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SYNCHROTRON LIGHT MONITOR FOR THE ADVANCED PHOTON SOURCE BOOSTER SYNCHROTRON*

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Abstract

A new synchrotron light monitor has been tested for the booster synchrotron of the Advanced Photon Source. Visible light synchrotron radiation is collected by a mirror on a path tangential to the electron beam orbit, and directed to an optical imaging system and camera. This is planned to be a non-intercepting, transverse beam-size monitor even with the higher stored beam charges (~17 nC) needed for the Advanced Photon Source Upgrade. In the present work, we describe the present synchrotron radiation diagnostic layout. An analysis of the synchrotron radiation power on the mirror, the optical layout with components, and features of the control system will be presented.

INTRODUCTION

Synchrotron radiation (SR) presents a significant thermal load on components in electron storage rings. As such, typically absorbers are designed with an inclined profile, and composed of a metallic material such as copper, to conduct heat away from the surface.

The motivation for the present work is to enable accurate measurement of beam properties during high-charge studies of the booster synchrotron for the Advanced Photon Source Upgrade (APS-U) [1, 2]. During those studies, it appears that the support for the mirror that reflects SR out of the vacuum deflects under thermal load from SR [3].

In the present work, we calculate the heat load on the mirror of the booster synchrotron photon monitor at the Advanced Photon Source (APS). We present the details of the mirror design. We summarise stability results using the diagnostic.

BACKGROUND

The beam profile monitors are required to support beam size measurements of the electron beam in the booster. Three photon ports are available for use as synchrotron light photon monitors in the booster [4–7]. Previously, only two ports had been instrumented. Under thermal loading, components of the assembly supporting the mirror in these ports expanded under thermal loading. The expansion was so significant that the image of the beam was deflected off sensors used to measure the beam transverse and longitudinal dimensions [3, 8]. Subsequently, this makes it difficult to routinely measure some properties of the electron beam such as emittance and energy spread.

To support physics goals of measuring the emittance in the booster, we propose to instrument all three photon monitors. The position of the beam image on the beam profile monitors needs to remain within a small enough displacement from nominal that it does not move off laterally the imaging and diagnostic devices.

SR POWER ON THE MIRROR

For an electron beam, the vertical distribution of SR power $\frac{\mathrm{d}P}{\mathrm{d}\Omega}$ in units of $\left[\mathrm{W\,mrad^{-2}}\right]$ is calculated by [9]:

$$\frac{\mathrm{d}P}{\mathrm{d}\Omega} = 5.42E^4BI_b\frac{1}{\left(1+\gamma^2\psi^2\right)^{5/2}}\left[1+\frac{5\gamma^2\psi^2}{7\left(1+\gamma^2\psi^2\right)}\right], \tag{1}$$

where E is in units of [GeV], B is in units of [T], I_b is in units of [A], γ is the Lorentz factor, and ψ is the vertical angle in units of [rad].

The peak power density (on-axis) $\frac{\mathrm{d}P}{\mathrm{d}\Omega}$ in units of $\left[\mathrm{W\,mrad^{-2}}\right]$ is given by [9]:

$$\frac{\mathrm{d}P}{\mathrm{d}\Omega} = 5.42E^4BI_b. \tag{2}$$

Integrating over the vertical angle, the power density in the horizontal direction $\frac{\mathrm{d}P}{\mathrm{d}\Omega}$ in units of $\left[\mathrm{W\,mrad^{-1}}\right]$ is given by [9]:

$$\frac{\mathrm{d}P}{\mathrm{d}\Omega} = 4.22E^3BI_b. \tag{3}$$

Calculation

We propose to perform a piecewise integration of the SR power, at intervals of 1 ms. Parameters used in the present calculation are summarised in Table 1. These parameters are approximate, and close to the nominal booster ramp [10–12].

Table 1: Booster and Electron Beam Parameters

Parameter	Symbol	Value	Ref.
Booster circumference	C	368 m	[1]
Charge	q	17 nC	[2]
Beam current	I_b	13.9 mA	…
SR source to mirror	d	2.85 m	…
Bending radius	ρ	33.3 m	[13]
Energy at injection	E_i	425 MeV	…
Energy at extraction	E_e	7.1 GeV	…
Ramp time (E_i-E_e)	t_r	0.25 s	…
Booster period	T_B	1.0 s	…
Photon port width	w	60 mm	…
Photon port height	h	37 mm	…

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Results

Figure 1 shows the profile of electron beam energy as a function of time during the ramp, using the parameters given in Table 1. In Fig. 2, we plot the profile of the magnetic field with the time during the ramp.

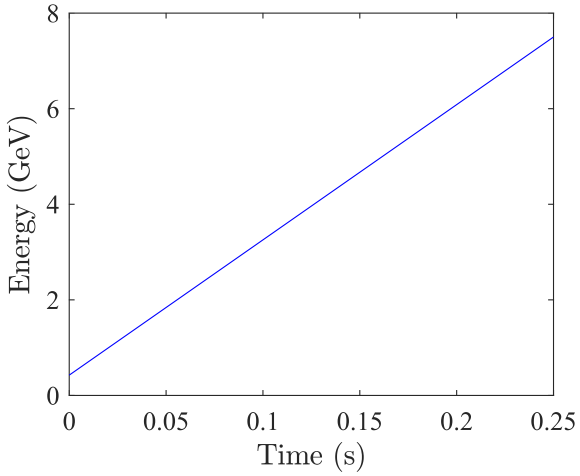

Figure 1: Beam energy as a function of time.

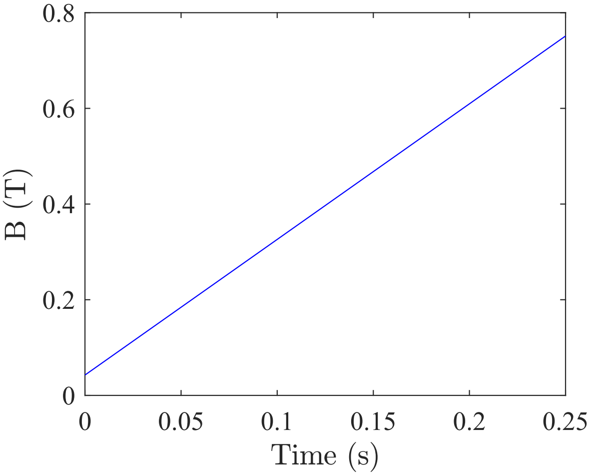

Figure 2: Magnetic field as a function of time.

Using Eq. (1), in Fig. 3 we plot the SR power as a function of both time during the ramp and vertical position at the location of the mirror.

Using Eq. (2), we plot the peak SR power density (on-axis) as a function of time during the booster ramp. We see that the dependence of SR power on the beam energy to the fourth power results in power deposition principally at the highest beam energies in the ramp.

Using Eq. (3), we calculate the SR power integrated over the full vertical fan, as a function of time. This is presented in Fig. 4.

Using the trapezoidal rule, we numerically integrate the power in Fig. 4, which gives 0.783 W mrad^{-1} (per unit horizontal bending angle). We can calculate the horizontal angular size of the photon port as w/d = 21.1 mrad. Hence using the product of the two, we can calculate the total power on the chamber during the ramp to be 16.5 W (across the whole width of the photon port). This is the power that would occur if the booster always had beam (duty factor of 1). However, the duty factor is necessarily reduced, to accommodate ramping of the booster magnets, and stacking in the upstream Particle Accumulator Ring. Hence, we define a duty factor as t_r/T_B = 0.25. Hence the time-averaged SR power across the photon port is 4.1 W.

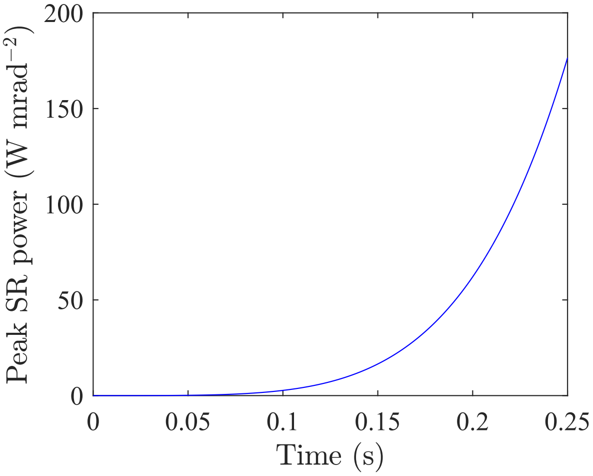

Figure 3: Peak SR power (Eq. (2)) as a function of time during the booster ramp. Essentially, this is equivalent to a line profile through Fig. 5 at vertical position = 0 mm (the orbit plane of the beam).

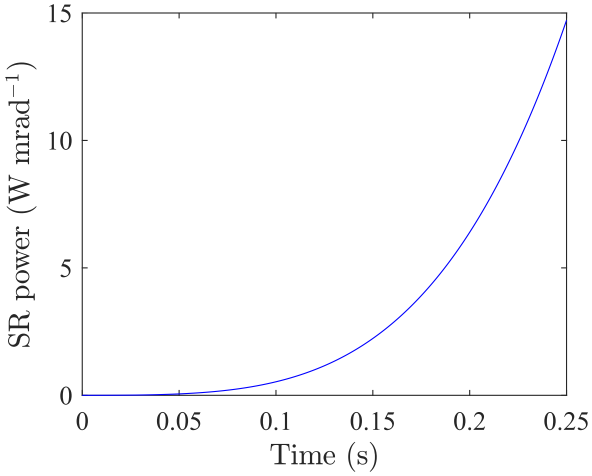

Figure 4: Total SR power on the mirror (Eq. (3)) as a function of time during the booster ramp.

PROFILE MONITOR LAYOUT

The beam profile monitor optical path and principal components are illustrated schematically in Fig. 6.

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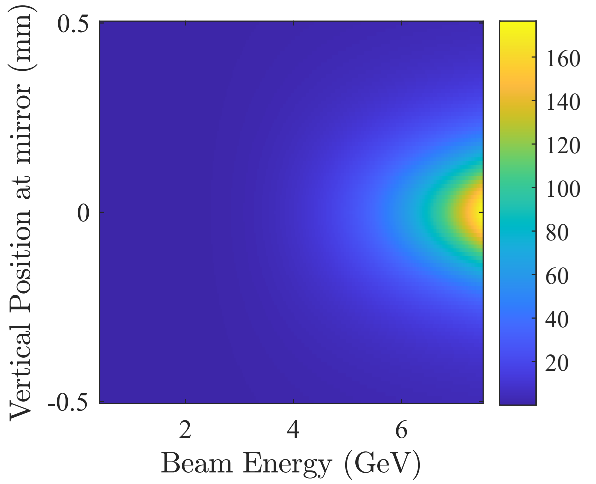

Figure 5: SR power distributed as a function of both time during the ramp and vertical position at the location of the mirror (Eq. (1)).

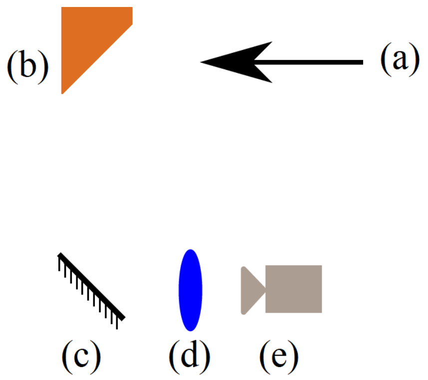

Figure 6: Schematic of beam profile monitor in the booster ring. (a) SR from electron beam. (b) Glidcop mirror. (c) Out-of-vacuum mirror. (d) Motorised zoom-focus lens. (e) Digital camera.

Components of the beam profile monitor are located physically within the booster synchrotron enclosure, which is illustrated in Fig. 7.

Mirror

Since the average SR beam power on the mirror was small (4.1 W), we endeavoured to improve imaging stability using a rigid mirror assembly composed of a bulk material. Glidcop was selected as the mirror substrate material.

The mirror was fabricated and polished in-house. The mirror substrate was cut and then polished using Loose Abrasive Polishing (lapping) to achieve the desired mirror surface finish. The mirror surface was specified as 60-40 scratch-dig, and a flatness error of 1λ. The mirror geometry is illustrated in Fig. 8.

For polishing, lapping was performed in several stages. The Glidcop Mirror and polishing fixture assembly were mounted in a precision vice on an Okamoto surface grinder (Fig. 9). The finished polished mirror is illustrated in Fig. 10.

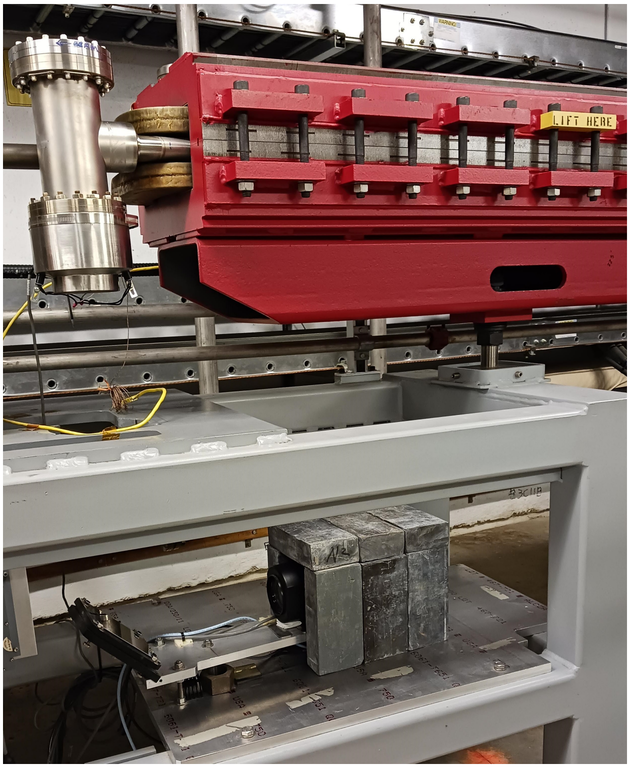

Figure 7: Photograph of beam profile monitor in the booster ring.

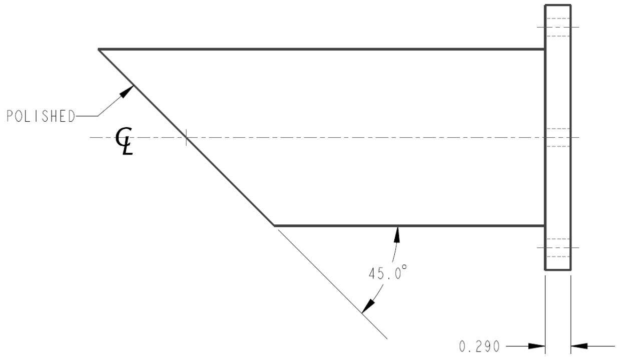

Figure 8: Mirror geometry.

IMAGE STABILITY

The principal goal of this mirror was to improve the image stability under an increased thermal load. We have tested the mirror performance in machine studies. For the existing synchrotron light monitors (denoted 1 & 2), lateral drift in the image position is observed as the mirrors distort under thermal loading from SR [3].

The most demanding beam condition under which we have tested the mirror is a 5 nC beam charge at 2 Hz repetition rate. This represents an average SR power on the mirror of 2.4 W, which is representative compared to the design of 4.1 W. We seek to evaluate the performance of the mirror

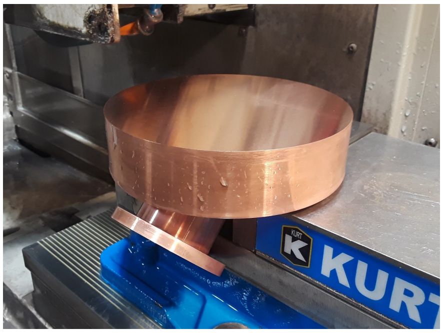

Figure 9: Photograph of the mirror and polishing fixture during machine lapping.

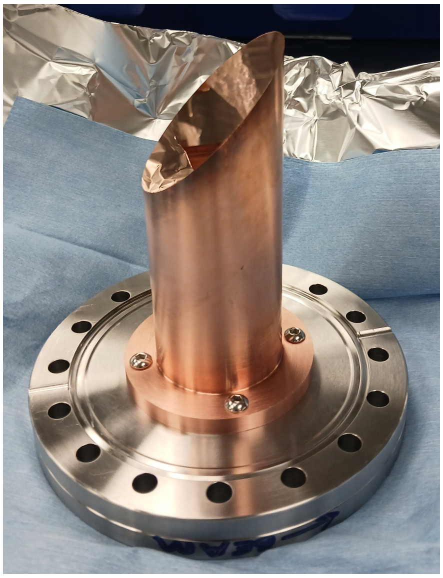

Figure 10: Finished mirror after final polishing.

stability under thermal load. We observed the electron beam simultaneously using two synchrotron light monitors: an existing synchrotron light monitor (B:SLM1) and this new monitor using a new mirror (B:SLM3). The motion of the beam image on both monitors is illustrated in Fig. 11.

SUMMARY

We have specified, designed and fabricated a mirror to observe and image visible synchrotron light from the booster synchrotron at the APS. We have calculated the SR power on mirror under anticipated beam conditions for APS-U operations, giving a maximum SR power on the mirror of 4.1 W. The mirror was fabricated and installed in the booster. We have tested the mirror under representative thermal loading and find that the mirror achieves the primary objective of stably transporting the SR power without measurable distortion.

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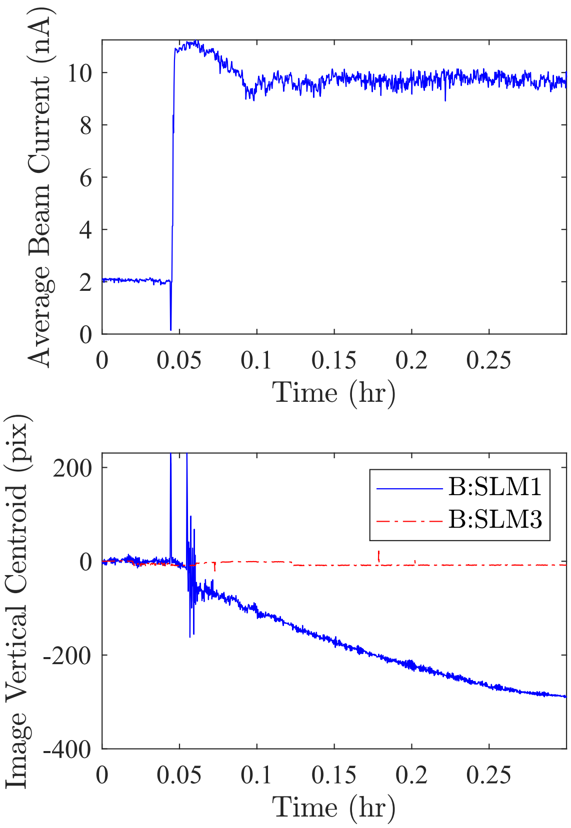

Figure 11: Electron beam image centroid position measured using two synchrotron light monitors. Over a 15 minute period, the centroid position on the old mirror (B:SLM1) drifts significantly, while there is no measurable drift observed for the new mirror design (B:SLM3).

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