

## DESIGN OF AN X-RAY IMAGING SYSTEM FOR THE LOW-ENERGY RING OF PEP-II\*

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### Abstract

An x-ray beam-size monitor for positrons in the low-energy ring (LER) of the PEP-II B Factory at SLAC is being designed to accommodate the present 2-A, 3.1-GeV beam and anticipated currents of up to 4.7 A. The final photon stop of an arc will be rebuilt to pass dipole radiation through cooled apertures to optics 17 m from the source. The initial installation will use pinhole optics with a calculated resolution of 35  $\mu\text{m}$ . We then plan an upgrade using zone-plate imaging to obtain a resolution of 6  $\mu\text{m}$ . Two multilayer x-ray mirrors precede the zone plate, limiting the bandwidth to 1%, in order to avoid chromatic blurring and protect the zone plate. Despite the narrow bandwidth, the zone plate's larger diameter compared to a pinhole camera allows for a comparable photon flux. We will image all of the available 1700 LER bunches and also measure them individually, searching for variations along the train due to electron-cloud and beam-beam effects, using a scanning detector conceptually derived from a wire scanner. A mask with three narrow slots at different orientations will scan the image to obtain three projections. In one passage, signals from a fast scintillator and photomultiplier will be rapidly digitized and sorted to profile each bunch.

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An x-ray beam-size monitor for positrons in the low-energy ring (LER) of the PEP-II B Factory at SLAC is being designed to accommodate the present 2-A, 3.1-GeV beam and anticipated currents of up to 4.7 A. The final photon stop of an arc will be rebuilt to pass dipole radiation through cooled apertures to optics 17 m from the source. The initial installation will use pinhole optics with a calculated resolution of 35  $\mu\text{m}$ . We then plan an upgrade using zone-plate imaging to obtain a resolution of 6  $\mu\text{m}$ . Two multilayer x-ray mirrors precede the zone plate, limiting the bandwidth to 1%, in order to avoid chromatic blurring and protect the zone plate. Despite the narrow bandwidth, the zone plate's larger diameter compared to a pinhole camera allows for a comparable photon flux. We will image all of the available 1700 LER bunches and also measure them individually, searching for variations along the train due to electron-cloud and beam-beam effects, using a scanning detector conceptually derived from a wire scanner. A mask with three narrow slots at different orientations will scan the image to obtain three projections. In one passage, signals from a fast scintillator and photomultiplier will be rapidly digitized and sorted to profile each bunch.

## INTRODUCTION

### PEP-II

In the PEP-II *B* Factory at the Stanford Linear Accelerator Center [1], collisions of 9-GeV electrons in the high-energy ring (HER) with 3.1-GeV positrons in the low-energy ring (LER) produce  $B\bar{B}$  meson pairs moving in the lab frame to allow measurement of *CP* violation. Since installing the *BABAR* detector in 1999 at PEP's one interaction point, both currents and luminosity have increased steadily. Beam currents have reached 1.55 A of electrons colliding with 2.45 A of positrons using 1600 bunches, for a peak luminosity of  $9.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ . Further gains over the next few years will come from adding RF power to increase the currents by almost a factor of 2, and from extensive modifications to the inner IR to reduce IP  $\beta$  functions and improve cooling.

### Visible Synchrotron-Light Monitors on PEP-II

PEP's synchrotron-light monitors (SLMs), using visible light, have been described previously [2]. For an improved measure of the vertical beam size in each ring,

we have supplemented the SLM with a synchrotron-light interferometer [3] that splits light from the same source.

The LER visible SLM is limited by coupling at the source point, a dipole 30 m from the IP, within the complex path that separates the outgoing LER from the incoming HER and within a sequence of skew quadrupoles that compensate for the 1.5-T solenoidal field in *BABAR*. The large coupling there makes it difficult to project vertical beam-size measurements to the IP. This source location was chosen to defer the difficulties and costs of extracting light from a LER arc dipole. Unlike the HER, the LER has short (45 cm) dipoles with extruded aluminum vacuum chambers. The synchrotron emission passes through a narrow neck into an antechamber, and then, at 4° to grazing incidence, strikes a photon stop [4] made of water-cooled Glidcop [5] (OFHC copper strengthened by grains of aluminum oxide) and designed to absorb 15 kW. For visible light, the difficulty of modifying a photon stop is compounded by having to change the hottest region, in order to take light that has not diffracted in the neck leading to the antechamber.

## X-RAY SOURCE AND BEAMLINE

### Source Location

We want the new x-ray monitor to be located at a source dipole far from the coupled region around the IP. For good vertical resolution, choosing a dipole next to a QD of the FODO lattice in the arcs gives a large  $\beta_y$ . We need sufficient drift space afterward to separate the photons from the positrons and sufficient beamline space in the tunnel (which, unlike a synchrotron light source, is underground with no access for user beamlines) to image the x rays onto a detector with little demagnification.

These criteria led to a location at the penultimate dipole of Arc 7, as the positrons head into Straight 6. Emission from the first 2/3 of an arc bend arrives at a photon stop 5 m downstream. Photons from the last 1/3 are not sufficiently bent away from the positrons, and so arrive at the subsequent photon stop, 13 m from the source, striking it at the edge by the aisle, farthest from the  $e^+$  beam. To extract the x rays, we are replacing this arc chamber with one having a photon stop that is narrower on the aisle side so that these photons can continue to the end of the antechamber. To avoid demagnification, the detector must be at a distance downstream comparable to the 13 m from source to photon stop. Since this is the final photon stop of the arc, the length of the x-ray beamline beyond is not

Table 1. Parameters at the source point.

Critical energy, $E_c$	4.9 keV
Horizontal rms beam size, $\sigma_x$	560 $\mu\text{m}$
Vertical rms beam size, $\sigma_y$	180 $\mu\text{m}$
Possible future vertical size	80 $\mu\text{m}$

restricted by the curvature of the arc and positions the detector conveniently near control racks in the hall at the middle of the straight section.

### From Photon Stop to Gate Valve

The end flange of the new arc chamber will be followed by an additional grazing-incidence photon stop with a 5-mm-diameter hole to limit the size of the x-ray beam and the heat load on subsequent components. To avoid hitting part of the rim of the hole at normal incidence, the photon stop will be conical. The light will hit the interior of this Glidcop cone at  $7.5^\circ$  to grazing incidence, with the centre of the fan exiting through the 5-mm hole at the vertex.

A gate valve will follow the conical stop, to separate the vacuum of the imaging beamline from the ring. Since the valve would be damaged by the x-ray heat load, a retractable, water-cooled, Glidcop stop will be placed between the conical stop and the valve. A viewport below the retractable stop will allow us to image the x-ray spot by its fluorescence on the Glidcop.

### Graphite Filter and Photon BPM

A filter to remove photons below the 5-keV critical energy will halve the heat on downstream surfaces. In addition, the resolution for pinhole imaging (see below), degrades from diffraction of long-wavelength photons. We plan to insert a filter made of 6 sheets of pyrolytic graphite with thicknesses from 5 to 75  $\mu\text{m}$  and totalling 175  $\mu\text{m}$ . These will get quite hot, especially the first, thinnest sheet, which absorbs low energies and so should reach 1700 K for our highest anticipated current of 4.7 A. The sheets are spaced sufficiently to allow radiative cooling into a blackened, water-cooled copper holder.

Because the imaging optic is 17 m from the source, it is important to maintain both the position and angle of the positron beam in the dipole. We plan a slow feedback ( $\approx 10$  sec) using the beam-position monitor (BPM) next to the source and a photon BPM just upstream of the optic. At this BPM we will trim the diameter of the x-ray beam from 5 to 3 mm in another conical aperture. The

Table 2. Zone-plate imaging design.

Photon energy	8 keV
Bandwidth	0.84%
Number of zones	1420
Diameter of zone plate	2.5 mm
Diameter of central stop	1.5 mm
Thickness of outer zone	440 nm
Distance from source to zone plate	17.2 m
Distance from zone plate to image	12.1 m
Magnification	0.70
Resolution, on source plane	6 $\mu\text{m}$

fluorescence from the Glidcop cone will be viewed by four x-ray photodiodes that are collimated to see the top, bottom, left and right sides of the aperture. The difference signals will then indicate the position of the x-ray fan.

## IMAGING

### Pinhole Camera

The simplest x-ray imager is a pinhole camera. We are constrained by the PEP layout to a distance from source to pinhole of 17.2 m. To avoid excessive demagnification, the detector must be a similar distance away, limited ultimately by the tunnel wall. We choose a distance from pinhole to detector of 12.1 m, for a magnification of 0.70. Accounting for both geometric and diffraction effects, the resolution improves for short wavelengths, but this choice must be balanced against the emission spectrum. If we choose 8 keV, a bit above the 5-keV critical energy, then the optimal resolution is 37  $\mu\text{m}$  (projected to the source plane) with a 39- $\mu\text{m}$  pinhole diameter. With our spectrum, cut at the low end by the graphite filter, the higher energy photons reduce the calculated optimum to 33  $\mu\text{m}$  with a 35- $\mu\text{m}$  pinhole. Adding this resolution in quadrature to the beam size gives the expected measurement.

The pinhole must be thick enough to stop transmission outside the hole, but not too thick compared to the hole diameter in order to avoid tight angular tolerances. We have ordered a 100- $\mu\text{m}$ -thick, 7-mm-diameter Pt-Ir (90:10) disk with four holes of diameters 30, 50, 70, and 100  $\mu\text{m}$ . The plate will be mounted on the downstream side of a water-cooled Glidcop plate with four somewhat wider holes, to minimize the heat load on the platinum without acting as the optical aperture. The assembly will be installed on motorised  $xy$  translation stages, allowing any one of the four holes to be illuminated. We can also use all holes at once to compare four separated images on the detector.

### Zone Plate and Multilayer Mirrors

Future plans for modifications to the lattice and for lower coupling may decrease the vertical beam size to 80  $\mu\text{m}$ , which would run into the limits of the expected pinhole resolution. For this phase, we are exploring diffractive imaging using a zone plate [6]. Our design (Table 2) uses 8-keV x rays (just above the 5-keV critical energy) to obtain a calculated resolution of 6  $\mu\text{m}$ .

Only the first-order diffraction from the zone plate is of interest. In particular, the zeroth order (undiffracted rays) from source to detector must be blocked by an opaque stop on the zone plate's centre. The large horizontal size of our beam forces a larger size for the zone plate in order to block undiffracted rays from off-axis source points.

A narrow bandwidth, needed both to avoid chromatic blurring (since the focal length varies with photon energy) and to reduce the power on the delicate zone plate, will be obtained by preceding the zone plate with a pair of silicon x-ray mirrors coated with alternating layers of B<sub>4</sub>C and Mo. The pair has a calculated peak reflectivity of 51%

over a bandwidth of 0.84% (full width at half maximum). Compared to pinhole imaging, the power lost to the narrow bandwidth is countered by the larger diameter of the zone plate. A major issue at this time is the careful thermal design of the first mirror, to avoid distortion of the reflected beam by a bowing or bulging due to the incident heat load.

We wrote a Monte-Carlo code that traces rays from source to image, also tracking harmonics of 8 keV and odd diffraction orders from -1 to +3, all weighted by diffraction efficiency, source intensity, and mirror reflectivity. (Even harmonics do not contribute when neighbouring transmissive and opaque zones have equal width.) We also track rays that pass outside the outer ring of the zone plate, through the thin substrate film. The code validates the design, but also indicates the need for masking the various higher-order and harmonic rays on the image plane, since they strike just outside the image and must not be allowed to interfere with curve fits.

## DETECTORS

### *Measuring the Bunch Train*

We are planning two detectors, both suitable for either imaging scheme. After installing the x-ray monitor during PEP's summer shutdown, we will commission the system with a basic detector that offers no time resolution, and so gives measurements integrated over the ring's fill pattern. The detector will be on a small optical table in the tunnel at the end of the beamline. The radiation will exit the vacuum through a beryllium window and strike a YAG:Ce scintillator. A lens, made of fused silica to resist x-ray browning, will image the YAG's green emission with a magnification of 1.5 onto a CCD video camera. The lens working at an F-number of 6.7 to avoid aberration, will be focused by a motorized translation stage. Between the lens and camera, a mirror with motorized tilt adjustment will centre the beam on the camera while keeping it out of the path of any remaining x rays. The Pulnix TM7 camera has an electronic shutter that can be remotely controlled to adjust for different beam currents.

### *Measuring Bunch-by-Bunch Profiles*

We have begun exploring a longer-range plan to measure the size of each bunch in the ring. Our typical fill pattern uses a bunch spacing of 4.2 ns, two periods of the 476-MHz RF. Gated, intensified cameras with the ability to isolate and measure single bunches separated by 2 ns are available. However, even with a reduced region of interest selected on the CCD, they operate at a few hertz, making the acquisition of every bunch a slow affair.

Counter-intuitively, a mechanical scanner can accomplish this task much faster. The well known linac wire scanner moves three wires—oriented vertically, horizontally, and at 45° to horizontal—across an electron beam, and measures its projections onto three axes— $x$ ,  $y$ , and  $u$ —by the radiation received downstream. Here we consider an analogous x-ray mask, such as 100  $\mu\text{m}$  of tungsten, with three narrow slots, placed on the image

plane formed by the pinhole or zone plate. A fast scintillator and photomultiplier are placed within a few mm on the downstream side of the mask. The PMT emits a pulse as the x rays from each positron bunch pass through a slot. With suitable fast electronics, similar to our bunch-current monitors [7], the signals from each bunch can be digitized and sorted. In a few seconds, as the mask is scanned across the x-ray image, we can acquire three profiles of each bunch, allowing the computer to determine for each the sizes along the major and minor axes and the tilt.

This scanner can be a linear translator, like the wire scanner. Mechanically, a rotary motion may be more robust, comparable to an optical chopper wheel. With a large enough radius, such as 100 mm, the change in the slot orientation with rotation does not cause difficulty.

Scintillators of sufficient speed have recently been devised. A pulse width of under 1 ns FWHM has been measured with ZnO:In [8]. Phototubes with 1-ns response, such as the Hamamatsu R7400U-06, are also available. Because the scintillator would be directly behind the x-ray image plane and in optical contact with the window of the PMT, we would capture a  $2\pi$  solid angle, far greater than that possible with a relay lens into a camera. A thin aluminum coating on the front face of the scintillator would boost the solid angle to a full  $4\pi$ .

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