1 μm

KPP requirements:

εx = 130 pm rad, ΔE/E = 0.135 %

σex = 15.0 μm

σey = 14.9 μm

The principal physics requirement of the absolute beam size monitor is that the resolution of the instrument (√σ) not increase the emittance measured by the beam size (ε) by more than 10%. Adding in quadrature, √σx2 + σy2 < 1.1ε, 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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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.

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 $32 \times 32 \mu$m in a 100 µm 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-
line readback of the beam size for beam size optimization and control at a rate up to ∼10 k 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].](image)

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 ∼10 k 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 (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**

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

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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