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BEAM SIZE MEASUREMENT AND PSF EVALUATE OF KB MIRROR MONITOR AT SSRF*

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Abstract

A Kirkpatrick Baez mirror imaging system was designed and installed to measure the transverse beam size and emittance of SSRF storage ring. Two crossed cylindrical mirrors are used to image the dipole source point in the horizontal and vertical direction. Both mirrors could be moved in and out in order to interchangeable with an original X-ray pinhole system. Hard X-ray with peak energy of 20.5 keV was focused at the X-ray scintillator camera. Aberration and point spread function which would cause image blur were evaluated. System commissioning and optimization have been done. PSF measurement was acquired using beam based calibration scheme by varying the beam images with different quadrupole settings and fitting them with the corresponding theoretical beam sizes.

INTRODUCTION

HEPS is a 6GeV ultralow-emittance storage ring light source to be built in Beijing, China [1]. This future light source is expected to achieve 60 pm·rad ultralow-emittance with MBA (Multiple-Bend Achromat) lattices design for constructing a so-called diffraction-limited storage ring [2]. Both horizontal and vertical beam sizes of HEPS storage ring are approximately 5~10 microns. It's a challenge for measuring such small beam size in both directions. To this end, Kirkpatrick Baez (KB) mirror imaging system was evaluated to measure it. A test KB system was designed and tested specific to SSRF storage ring [3].

BEAMLINE DESIGN

System Layout

A schematic of the KB monitor system layout is showed in Fig.1.

Synchrotron radiation from the dipole first crosses a 1mm thickness and 2mm diameter aluminum window at the frontend, which defines the X-ray open angle to be 0.35mrad. The Al window acts as a filter, is used to isolate the vacuum from air, photon energy below 10keV is cut off. The KB mirror pair is located in an independent vacuum chamber to prevent oxidation, with two entrance slits on its upstream end that defines the system's angular acceptance.

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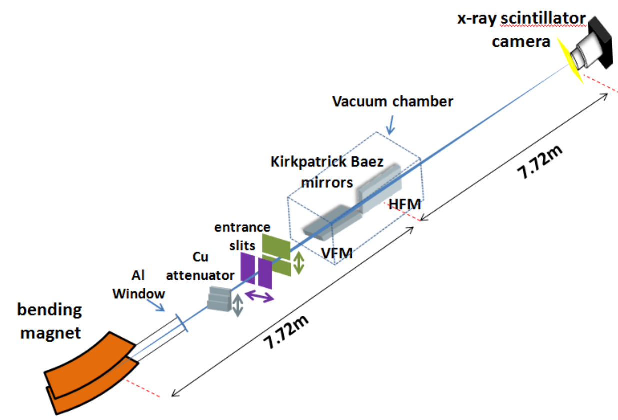

Figure 1: Schematic diagram of KB mirror system.

We use 1:1 imaging in our KB system with two cylindrical mirrors. The front mirror placed horizontally is called vertical focusing mirror (VFM), the back mirror placed vertically is called horizontal focusing mirror (HFM). HFM is located equidistant between the source and image for 1:1 imaging, meanwhile the magnification of VFM is 1.1. In front of the entrance slits, a Cu attenuator is used both to attenuate the photon flux and to protect the mirrors from long time high heat load running.

Table 1: Designed KB Mirror Parameter

	VFM	HFM
shape	cylindrical	cylindrical
radius of curvature	2.57 km	2.57 km
grazing angle	3 mrad	3 mrad
substrate	silicon	silicon
coating	Rh	Rh
acceptance angle	122 μrad	117 μrad
size L ×W× H	320×40×40mm^3	320×40×40mm^3
clear aperture L×W	300 mm×10 mm	300 mm×10 mm
RMS roughness	<0.2 nm	<0.2 nm
RMS slope error	<0.3 μrad	<0.3 μrad
distance to source	7.36 m	7.72 m
distance to image	8.08 m	7.72 m
magnification	1.1	1

Detailed parameters are shown in Table 1. For VFM, the average RMS slope error is 0.293 μrad, radius of curvature is 2.599 km. For HFM, the average RMS slope error is 0.381 μrad, radius of curvature is 2.55 km. Because of reflective optics design, there is no chromatic aberration in KB optics. As the magnification is approx. 1 in our case,

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there is no spherical aberration. Coma becomes the major part which can also be ignored after calculation.

Detector

We use two X-ray scintillator cameras to acquire the image of beam profile, which can be interchangeable with each other by using motorized translation stages.

The first camera (cam1) is an original camera of X-ray pinhole system with a 400 μm thickness YAG:Ce scintillator. A macro-lens is used to imaging the screen on a CCD camera (pixel size 4.65 μm) with a magnification of 2.

The second camera (cam2) is an update camera. It has a better resolution of about 1.5 μm with 5 μm thickness LuAG:Ce produced by Crytur. A microscope with a CCD camera is used to view the image on the scintillator. The CCD camera (Kodak KAF-8300) has a pixel size of 5.4 μm. With 20x magnification microscope objectives, the effective pixel size is 0.27 μm.

POINT SPREAD FUNCTION

The accuracy of the KB mirror monitor is determined by the RMS width of Point Spread Function (PSF). The obtained image is the convolution of the source profile with the PSF of the whole system, including several independent terms: PSF of the diffraction, PSF of the X-ray camera, and image blur caused by mirror slope error. We calculate the PSF assuming the source and the PSF to be Gaussian. Let's set Σ the RMS Gaussian size of the image, then it can be expressed as follows:

$$\Sigma^2 = (\sigma \times M)^2 + S_{diff}^2 + S_{slope}^2 + S_{camera}^2 = (\sigma \times M)^2 + S_{sys}^2 \tag{1}$$

where σ is the rms size of the image of the photon source at the bending magnet, M is the magnification of KB mirror, S_{diff} is the diffraction introduced by the aperture, S_{slope} is the rms image blur induced by mirror slope error, S_{camera} is the rms spatial resolution of the X-ray camera, S_{sys} is the effective rms PSF of the whole system.

Diffraction Limit

To calculate the image smear induced by aperture diffraction, we fits a Gaussian to the diffraction pattern of a circular or rectangular aperture, and treats the width of the Gaussian as a smearing term, S_{diff}, to be taken in quadrature with the beam size [4]. In this case,

$$S_{diff} \approx 0.4 \frac{\lambda}{2NA} \tag{2}$$

NA is numerical aperture of the imaging system, which is the half open angle of aperture; λ is the wavelength of X-ray, we use peak wavelength 0.06nm (20.5keV) here for calculation. There is small difference in aperture between vertical direction and horizontal direction.

For horizontal direction, the entrance angle is determined by dissector slit, which is 450 μm so that the entrance angle is 64.3μrad. By using Eq. (2), the diffraction limit of HFM is $S_{diff}^{HFM} \approx 0.37$ μm, which is proportional to λ.

For vertical direction, the entrance angle is determined by synchrotron light vertical opening angular σ_{SR}:

$$\sigma_{SR} = \frac{E_0}{E}\left(\frac{\lambda}{3\lambda_c}\right)^{1/2} \tag{3}$$

Where E_0 =0.51 MeV, is electron rest mass energy; E=3.5 GeV, is the electron energy of SSRF storage ring; λ_c=0.326 nm, is the critical wavelength of SSRF dipole. From Eq. (2) and Eq. (3), the VFM diffraction limit can be express by

$$S_{diff}^{VFM} \approx 0.4 \frac{E}{E_0}(3\lambda_c \cdot \lambda)^{1/2} \propto \lambda^{1/2} \tag{4}$$

The calculated value is $S_{diff}^{VFM} \approx 0.66$ μm, which is proportional to $\lambda^{1/2}$.

Slope Error

Slope error can be amplified by mirror-to-image distance q when X-ray is reflected away from the surface. Image blur due to the slope error depends on the focal length of the mirror and the RMS slope error: $S_{slope}=2\times\sigma_{slope}\times q$, where σ_{slope} is the RMS slope error. Table 2 shows the average RMS slope error, and the calculated image blur of VFM and HFM.

Table 2: Measured RMS Slope Error and the Caused Image Blur

	Slope error (σ_{slope})	Mirror to image distance (q)	Blur function (S_{slope})
VFM	0.29 μrad	8.08 m	4.69 μm
HFM	0.38 μrad	7.72 m	5.87 μm

Camera Resolution

In order to measure PSF of the X-ray camera composed by scintillator screen, macrolens and camera, we place an opaque mask covering the left part of the screen in front of the X-ray camera. The opaque mask with sharp edge is made by a tungsten bar. Figure 2 shows the measurement results of cam1 and cam2 used in our system. The resolution of Cam 1 is 19.7 ± 0.4 μm. Cam2 has a big improvement with resolution of 1.53± 0.04 μm.

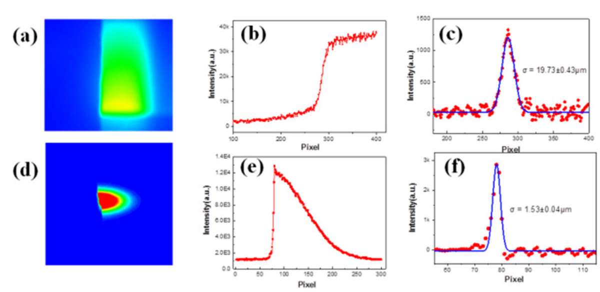

Figure 2: Image of tungsten bar edge observed in X-ray fan with (a) cam1 and (d) cam2. Profile of the edge of (b) cam1 and (e) cam2. The derivative of the profile (red) and a fitted Gaussian curve (blue) of (c) cam1 and (f) cam2.

System PSF Evaluation

We briefly summarize the total width of PSF S_{sys} of the KB system. It is calculated by using the quadratic sum of each item. Table 3 summarizes the PSF of vertical and horizontal directions with different scintillator cameras. It shows that when using cam1, the camera resolution is the

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dominant item contributing the biggest part to image extension. After the updated camera cam2 with 1.5 μm resolution was installed, the major part becomes the slope error item.

Table 3: Calculated PSF of the KB System in Vertical and Horizontal Directions

	S_{diff}	S_{slope}	S_{camera}		S_{sys}
Vertical	0.66μm	4.69μm	Cam1	19.73μm	20.29μm
			Cam2	1.53μm	4.97μm
Horizontal	0.37μm	5.87μm	Cam1	19.73μm	20.59μm
			Cam2	1.53μm	6.08μm

EXPERIMENT RESULT

Beam Imaging Result

We present here the imaging result of the electron beam with cam1 during top-up mode at 240 mA beam current in Fig. 3 (Data from 2017/07/20). The transverse beam sizes was Σ_x=77.5 μm horizontal by Σ_y=34.3 μm vertical as obtained from the CCD camera output before PSF calibration. After PSF calibration with the data in Table 3, the beam size is σ_x=74.7 μm and σ_y=25.1 μm.

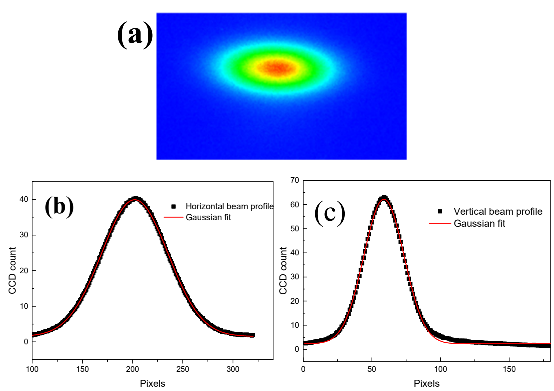

Figure 3: (a) Observed image of the KB mirror monitor in the SSRF control room.(b) Horizontal and (c) vertical beam profiles with their fitted gaussian curves.

Beam-based Calibration

In order to evaluate the online PSF with cam1, a beam-based calibration method [5] was used. We gradually change the horizontal beam size σ_x at the source point by modifying the power supply current, I_{Q5}, of the 5th set of the quadrupoles, and measuring image size Σ_x at each I_{Q5} setting. It's obvious that σ_x is what we want to acquire from Σ_x with quadratic subtraction as given by the Eq. (1) with a correct PSF width S_{sys}. However, we can use a model horizontal beam size σ_x^{model}, which can be calculated using linear optics from closed orbits (LOCO), to evaluate the PSF.

After the linear optics measurements and the optimization procedure by LOCO, the maximum beta function beating of the SSRF storage ring has been minimized to be smaller than 1%. In this case the difference of the beam parameters between the model and the practical machine is also smaller than 1%. The model horizontal beam size σ_x^{model} is calculated by

$$\sigma_x^{model} = \sqrt{\beta_x \varepsilon_x + (\eta_x \sigma_e)^2} \tag{5}$$

Where β_x and η_x are the betatron and dispersion functions at the source point and in the horizontal plane; and ε_x and σ_e are the horizontal emittance and relative energy spread of the electron beam.

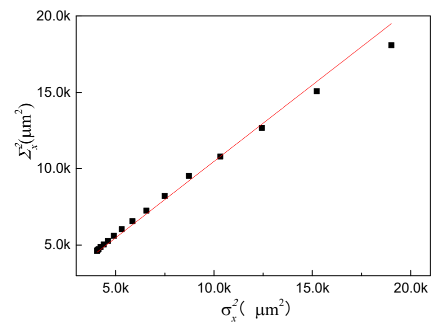

Figure 4: Least-square linear fitting of the squre of Σ_x and σ_x^{model}.

In order to determin the PSF, a least-square linear fitting method is used to fit the squre of Σ_x and σ_x^{model} with Eq.(1) at each I_{Q5} setting, the fitting slope is set to be 1(Fig.4). The fitting value is S_{sys} = 21.9±2.5 μm. It's well coincident with the off-line calculated value of 20.59 μm in Table 3. Figure 5 shows the beam size comparison of model theoretical value and measurement value with on-line PSF calibration. The measurement value is in good agreement with the theoretical value.

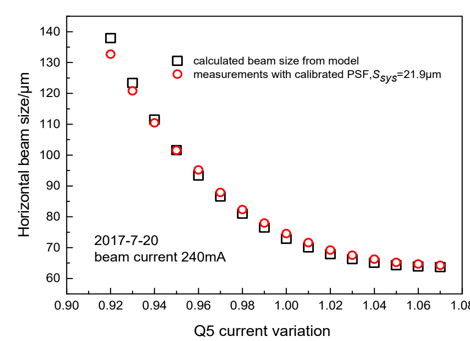

Figure 5: Comparison between theoretical beam size and measured beam size with on-line calibrated PSF.

CONCLUSION

A KB mirror beam size monitor is presented in this paper. We have evaluated the PSF of the system by calculating each item which could cause image blur. A beam-based calibration experiment is done to determine the PSF with the original camera. The experimental PSF result is well coincidence with the calculated data. A new X-ray camera with 5 μm thickness LuAG:Ce scintillator was installed. It has a resolution of about 1.5 μm. The calculated PSF of KB mirror monitor with the new camera is 4.97 μm vertically and 6.08 μm horizontally, slope error induced image

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broaden becomes the major contribution. The PSF is hopeful to be further improved with a pair of lower slope error KB mirror.

REFERENCES

[1] G. Xu, X.H. Cui, Z. Duan *et al.*, "Progress of the Lattice Design and Physics Studies on the High Energy Photon Source", in *Proc. IPAC'17,* Copenhagen, Denmark, May 2017, paper WEPAB052, pp. 2697-2699, doi:10.18429/JACoW-IPAC2017-WEPAB052

[2] Y. Jiao, G. Xu, "Optimizing the lattice design of a diffraction-limited storage ring with a rational combination of particle swarm and genetic algorithms", *Chinese Phys. C*, 41(2), 027001(2017), doi: 10.1088/1674-1137/41/2/027001

[3] D. C. Zhu *et al*, "Beam Profile Measurement Using Kirkpatrick Baez Mirror Optics at Shanghai Synchrotron Radiation Facility", in *Proc. IPAC'16,* Busan, Korea, May 2016, paper MOPMB036, pp. 167-170, doi:10.18429/JACoW-IPAC2016-MOPMB036

[4] J. W. Flanagan, "Diagnostics for Ultra-low Emittance Beams", in *Proc. IPAC'11*, San Sebastián, Spain, September 2011, paper WEYB01, pp. 1959-1963.

[5] Y. B. Leng, G. Q. Huang, M. Z. Zhang *et al.*, "The beam-based calibration of an X-ray pinhole camera at SSRF", *Chinese phys. C*, 36(1), 80-83 (2012), doi: 10.1088/1674-1137/36/1/014