The beam-based calibration of an X-ray pinhole camera at SSRF*

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Abstract: A pinhole camera for imaging X-ray synchrotron radiation from a dipole magnet is now in operation at the Shanghai Synchrotron Radiation Facility (SSRF) storage ring. The electron beam size is derived by unfolding the radiation image and the point spread function (PSF) with deconvolution techniques. The performance of the pinhole is determined by the accuracy of the PSF measurement. This article will focus on a beam-based calibration scheme to measure the PSF system by varying the beam images with different quadrupole settings and fitting them with the corresponding theoretical beam sizes. Applying this method at SSRF, the PSF value of the pinhole is revised from 37 to 44 μm. The deviation in beam size between the theoretical value and the measured value is minimized to 4% after calibration. This optimization allows us to observe the horizontal disturbance due to injection down to as small as 0.5 μm.

Key words: beam diagnostics, X-ray pinhole camera, point spread function, beam size measurement

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1 Introduction

Transverse beam emittance is a crucial parameter of an accelerator because it is directly related to the brilliance of a synchrotron light source. Due to its non-destructive nature, synchrotron radiation from a bending magnet is a versatile tool for beam profile measurements and is used in nearly every accelerator [1]. The spatial resolution of transverse beam profiling is now demanded to be better than a few microns on the most high brilliance light sources, so for this purpose X-ray pinhole cameras are widely used due to their simple setup and high practical reliability [2–5]. Typically, a pinhole-based emittance monitor has a limited resolution of $\geqslant 10$ μm. Recent calculations taking into account the spectral distribution of the source and applying numerical methods to precisely evaluate the diffraction, have shown that with the correct choice of pinhole size and magnification, an adequate resolution can be achieved. Precise calculation or calibration of the point spread function of the whole system is required in this case [6, 7].

As a third-generation national X-ray light source, the Shanghai Synchrotron Radiation Facility (SSRF) storage ring must be held to a high performance level [8]. An X-ray pinhole camera is applied to monitor the beam position and to measure the beam size and emittance precisely. The point spread function of the X-ray pinhole camera is estimated with analytical methods in the design stage. In order to determine the practical value of the point spread function, an on-line experiment has been carried out. The details and the results of this beam-based calibration will be discussed in this paper.

2 System setup

2.1 SSRF X-ray pinhole layout

The basic layout and components of the SSRF pinhole camera are shown in Fig. 1.

The X-ray beam from the bending magnet goes to an aluminum window which transmits only the high-energy photons from vacuum to air. A pinhole array

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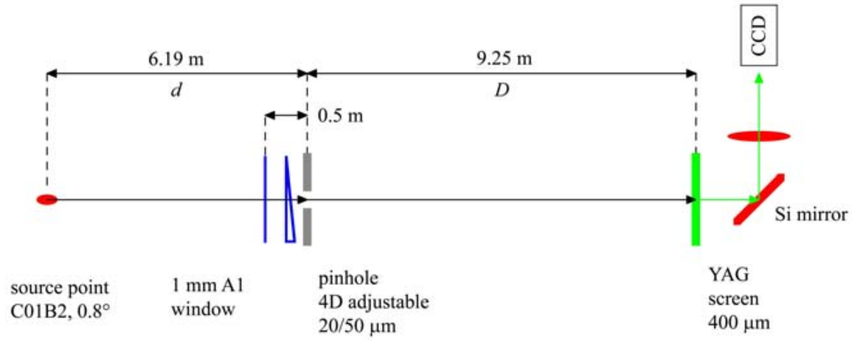

Fig. 1. System layout of SSRF X-ray pinhole camera.

combined with a horizontal and a vertical set of tungsten slits is placed after the window, as close as possible to the source, 6.19 m in our case. The X-ray image of the pinhole is converted into a visible light image at a peak wavelength of 530 nm with a YAG screen (400 μm thick). The screen is placed 9.25 m away from the pinhole, so that the image is magnified by a factor of 1.5. To acquire and measure the size of the source, we image the screen with a macro-lens (Componon 2.8/50 from Schneider-Kreuznach) focusing on a compact IEEE 1394 CCD camera (AVT Guppy F-080B, pixel size 4.65 μm). A LabVIEW and shared memory IOC core technique-based application has been developed to control the camera and communicate with the control system through EPICS CA protocol. The x and y position of the CCD, and the x and y position and angles of the pinhole array can be remotely adjusted [9].

2.2 Point spread function calculation

The measurement performance of the transverse electron beam size is given by the width of the point spread function (PSF) of the X-ray pinhole camera. The image formed on the camera is the convolution of several independent contributions, including beam size, pinhole size, YAG screen and CCD. Let us call Σ the rms Gaussian size of the acquired image and assume the source and the PSF to be Gaussian. Then Σ can be expressed as follows [10]:

$$\Sigma = \sqrt{(S\cdot C_{\rm mag})^2+S_{\rm aper}^2+S_{\rm diff}^2+S_{\rm scr}^2+S_{\rm CCD}^2}$$

$$= \left[\left(S\frac{D}{d}\right)^2+S_{\rm sys}^2\right]^{1/2}, \tag{1}$$

where S is the rms size of the image of the photon emitted by the electron beam at the source point; $S_{\rm aper}$ is the geometrical contribution introduced by the finite size of the pinhole; $S_{\rm diff}$ is the diffraction contribution by the small pinhole; $S_{\rm scr}$ is the spatial resolution of the screen; $S_{\rm CCD}$ is the spread induced by the camera, which includes pixel size, lens aberration and depth of focus through the finite thickness of the screen and aperture of the lens; $S_{\rm sys}$ is the effective PSF of the whole pinhole system; $C_{\rm mag}$ is the magnification factor of the pinhole camera; d is the distance from the source point to the pinhole and D is the distance from the pinhole to the screen.

Let A be the aperture size of the rectangular shaped pinhole. The contribution of the diffraction for a monochromatic photon beam of wavelength λ is given analytically by [10]

$$S_{\rm diff}=\frac{\sqrt{12}}{4\pi}\frac{\lambda D}{A}. \tag{2}$$

A simple geometrical computation shows that $S_{\rm aper}$ can be expressed as [10]:

$$S_{\rm aper}=\frac{A}{\sqrt{12}}\frac{D+d}{d}. \tag{3}$$

For the calculation of the PSF of the pinhole, the spectrum of the source needs to be taken into account. In our case the spectrum is the synchrotron radiation from a bending magnet, filtered in energy and intensity by a 1 mm thick Al window, a 2 mm thick Cu filter and 9.7 m of air. Fig. 2 shows the photon beam spectra at the source point, after a 1 mm Al window and a 2 mm Cu filter calculated by the XOP[1)] software package.

Applying the practical values of $d=6.19$ m, $D=9.25$ m and $A=50.0$ μm, we can get $S_{\rm aper}$ to be 36.0 μm. Integrating the expression (2) over the spectrum, we can get $S_{\rm diff}$ to be 0.9 μm. Then the rms combination of $S_{\rm aper}$ and $S_{\rm diff}$ is determined to be 36.0 μm for the 50.0 μm pinhole at SSRF.

1) http://www.esrf.eu/UsersAndScience/Experiments/TBS/SciSoft/xop2.3/Main

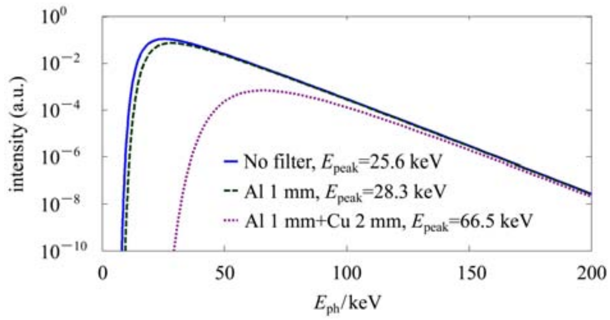

Fig. 2. The spectrum of the extracted X-ray photon beam.

S_{scr} and S_{CCD} are hard to calculate analytically or numerically, and have to be derived experimentally. The width of the PSF of S_{scr} and S_{CCD} is estimated to be 10.0 μm for our 400 μm YAG screen in the design stage based on the experiments on targets of different materials at the Diamond Light Source [6].

The total effective PSF of the whole pinhole system S_{sys} is calculated to be 37.4 μm with the above configuration in the design stage.

3 Beam-based calibration

In order to verify the usability and reliability of the pinhole camera and determine the width of the system point spread function, a new beam-based calibration method had been developed in the SSRF storage ring. By varying the beam size, S, at the source point and measuring image size, Σ, the practical S_{sys} can be derived from Eq. (1) using the least-square fitting method.

After the linear optics measurements and the optimization procedure known as linear optics from closed orbits (LOCO), the maximum beta function beating of the SSRF storage ring had been minimized to be smaller than 1%. In this case the difference of the beam parameters between the model and the practical machine was also smaller than 1%. We could use the beam size value of model S_{model} instead of the practical beam size value S.

As we know, the beam size could be described as follows [6]:

$$S_i^2 = \beta_i\epsilon_i + (\eta_i\sigma_\epsilon)^2, \tag{4}$$

where S_i is the beam size in the horizontal or vertical plane, respectively, $(i = x,\ y)$, β_i and η_i are the betatron and dispersion functions at the source point and in the corresponding plane; and ϵ_i and σ_ϵ are the emittance and the relative energy spread of the electron beam.

The PSF calibration experiment was carried out in a horizontal plane with 500 electron beam bunches, while the current was around 170 mA. The beam size of the source point was changed by modifying the power supply current, I_{Q5}, of the 5th set of the quadrupoles. The measured image sizes, Σ_x, at the CCD plane were recorded for each I_{Q5} setting. Applying the machine parameters (ϵ_x, β_x, η_x and σ_ϵ), which were derived from the optimized model corresponding to different I_{Q5} settings, to Eq. (4), the expected beam sizes S_x could be obtained as in Table 1. In this calculation, an energy spread σ_ϵ of 0.0011 was used, based on the previous experiment.

Table 1. The expected beam sizes and the corresponding Gaussian image sizes obtained from various machine parameters.

I_{Q5}/ A	ϵ_x/ (nm·rad)	β_x/ m	η_x/ m	S_x/ μm	Σ_x/ μm
0.94	6.54	1.04	0.084	130.2	184.0
0.95	5.61	0.99	0.076	117.8	167.2
0.96	4.84	0.94	0.069	106.8	153.7
0.97	4.46	0.90	0.063	98.6	142.5
0.98	4.15	0.86	0.058	91.7	133.3
0.99	3.97	0.83	0.053	85.7	125.9
1.00	3.91	0.79	0.049	80.9	120.0
1.01	3.93	0.76	0.045	76.8	116.9
1.02	4.03	0.73	0.041	73.2	112.7
1.03	4.21	0.70	0.039	71.7	109.5
1.04	4.44	0.68	0.035	69.2	106.9
1.05	4.73	0.65	0.032	67.4	105.1
1.06	5.07	0.62	0.029	66.0	103.7
1.07	5.46	0.58	0.025	63.8	102.7

Figure 3 shows the beam size comparison of calculation and measurements. It is obvious that the experimental data have good agreement with the modeling data, which verifies the good usability and reliability of the SSRF X-ray pinhole camera.

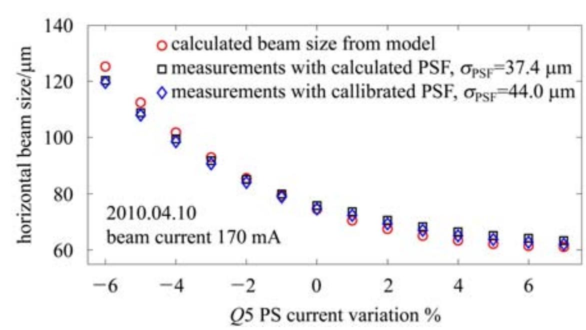

Fig. 3. Comparison between calculated beam size and measured beam size.

Fitting Σ_x and S_x data with Eq. (1) using the least-square method, the effective width of the PSF pinhole camera had been determined to be 44.0 μm larger than the expected value 37.4 μm. There are two probable causes of this disagreement. The first one is that the Gaussian PSF assumption was not completely suitable for a large sized pinhole (50 μm in this case) because the geometrical effect, whose PSF is rectangular, was in a more dominant position. The second was that the estimate of the PSF of $S_{\rm scr}$ and $S_{\rm CCD}$ was not completely suitable for the SSRF pinhole setup.

4 Applications

The beam-based calibration experiment showed the micron level sensitivity of the SSRF pinhole camera. After applying the new calibrated PSF, the system performance was improved and can now be qualified as a precise beam status monitor. The differences between the measured beam sizes and the modeling beam sizes decrease from 5% to smaller than 4% after the beam-based calibration.

At present, the pinhole camera is routinely used as both a beam imaging device to monitor transverse distribution and as an emittance diagnostic tool. During user runs, the SSRF storage ring horizontal beam size at the bending magnet is normally stable within a 2 μm range (2.9%), as shown in Fig. 4(a). The disturbance of horizontal beam size induced by injection has been observed as small as 0.5 μm, as shown in Fig. 4(b).

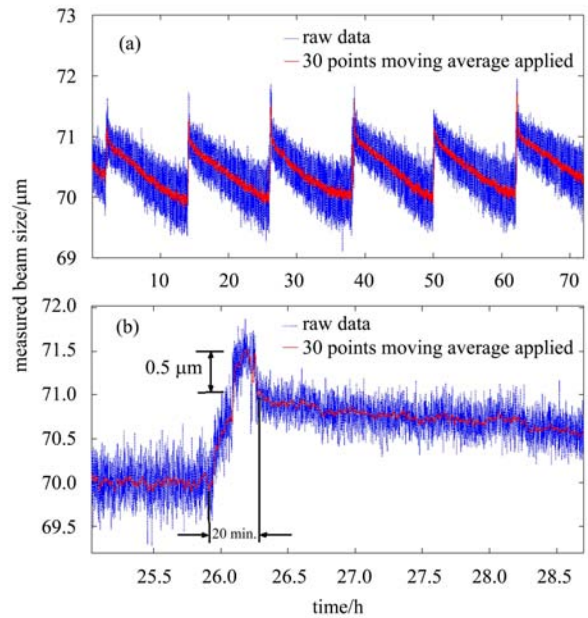

Fig. 4. (a) 70 h history data of horizontal beam size. (b) Beam size disturbance due to injection.

5 Conclusion

An X-ray pinhole camera diagnostic has been built at SSRF. To determine the width of the PSF system for the pinhole camera, a beam-based calibration method has been introduced. This calibration allows us to derive a more accurate resolution for the system. The variation in the horizontal beam sizes between the theoretical values and the measured ones is as small as 4% after calibration.

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