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Design considerations for mirrors at the Advanced Photon Source

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ABSTRACT

Detailed ray-tracing studies and preliminary thermal analysis are presented for two mirrors that will be installed at the Advanced Photon Source. The first mirror is designed to accept white radiation from a bending magnet. This radiation is 5 mrad in the horizontal direction and 73 μ rad in the vertical. A 1.5 m long toroidal mirror is planned. The second mirror accepts radiation from an undulator. This radiation is 55 μ rad and 25 μ rad in horizontal and vertical directions, respectively. A 70-cm toroidal mirror is planned. Both mirrors are optimized for 1:1 focusing in order to minimize optical aberrations. Design specifications are presented. Suitable materials for the mirror substrates and reflective surfaces are discussed as well.

1. INTRODUCTION

The Advanced Photon Source (APS), currently under construction at Argonne National Laboratory, USA, belongs to the new generation of dedicated synchrotron sources, as do the European Synchrotron Radiation Facility in Grenoble, France, and the Spring-8 Project in Japan. These facilities will employ insertion devices to produce the specific radiation properties of very low emittance (small source size and small beam divergence), wide spectral distribution, and high power. To successfully deliver the beam to experimental stations while preserving its brightness will require careful and, in many cases, quite innovative designs of the x-ray optical components. In particular, the design and subsequent performance of mirrors and monochromators will be of significant importance.

In this paper, mirrors that are planned for two typical APS beamlines will be discussed. We have chosen one bending magnet (BM) and one insertion device (ID) beamline because various parameters, such as mirror length, heat load, and manufacturing tolerances, strongly depend on the device producing the radiation. For example, while a mirror used to focus bending magnet radiation will be very long (1.5 m), it does not have to withstand high power loads. On the other hand, for a mirror used to focus undulator radiation, the requirements are reversed; it is of moderate length (70 cm) but, depending on the beamline configuration, the mirror may be exposed to severe thermal loads.

Mirrors fabricated for synchrotron radiation are multipurpose optical elements that can be broadly classified into two categories, curved and flat. Curved mirrors are primarily used for focusing x-rays on to a sample, but they can also eliminate higher harmonics. Flat mirrors are used to deflect the beam and, like curved mirrors, can filter out the unwanted power spectrum. General criteria necessary for mirrors' to preserve beam emittance and brilliance are discussed by Freund et al.¹

Ray-tracing studies using SHADOW² were performed in order to make design specifications for mirrors and also to determine their optimum position in the beamlines.

2. MIRROR FOR APS BENDING MAGNET RADIATION

Bending magnet beamlines at the APS are going to be the first beamlines that will deliver photons to experimental stations, and their design has to be carefully considered. In the mature phase of the facility operation, BM beamlines will be used as staging areas and, in some cases, as dedicated beamlines for developing and testing x-ray instrumentation. For example, development of x-ray phase plates for production and manipulation of polarization states and development of fast detectors with high spatial resolution will primarily be performed on a BM beamline.

We plan to install a focusing toroidal mirror as the first optical element in the beamline. To accomplish one of the unique features of the APS,³ which is to provide a low-emittance beam (7.3 nm-rad in horizontal and 0.73 nm-rad in vertical direction), a large circumference storage ring (1060 m) has been designed and is currently being constructed. The consequence of a large circumference ring is a long front end (22 m), which, in turn, limits the closest positioning of the first optical element to 24 meters from the source (center of the bending magnet). To minimize optical aberrations, 1:1 focusing is chosen; this, in turn, requires the experimental station to be 48 meters from the source. Although the glancing angles for total external reflection are small,⁴ typically from 3 mrad to 11 mrad, in order to avoid inclined beam transport we have decided to place a flat mirror immediately after the toroidal one. The flat mirror will redirect x-rays and allow for a fixed height of the exit beam independent of the energy regime and a non-inclined beam transport.

The length of the mirror plays an important role due to limited technological capabilities of vendors to produce focusing mirrors longer than 1 meter. This is primarily due to the limited availability of profilometers (only one is currently in development⁵ at ESRF)^{6,7} for measuring such an optic.

Ray-tracing studies were performed for various photon energies to determine the percentage of photon flux intercepted by a finite mirror length. Three photon energies were considered: 8 keV, 16 keV, and 24 keV, and three mirror lengths: 1 m, 1.5 m, and 2.0 m.

The results are summarized in the following table:

Energy (keV)	Length (m)	Reflected (%)
8	1.0	98.4
16	1.0	46.7
16	1.5	58.9
16	2.0	69.0
24	1.0	29.1
24	1.5	38.9
24	2.0	46.1

Clearly, a 1.5 meter long mirror is a good compromise. Mirrors of that length can be manufactured with adequate tolerances (5 Å RMS roughness and 10 µrad slope error) and still achieve a reasonable flux of reflected photons.

The heat load on the mirror surface is calculated to be 0.2 W/mm², which can be easily dissipated by water cooling.⁸ To represent the results of ray-tracing, we show (in Fig. 1) a BM source created with the following parameters:

E (Gev)	7.0
I (mA)	100
R (m)	38.96
e_x (nm-rad)	7.3
e_y (nm-rad)	0.73
Σ_x (mm)	0.11
Σ_y (mm)	0.11
$\partial\Sigma_x$ (mrad)	5
$\partial\Sigma_y$ (µrad)	73

In this table, E is the positron energy, I is the beam current, R is the bend radius, e_x and e_y are the horizontal and vertical emittance, Σ_x and Σ_y are the source size, and $\partial\Sigma_x$ and $\partial\Sigma_y$ are the beam horizontal and vertical divergence, respectively.

Once the source was created, an "infinite" mirror was placed 24 m from the source. The image this mirror created 48 m from the source is shown in Fig. 2. However, if a more realistic 1.5 m long mirror is considered, 41.1% of the flux was lost (Fig. 3).

Finally, design parameters for a mirror on the BM beamline are listed below:

Mirror Substrate:	GlidCop
Mirror Surface:	Platinum
Mirror Location:	24 m
Image Projected:	24 m
Horizontal Acceptance Angle:	5 mrad
Critical Angle:	5.3 mrad
Sagittal Radius:	0.12721 m
Tangential Radius:	4527.8404 m
Mirror Length:	150 cm
Mirror Width:	20 cm

3. MIRROR FOR APS UNDULATOR A RADIATION

The combination of high total power (1.5 KW) and high power density (140 W/mm²) of Undulator A (Phase I) at the APS imposes a considerable challenge to the design of x-ray optical components. Significant results^{9,10} have been achieved at the APS in reducing the high-heat load on the first crystal of the monochromator by implementing the concept of the "inclined geometry". Furthermore, by using liquid gallium as a coolant with its high heat transfer coefficient, the heat was efficiently transported away from the surface.¹¹ The bandpass of this type of Si(111) double crystal monochromator is of the

order of 5 eV; consequently, the total flux passed through the monochromator is down by more than three orders of magnitude. Therefore, for a mirror located downstream of the monochromator, the heat-load problem is non-existent.

Ray-tracing was performed for a mirror located 41 m from the source operating at a photon energy of 15 keV. The source, shown in Fig.4, was created using the following parameters:

L_0 (cm)	3.3
K	1.9
N	70
Σ_x (mm)	0.308
Σ_y (mm)	0.085
$\partial\Sigma_x$ (μ rad)	55
$\partial\Sigma_y$ (μ rad)	25

In this table, L_0 is the undulator period, K is the deflection parameter, N is the number of periods, Σ_x and Σ_y are the source size and $\partial\Sigma_x$ and $\partial\Sigma_y$ are the beam horizontal and vertical divergence, respectively.

The image created 81 m from the source is shown in Fig.5. Design parameters for a mirror are:

Mirror Substrate:	Silicon
Mirror Surface:	Nickel
Mirror Location:	41 m
Image Projected:	40 m
Horizontal Acceptance Angle:	55 μ rad
Critical Angle:	4.1 mrad
Sagittal Radius:	0.16608 m
Tangential Radius:	9872.7356 m
Mirror Length:	70 cm
Mirror Width:	3 cm

4. CONCLUSION

While we have only considered two simple cases, it is evident that the new generation of dedicated synchrotron sources will require new design concepts, fabrication techniques, and even new ways to specify tolerances in order that the brightness of these machines be preserved by the mirror optic. It will be paramount to the success of the mirror fabrication program that metrology be pushed to new frontiers. For the case of the mirror as the first optic in an APS undulator beamline, detailed and in-depth thermal analysis will be required for the mirror surface and substrate. Further, traditional optical analysis utilizing such concepts as the power spectral density function¹² to describe surface roughness and figure error induced by the fabrication process and thermal loading of the optic will be essential. These treatments consider the scattered image as well as the specularly reflected image. The new generation synchrotron sources will force the extension of the thermal-optical analysis frontier.

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Figure 1. Bending Magnet source at the APS. Each tick-mark corresponds to 1 mm.

Figure 2. Image created on a bending magnet beamline by a mirror whose length was not constrained.

Figure 3. Image created by a 1.5 m long mirror on a bending magnet beamline. The mirror was placed 24 m from source. Compared to an "infinite mirror" of Fig.2, 41.1% of the flux was lost.

Figure 4. Undulator A source at the APS. Undulator period L_0 3.3 cm and deflection parameter $K=1.9$

Figure 5. Image created by a 70 cm mirror on the undulator A beamline

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