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**Beam Size Measurement of the Stored Electron
Beam at the APS Storage Ring
Using Pinhole Optics**

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Z. Cai, B. Lai, W. Yun, E. Gluskin, D. Legnini, P. Illinski, and G. Srajer

Advanced Photon Source, Argonne National Laboratory
Argonne, IL 60439

Abstract

Beam sizes of the stored electron beam at the APS storage ring were measured using pinhole optics and bending magnet x-rays in single-bunch and low-current mode. A pinhole of 25 μm and a fast x-ray imaging system were located 23.8 m and 35.4 m from the source, respectively. The x-ray imaging system consists of a CdWO_4 scintillation crystal 60 μm thick, an optical imaging system, and a CCD detector. A measurement time of a few tenths of a second was obtained on a photon beam of $E > 30$ keV produced in a bending magnet from a 7-GeV electron beam of 2-mA current. The measured vertical and horizontal sizes of the electron beam were in reasonable agreement with the expected values.

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I. Introduction

The 7-GeV Advanced Photon Source (APS) at Argonne National Laboratory is one of the third-generation synchrotron radiation sources capable of providing photon beams with high brilliance. It is well known that, at given current and energy of an electron beam in the storage ring, the brilliance of the photon beam from an undulator is given by a convolution of the photon beam brilliance produced by an electron beam of zero emittance (which depends, in a diffraction-limit case, on the photon energy and the undulator structure) with the probability distribution of the electrons in the emittance phase space.¹ Therefore, low emittance of an electron beam in the storage ring is an important issue of the third generation sources. As the APS begins operation, beam emittance measurement become an essential part of the commissioning process to diagnose parameters of stored electron beam. This motivated us to carry out measurements on electron beam size, an important parameter of beam emittance, while commissioning the first (bending magnet) beamline on the APS.

Because of low emittance, the electron beam divergence is vastly exceeded by the natural opening angle of the bending-magnet radiation, making the divergence difficult to determine. Instead, the photon beam size is a true characterization of the electron beam size. With measured beam sizes, one is able to estimate the beam emittances from the Twiss parameters determined by the magnet lattice structure in the storage ring.²

A x-ray pinhole camera has the same optical properties as the more familiar visible-light pinhole camera. X-rays from different source points pass through a small pinhole and form an inverted source image at a screen downstream. Source size can be deduced from the size of the image. This technique has been used successfully to determine stored beam size at the Cornell Electron Storage Ring (CESR)^{3,4} and the European Synchrotron Radiation Facility (ESRF).⁵ In this paper, we report the results of size measurements on the 7 GeV electron beams in the APS

storage ring in single-bunch and low-current mode using pinhole optics and bending-magnet radiation.

II. Experimental Setup

The measurements were carried out at the B station of 1-BM using a pinhole imaging system consisting of a pinhole and a screen downstream. Fig. 1 is a schematic of the experiment. The x-ray source is the synchrotron radiation from the electron beam at the center of a bending magnet. The radiation was extracted from the storage ring through a beryllium window 500 μm thick and an aluminum window 250 μm thick. A pinhole and an x-ray imaging system (screen) were located 23.8 m and 35.4 m, respectively, from the source point. Thus, the source image is demagnified 2.05 times by the pinhole imaging system. The beamline slits, 1 m upstream from the pinhole, were set to 2 mm (vertical) X 3 mm (horizontal).

The pinhole consists of two pairs of long slits assembled in across, each slit being made of two 1.45-mm-thick tungsten blades. The edges of the blades were optically polished, and the roughness of the edges was found to be less than 0.2 μm . The large aspect ratio of the pinhole, due to its large thickness and small opening (see following), requires a precise angular alignment to place it parallel to the optical axis of the system. Otherwise, an effective reduction of the pinhole size will result. Therefore, an ionization detector was installed, and the x-ray transmission of the pinhole was measured as a function of pinhole's angular orientation about the x and y axes (horizontal and vertical axes, both perpendicular to the x-ray beam). The pinhole was thus aligned to obtain maximum x-ray transmission. The vertical and horizontal pinhole sizes were also examined by scanning a 0.3-mm-thick tungsten knife edge (at 35 mm downstream from the pinhole) across the beam and measuring the x-ray transmission of the knife edge as a function of its positions. Fig. 2 illustrates the intensity profiles of edge scans in both vertical and horizontal directions. From those profiles, the pinhole size was found to be 25 μm vertically and 19 μm horizontally. The straight lines and the sharp turning points in each profile indicate sharp pinhole

edges. Most of the x-rays from the bending magnet are absorbed by a beam mask in the front end and the beamline slits, leaving less than 0.2 W to be absorbed by the pinhole, which does not require anything more than air cooling.

The x-ray imaging system consists of a 60- μm cadmium tungstate (CdWO_4) scintillator (which converts the x-ray source image into a visible light image), an optical-lens system, and a CCD camera with low dark current ($< 2\text{e}^-/\text{hour}$) and low read noise ($5\text{e}^- \text{rms}$) placed in the imaging plane of the optical-lens system. The main purpose in using the optical imaging system was to increase the spatial resolution and the dynamic range of the CCD detector. The magnification of the optical lens system was calibrated using a mesh (1000 periods per inch) and was found to be 7.16. Fig. 3 displays the image broadening (scaled by the magnification of the optical lens system), generated by the optical lens system due to finite focal depth, versus the displacement of an object from a plane of best focusing towards the lens system. For a displacement less than 60 μm , image broadening is about 2 μm , dominated by the inherent resolution of the lens system. The resolution of the lens system could be maintained when a thin scintillator was employed. The CCD chip had 1024×1024 pixels and covered an area of $1.95 \times 1.95 \text{ cm}^2$. Thus, the detector resolution at the scintillator plane was 2.65 μm , comparable to the resolution of the optical lens system.

The Fraunhofer diffraction of x-rays from the pinhole results in an angular spreading of the x-ray beam and, thus, broadening of the source image. The FWHM angular divergence due to the diffraction is about λ/d , where λ is the wavelength of the x-rays and d is the dimension of the pinhole. Because a white beam was used and the width of the diffraction pattern was photon energy dependent, the deconvolution of the source image from x-ray diffraction is rather complicated. Therefore, a silicon attenuator with a thickness of 12 mm was placed 2 mm upstream from the scintillator to cut off the low energy x-rays and, hence, to reduce the diffraction effect. Fig. 4 illustrates calculated spectra of the incident x-ray beam, and this beam attenuated both by the 11.6-m air path (between the pinhole and the optical imaging system) and by the 12-mm silicon crystal. The x-ray energy was cut off below 30 keV.

III. Data Analysis and Results

Pinhole imaging is based on the law of rectilinear propagation of the geometrical optics, i.e., light rays in homogeneous media propagate in straight lines. Consider a source with Gaussian distribution of its intensity in the phase space, a pinhole and a screen downstream located at Z_1 and Z_2 , respectively, from the source, and a vertical (or horizontal) intensity profile of the source image on the screen. The ratio of the intensities in the profile, $I(y)$, with on-axis intensity, $I(0)$, can be expressed, if not including the diffraction effect, as a multiplication of three Gaussian functions,⁶

$$\frac{I(y)}{I(0)} = \exp\left[-\frac{y^2}{2\sigma_a^2}\right] \exp\left[-\frac{y^2}{2\sigma_b^2}\right] \exp\left[-\frac{y^2}{2\sigma_c^2}\right], \quad (1)$$

with

$$\sigma_a^2 = \left(\frac{Z_2 - Z_1}{Z_1}\right)^2 \sigma_y^2 + \left(\frac{Z_2}{Z_1}\right)^2 \sigma_s^2 + \frac{\sigma_s^2 \sigma_y^2}{Z_1^2 \sigma_y'^2}, \quad (2a)$$

$$\sigma_b^2 = (Z_2 - Z_1)^2 \sigma_y'^2 + \sigma_s^2 + \frac{Z_2^2 \sigma_s^2 \sigma_y'^2}{\sigma_y^2}, \quad (2b)$$

$$\sigma_c^2 = Z_2^2 \sigma_y'^2 + \sigma_y^2 + \frac{(Z_2 - Z_1)^2 \sigma_y^2 \sigma_y'^2}{\sigma_s^2}. \quad (2c)$$

Where σ_y and σ_y' are, respectively, the rms size and divergence of the source (vertical), and σ_s is the rms size of the pinhole. Eq. (1) describes a special case for a pinhole placed on the optical axis; otherwise, the intensity ratio will be a product of three Gaussian functions centered at different vertical positions in the screen plane if the pinhole is positioned off the optical axis. The width of the measured intensity profile σ is thus,

$$\frac{1}{\sigma^2} = \frac{1}{\sigma_a^2} + \frac{1}{\sigma_b^2} + \frac{1}{\sigma_c^2}. \quad (3)$$

Generally, the width of measured intensity profile on the screen is determined by the values of σ_a , σ_b , and σ_c . However, if one of them is much smaller than the others, the intensity profile will be mainly determined by this smaller value.

The correctness of Eq. (1) can be verified by considering the following cases: for $\sigma_y \rightarrow \infty$, the width of the source image on the screen becomes $\sigma^2 = [(Z_2 - Z_1) / Z_1] \sigma_y^2 + (Z_2 / Z_1) \sigma_s^2$, an expression usually used to describe the pinhole optics (the first term gives the source size scaled by the magnification of the pinhole imaging system, and the second term describes the size of the pinhole projected on the screen); if $\sigma_s \ll \sigma_y$ and the divergence of the source σ_y is so small such that $Z_1 \sigma_y \ll \sigma_s$, the width of the source image on the screen becomes $\sigma^2 = (Z_2 - Z_1)^2 \sigma_y^2 + \sigma_s^2$ (because σ_b becomes much smaller than σ_a and σ_c and the third term in Eq. (2b) is much smaller than the other two terms), which describes a case in which the rays from edge parts of the source can not reach the pinhole because of the small divergence and, thus, the image size is determined only by the source divergence and the pinhole-screen distance, rather than the source size; if $\sigma_y \ll \sigma_s$ and $Z_1 \sigma_y \ll \sigma_s$, the width of the source image on the screen becomes $\sigma^2 = Z_2^2 \sigma_y^2 + \sigma_y^2$ (because the third term in Eq. (2c) is much smaller than the other two terms and both σ_a and σ_b are much greater than σ_c), which describes a case where the size of the beam at the pinhole location is smaller than the size of the pinhole (or the pinhole does not exist). Moreover, when $\sigma_y = 0$, the width of the source image on the screen will be σ_s if $\sigma_y \gg \sigma_s$, or σ_y if $\sigma_y \ll \sigma_s$. These results agree with that determined from the law of rectilinear propagation of geometrical optics.

Clearly, the expression for the pinhole optics (mentioned in the first case above) is only one part of the description for the source-pinhole-screen system, and it becomes dominant only under some circumstances. In order to use this expression to determine the source size, the pinhole size and distances of the pinhole and the screen from the source have to be properly chosen so that the conditions are met for which the expression is valid. For a source of $\sigma_y = 40 \mu\text{m}$, $\sigma_y' = 25 \mu\text{rad}$ (less than the divergence of a 30-keV x-ray beam from a bending-magnet source at the APS), and

as to the other parameters (Z_1 , Z_2 , and σ_s) we chose in the measurements, σ_a differs from σ only by 0.1% and the difference between σ_a 's with and without inclusion of the third term in Eq. (2a) is less than 0.04%. These differences would be even smaller for a horizontal source size measurement. Therefore, the contributions to the measured source sizes from terms other than those listed in the first example above are negligible in our measurements.

The measurements reported here were carried out with an electron beam at low current (0.1-2 mA) and in single-bunch mode. Figure 5 shows the surface plot of the source image taken with the x-ray imaging system. With the 25 μm X 19 μm pinhole, we were able to record a good quality image within a few tenths of a second for any stored electron beam current higher than 0.1 mA. Before source images were taken, the pinhole was positioned on the optical axis by scanning it across the beam in both vertical and horizontal directions, assuring that intensity profile of the source image can be described by Eqs. (1) and (2) and, thus, simplifying data analysis. Table 1 lists some parameters of the pinhole imaging system, measured rms source image size at the screen, and deduced source sizes. The resolution of the x-ray imaging system consists of the CCD pixel size at the scintillator plane (2.7 μm), spatial resolution of the optical lens system (2.5 μm), and broadening (2.6 μm) due to finite thickness of the scintillator. In Table 1, the contribution to measured source size due to diffraction was estimated using 45-keV x-ray photons, an approximation when taking the x-ray spectrum into account.

It is not possible, using the intensity profile measured from the image on the screen, to uniquely deconvolve x-ray diffraction from the pinhole, unfold energy dependent absorption of x-rays in the scintillator, and thereby determine the beam size. Instead, we establish an analysis procedure that starts from Eq. (1), incorporates the effect of x-ray diffraction, the absorbed power spectrum of the scintillator, and the focal-depth effect due to the thickness of the scintillator, and then involves fitting to experimental data. First, we obtained the intensity profile of the source image at the scintillator screen, $F(\sigma)$, using

$$F(\sigma) = \int dE Q(E) f(E, \sigma) * D_{\text{diff}}(E) . \quad (4)$$

Where $Q(E)$ is the x-ray spectrum of the beam at the front surface of the scintillator, $f(E, \sigma)$ is the intensity profile of the source (rms size σ) image defined by photons of energy E (calculated from Eqs. (1) and (2)), and $D_{\text{diff}}(E)$ is the normalized diffraction profile. In Eq. (4) "*" refers to a convolution. Convolution of the intensity profile with diffraction profile gives the contribution to measured profile for x-rays of energies from E to $E+dE$. Note that f is a function of x-ray energy because of the energy dependence of the bending-magnet radiation opening angle, which mainly determines the divergence of the photon beam. Next, we calculated the intensity profile, $F_{\text{CCD}}(\sigma)$, received by the CCD detector taking into consideration the absorbed power by the scintillator and the broadening function due to the focal depth of the lens system, that is

$$F_{\text{CCD}}(\sigma) = \int dl P(l) F(\sigma) * B(l) . \quad (5)$$

Where $P(l)$ is the power absorbed by a layer of scintillation crystal of thickness dl at depth l , which was calculated using incident and absorbed spectra for the scintillator. $B(l)$ is the broadening function due to the focal depth for the image formed in the scintillation crystal at the depth l , and t is, thus, the thickness of the scintillation crystal. Using this procedure and varying the source rms size σ , we were able to fit the measured intensity profile.

The accuracy of the measurement depends on the accuracies of: the distances Z_1 and Z_2 , the calibration of the x-ray imaging system, and the pinhole size. The uncertainty in pinhole size will cause an error in determining source size when deconvolution of the image size from the broadening due to x-ray diffraction from the pinhole and the finite size of the pinhole are carried out. This error becomes sensitive when the source size is small. In our measurement, because a proper pinhole size was used and x-rays of energy below 30 keV were cut off, even without corrections due to x-ray diffraction and finite pinhole size, measured vertical beam size would be 14% larger for a particle beam size of 60 μm (1σ) and 28% larger for a particle beam size of 40 μm . With the corrections (or data fitting) based on our knowledge of pinhole size and x-ray spectrum, errors can be reduced to 6% and 15%, respectively. In the horizontal direction, the uncertainty of source size due to that of pinhole size is less than 2% for a source size of 150 μm .

The uncertainties of source sizes listed in Table 1 include those from the source distance measurement and the calibration of the x-ray imaging system. In the horizontal direction, the apparent source size increase due to orbit curvature of the particle beam is negligible (less than 2 μm).

We show in Fig. 6 the measured vertical beam size versus the tune split, the separation in horizontal and vertical betatron tunes, with a minimum tune split set at 0.007. When the tune split increased, the vertical beam size decreased quickly and saturated at about 50 μm . During changing of the tune split, measured horizontal beam sizes ranged from 140 μm to 155 μm , in agreement with that of a beam with design specification ($\sigma_x=110 \mu\text{m}$) broadened due to 0.1% particle energy dispersion. Thus, the performance of the APS storage ring has well exceeded its goal (110 μm in σ_y) in its initial phase. For the setup for this measurement, a point source would produce an image of size 16 μm at the screen (or 32 μm viewed at source), due largely to the pinhole size and the x-ray diffraction. The behavior of the vertical beam size at large tune split should be further studied.

In the pinhole imaging technique, because measured intensity profiles contain the convolutions of the source size with the pinhole size, the high accuracy of the measurement depends on a small pinhole size. However, a small pinhole size will cause severe diffraction of the x-rays from the pinhole, and it will also erode the accuracy of the measurement. Therefore, in order to optimize the measurement accuracy, a trade off between the convolutions of the source size with the pinhole size and with the diffraction from the pinhole has to be carefully chosen.

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Figure Captions

1. Illustration of experimental setup for source-size measurements. There were a photon beam mask, beamline slits, and Be-Al windows located at upstream from the pinhole. The pinhole and the scintillation crystal were located 23.8 m and 35.4 m, respectively, from the source.
2. Vertical and horizontal intensity profiles of knife-edge scans across the x-ray beam defined by the pinhole.
3. Image-broadening generated by the optical lens system due to focal depth.
4. Calculated spectra of the x-ray beam at the location of pinhole (dotted line), after 11.6-meter air attenuation (dashed and dotted line), and further attenuated by a 12-mm silicon crystal (solid line).
5. The photon source image on the scintillation screen captured by the CCD camera.
6. Measured vertical rms electron beam sizes as a function of tune split when the minimum tune split was set at 0.007.

Table 1. Contributions to measured source size

Term	Source	Horizontal	Vertical
$Z_2\sigma_s/Z_1$	pinhole size*	11.3 μm	14.8 μm
σ_{diff}	diffraction**	7.2 μm	5.4 μm
σ_{imaging}	resolution of x-ray imaging system	4.5 μm	4.5 μm
Σ	measured rms source-image size at screen	72.3 μm	34.4 μm
σ	electron beam size at source	145 $\pm$ 10 μm	62 $\pm$ 7 μm

* An approximation of a square function with a Gaussian function, $\sigma_s=d/(2\pi)^{1/2}$, has been employed.

** The diffraction broadening was calculated with x-ray energy $E = 45 \text{ keV}$.