A DESIGN STUDY FOR PHOTON DIAGNOSTICS FOR THE APS STORAGE RING SHORT-PULSE X-RAY SOURCE*

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Abstract

A short x-ray pulse source based on the crab cavity scheme proposed by Zholents is being developed at the Advanced Photon Source (APS). Photon diagnostics that visualize the electron bunches with transverse momentum chirp and verify the performance of the short x-ray pulse are required. We present a design study for the imaging diagnostics inside and outside of the crab cavity zone, utilizing both x-ray and visible synchrotron radiation. The diagnostics outside of the crab cavity zone will be used to map out stable operation parameters of the storage ring with crab cavities and to perform single-bunch, single-pass imaging of the chirped bunch, which facilitates optimizing the performance of the short-pulse source without disturbing other users around the ring.

INTRODUCTION

The Advanced Photon Source is developing a short x-ray pulse source based on the crab cavity scheme [1, 2]. It will use a pair of 2.8-GHz rf crab cavities located in sector 6 to produce a momentum chirp in the electron bunch. A second pair of crab cavities located at the end of sector 7 will be used to reverse the chirp and place all electrons in the bunch back to their stable orbit. In the zone between the two pairs of cavities (the crab cavity zone), the electron phase-space distribution will be nearly parallel to the y' axis inside the 7-ID insertion device, and nearly parallel to the y-axis at the 7-BM bend magnet source point. In this work, we will discuss options for utilizing the bend magnet (BM) radiation for beam diagnostics, synchronization, and x-ray experiments.

Inside the crab cavity zone, the projected vertical emittance of the perturbed bunch is over 100 times its normal value. In order to ensure that the users outside of the zone are not disturbed, it is critical that the cavities operate at precisely set phase and amplitude. An undulator-based, single-turn, single-bunch imaging camera in sector 35, timed for the chirped bunch, provides needed flux and spatial resolution for sensitive detection of the residual motion of the e-beam, and will be a valuable aid to the tuning of the second set of rf cavities.

THE BEND MAGNET SOURCE

In sector 6, an electron entering cavity 1 with vertical coordinates (y_0, y_0') receives a transverse kick according to its z-position in the bunch: $\Delta y' = (eV_0/E_e)\sin(2\pi z/\lambda_0)$, where V_0 is the peak cavity voltage, E_e is the electron energy, and λ_0 is the wavelength of the cavity. When the electron reaches the 7-BM bend magnet source, its position and directions are given by

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} \sqrt{\beta_y} & 0 \\ \dfrac{\alpha_y}{\sqrt{\beta_y}} & \dfrac{1}{\sqrt{\beta_y}} \end{pmatrix} \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \cdot \begin{pmatrix} \dfrac{1}{\sqrt{\beta_{y0}}} & \dfrac{-\alpha_{y0}}{\sqrt{\beta_{y0}}} \\ 0 & \sqrt{\beta_{y0}} \end{pmatrix} \begin{pmatrix} y_0 \\ y_0' + \dfrac{eV_0}{E_e}\sin\dfrac{2\pi z}{\lambda_0} \end{pmatrix}, \quad (1)$$

where ϕ is the betatron phase advance from the cavity to the BM source, and α_{y0} / β_{y0} and α_y / β_y are the alpha / beta functions at the cavity and the BM source, respectively. The electron emits photons in a cone with an rms divergence of $\sigma_\gamma = (0.62/\gamma)(\varepsilon_c/\varepsilon)^{0.46}$. Table 1 shows relevant parameters for the 7-BM source. We note that $Z\sigma_\gamma << \Delta y$ in the front end, the x-ray photons are within a vertical fan defined by,

$$\left| y_\gamma(Z) \right| \le \sqrt{\beta_{y0}\beta_y}\, \frac{eV_0}{E_e}\left(1 + \frac{Z\cos\phi}{\beta_y}\right). \quad (2)$$

Table 1: 7-BM Source Parameters

Cavity Pair 1 rf voltage, V_0	4 MV
Maximum deflection at the cavity	0.57 mrad
Beta function at the cavity, β_{y0}	5 m
Beta function at BM source, β_y	20 m
Maximum vertical offset at BM	5.7 mm
Vertical divergence angle of BM radiation, σ_γ	~ 60 μrad
Distance of new mask from source point, L_1	7.75 m
X-ray bean height due to divergence, $L_1\sigma_\gamma$	~ 0.47 mm
E-beam vertical slope at BM, $[dy/dt]_{BM}^{-1}$	10 ps/mm

Since $\cos\phi \sim 0$ near $\phi = 90^\circ$, and $Z < \beta_y$ in the front end, the x-ray beam is approximately parallel to the beamline axis, $\left| y_\gamma(z) \right| \le \sqrt{\beta_{y0}\beta_y}\,\Delta y_0'$. At the 7-BM source point the electron bunch is tilted vertically with a slope

$$\left[\frac{dy}{dt}\right]_{BM} = \frac{2\pi c V_0}{\lambda_0 E_e}\sqrt{\beta_{y0}\beta_y}\,. \quad (3)$$

Figure 1 shows three branch lines of the 7-BM beamline: (1) a visible light beam synchronized with the x-ray pulse, to be used by the sector 7 timing system, (2) a simple tilt diagnostic based on snapshot imaging of the x-ray beam profile, and (3) a short-pulse white x-ray source with its unique spectral and spatial properties.

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Visible Light Line

The electrons traversing through cavity 1 when the rf voltage crosses zero receive no vertical kicks. Hence they will arrive at 7-BM on-axis and go through 7-ID along the beamline axis. Therefore, the photons received on axis of 7-BM beamline are the best beam-derived timing signal other than the undulator beam itself.

The visible synchrotron light will be cross-correlated in a nonlinear crystal with the 7ID-E 20-fs-long Ti:Sapphire. The laser and visible light can be synchronized by modulating the phase of the rf used to synchronize the laser to the APS ring rf. Since the laser duration is much shorter than the synchrotron light, the cross-correlation signal is only present when the short laser pulse is present, thus one can determine in principle the arrival of the light with 20-fs resolution.

The vertical aperture of the light beam will be limited by the existing front-end aperture FM3 of 5.2 mm located 18.5 m from the source [3]. With ~ 7% of throughput, we expect ~ 4 × 10^7 visible photons (400 nm < λ < 700 nm) from a 16-mA bunch.

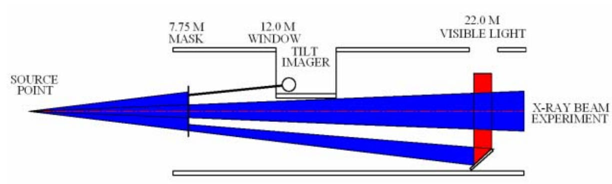

Figure 1: Schematics of three branch line of 7-BM.

Tilt Diagnostics

Since the BM x-ray beam propagates nearly parallel to the beamline axis, its vertical profile is a good approximation to the profile of the electron beam. The left panel of Fig. 2 shows an imaging setup using a scintillator and gated camera to capture a snapshot of the profile of the tilted bunch. The tilt diagnostics accepts ~ 0.1 mrad bend-magnet fan, which has an average power of 10 W. A shutter is needed to protect the scintillator from beam damage. It will be opened only briefly when images are acquired. An on-axis absorber will be used to block the dominant x-ray power from on-orbit bunches. The absorber further reduces the heat load on the scintillator and improves the signal-to-noise ratio of the image.

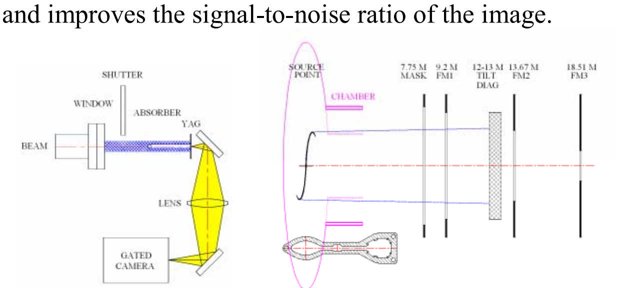

Figure 2: Left: schematics of a tilt diagnostic using a gated camera for snapshots of the tilted electron beam. Right: vertical aperture diagram of the beamline.

The right panel of Fig. 2 shows the vertical aperture diagram of the 7-BM front end. The existing storage ring chamber has a narrow neck that will clip the x-ray beam. We may apply one of the two possible remedies: machine the vacuum chamber to enlarge the vertical aperture, or reduce the e-beam size at the BM source point by reducing the vertical beta function to < 15 m. The first approach is preferred since it neither lengthens the x-ray pulse of the BM source nor puts unnecessary constraints on the lattice. From Fig. 2, we also note that the tilt diagnostics need to be located inside the front end before the aperture FM2 further clips the beam.

X-ray Beamline

Figure 3 shows the front-end modification for the 7-BM x-ray beamline. A set of vertical slits in the front end blocks on-axis x-rays so the beamline outputs x-rays only when the rf cavity is on. These slits and existing slits at L_2 = 22.5 m form a collimator that samples a small portion of the tilted electron beam. By approximating the slits with Gaussian functions, we derive the rms vertical size of the effective source seen through the collimator:

$$\sigma_{0,eff} = L_2 \sigma_{\gamma} \sqrt{\frac{\alpha_1^2 \alpha_2^2 + \alpha_1^2 + \alpha_2^2}{M^2 + \alpha_1^2 + \alpha_2^2}}\,, \qquad (4)$$

where $\alpha_i = 0.3 d_i / (L_i \sigma_\gamma)$ (i = 1, 2) are given by the slit widths d_1 and d_2, respectively, and $M = L_2/L_1 - 1$. The rms length of the x-ray pulse is

$$\sigma_t = \left[\frac{dy}{dt}\right]_{BM}^{-1} \sqrt{\sigma_{y0}^2 + \sigma_{0,eff}^2}\,, \qquad (5)$$

where σ_{y0} is the slice rms vertical beam size, or the beam size of the unperturbed beam. The peak flux of the x-ray pulse I_p is reduced from its original value I_{p0} by a factor $I_p / I_{p0} = \left(1 + \alpha_1^{-2} + \alpha_2^{-2}\right)^{-1/2}$. Figure 4 shows the 10-keV x-ray pulse length and the peak flux efficiency factor as a function of slit widths d_1 and d_2. The pulse length is not sensitive with the photon energy. This source's unique spatial and spectral properties should be useful for x-ray experiments. A Hamamatsu x-ray streak camera, running in synchroscan mode to take advantage of the suppressed background, will be used to study the x-ray pulse length and electron bunch tilt, thus verifying the phase and amplitude of the electron beam momentum chirp, and their stability.

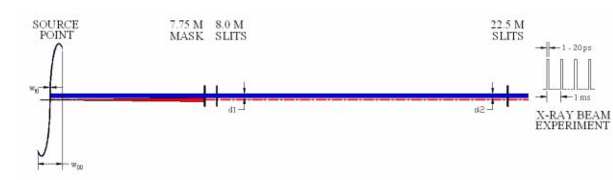

Figure 3: BM x-ray beamline in off-axis collimator mode.

THE UNDULATOR BEAMLINE

The monochromatic undulator radiation will be characterized using an x-ray streak camera. Streak images with cavities off give the phase and length of the undisturbed x-ray pulse, as well as their jitter shot-to-shot. As the cavity voltage is gradually increased, the momentum chirp gives undulator streak images similar to that in Figure 5. At full rf voltage, a large part of the chirped x-ray beam is shadowed by the ID beamline vacuum chamber. Only a small part of the beam can be seen by the streak camera to reveal the chirp rate and centroid information of the bunch.

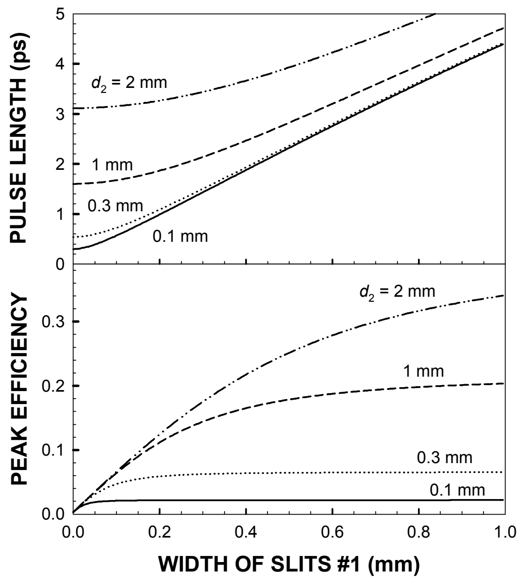

Figure 4: BM x-ray pulse length and peak flux efficiency.

For pump-probe experiments, the relative jitter of the arrival time of the laser and x-ray contributes directly to the time resolution of the experiment. X-ray streak camera may be used to measure the undulator and the laser simultaneously in the same streak image. If such measurements can be performed shot-by-shot during x-ray experiments, the measured timing jitter can be used to correct the data and significantly reduce the jitter.

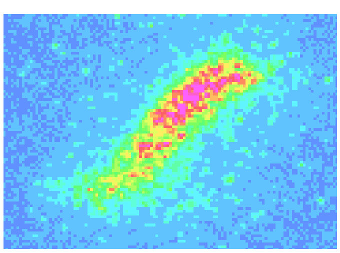

Figure 5: Visible light streak image of a tilted bunch [4].

OUTSIDE THE CRAB CAVITY ZONE

The APS diagnostics undulator line will be used to characterize the beam disturbance outside the crab cavity zone. Visible imaging has the capability of single-turn, single-pass imaging using high photon flux from the broadband optics. But its spatial resolution is limited to over 60 µm by diffraction at the APS. Bend-magnet-based pinhole optics and x-ray Fresnel zone plates have high spatial resolution, but their flux efficiencies are limited by small aperture or narrow energy band, respectively. Undulator-based beam imaging, however, has both high x-ray flux and superior spatial resolution [5].

Figure 6 shows the arrangements for the planned imaging optics. The undulator gap will be closed to produce high x-ray flux for single-bunch imaging. A fast shutter will be used to reduce the average beam power and to protect the scintillator from damage. A gated camera taking a snapshot of the tilted bunch after the cavity is fired will show the residual effect of the operation. A streak camera operating in transverse turn-by-turn imaging mode [5] will show the evolution of the transverse motion.

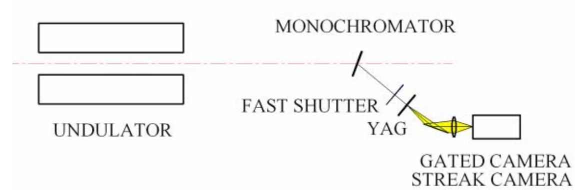

Figure 6: Optics arrangement for undulator-based fast imaging to detect beam motion / tilt outside of the zone.

SUMMARY

We performed initial design studies for the 7-BM beamline in the crab cavity zone of the APS short-pulse x-ray source. The beamline may be reconfigured into three functional branches: (1) a visible pulsed source synchronized with the x-ray pulse may be used to characterize timing jitters of the laser and x-ray sources; (2) a simple vertical beam profile imaging system may be used to provide information on the phase and amplitude of the momentum chirp of the electron beam; and (3) an x-ray collimator allows the sampling of the tilted electron bunch at the BM source, allowing an x-ray streak camera to visualize the vertical tilt of the electron bunch. This x-ray source has different spatial and spectral properties from the 7-ID source and may be used for x-ray experiments.

Single-turn, single-bunch imaging with 35-ID undulator monochromatic beam will be used to monitor the residual effect outside of the crab cavity zone to ensure that other users are not affected by the crab cavity.

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