BEAM PROFILE MEASUREMENT USING KIRKPATRICK BAEZ MIRROR OPTICS AT SHANGHAI SYNCHROTRON RADIATION FACILITY

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Abstract

For the third-generation light sources, the vertical emittance of a few pico-meter-radians which can be achieved with good coupling correction close to 0.1%, will lead to very small beam size. Several microns vertical beam sizes measurement has presented challenges for diagnostic capability in this region. A few techniques have been developed to make a precise measurement, such as visible light interferometer, x-ray imaging using Fresnel zone plates, compound refractive lenses or pinhole camera. In this paper, an x-ray reflective optics method based on the Kirkpatrick–Baez mirrors will be emphasis on discussed. The K-B mirror system will be installed and tested in SSRF to obtain the vertical beam size close to 20 microns, which is expected to be used for several microns vertical beam size measurement in the future light source named HEPS (High Energy Photon Source) in China.

INTRODUCTION

In third-generation synchrotron light source, the demand to obtain highly brilliant x-ray synchrotron radiation lead designers to product low-emittance electron beams. Measuring the electron beam emittance is therefore one of the most important diagnostics for a synchrotron light source. The unnormalized vertical emittance of current low-emittance rings in operation or under construction, have reached down to a few pm-rad [1,2]. The corresponding vertical beam size comes to the order of microns at bending magnet. It's a challenge to measure such a small beam by using the ordinal methods such as visible light imaging of synchrotron radiation (SR), as the spatial resolution is limited by diffraction of visible light (~400nm). Several other methods, such as visible light interference method [3], π polarization method [4], x-ray imaging optics using pinhole camera [5,6], Fresnel zone plates(FZP) [7], or compound refractive lenses(CRL) [8], were designed carefully to achieve the goal for micron level measurement.

Each method has advantages but also limitations. Visible light interferometer, developed by T. Mitsuhashi at KEK has better resolution than imaging method in visible light. However, the distance between the two slits is limited by the natural open angle of synchrotron radiation. For measuring approx. 5μm vertical beam size, SLS developed a new interferometer monitor which slits open angel was 5mrad [9], and using π polarization imaging method as a compatible design. In x-ray region, imaging methods have the potential to obtain higher resolution in principle, because the diffraction decreases with shorter wavelength. X-ray pinhole camera is widely used for its simple setup and high practical reliability. The resolution of pinhole optics is a balance between the diffraction limit (hole too small) and geometric blurring (hole too large). Fresnel zone plates and compound refractive lenses can achieve better resolution. However, they both require monochromatic light or they will introduce large chromatic aberrations. Therefore, the photon flux arriving at the detector would be very low and difficult to establish routine operation.

SSRF is the new third-generation x-ray synchrotron light source at ShangHai in China, operating at 3.5 GeV. To resolve beam profiles in the order of a few tens of μm, both x-ray pinhole camera method and visible light interferometer method were applied [10]. In this paper, we introduce a beam profile monitor based on Kirkpatrick-Baez (K-B) mirrors, which will be installed at summer shutdown in 2016, to measure the SSRF beam profile whose vertical beam size is approx. 20μm. The new setup uses the same bending magnet source point as the pinhole camera, so it's easier to compare the performance between the two monitors.

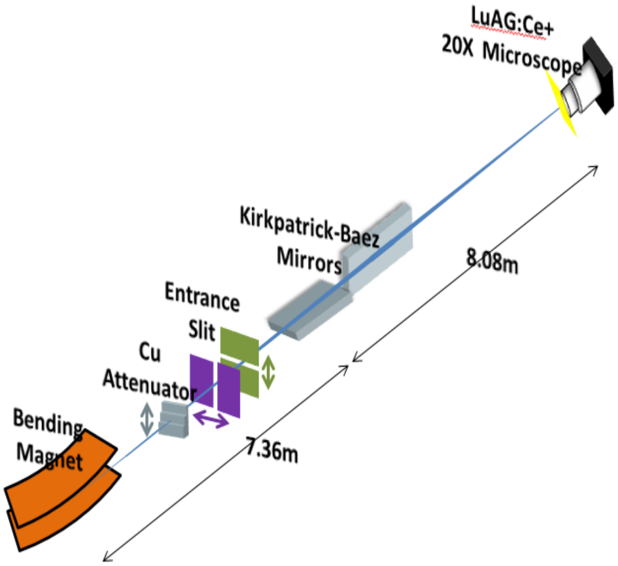

Figure 1: Schematic diagram of the K-B mirror system.

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SYSTEM LAYOUT

A schematic diagram of the K-B monitor system layout is showed in Fig.1.

Synchrotron radiation coming from the bending magnet first crosses a 1mm thick and 2mm diameter aluminum window at the frontend, which defines the x-ray open angle to be 0.35mrad. Al window is used to isolate the vacuum from air, which acts also as a filter. Photon energy below 10keV is cut off. The K-B 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. In order to isolate from any significant low frequency vibration, the mirrors are fixed with a $518\times712\times857\text{mm}^3$ granite block by UHV adjustment mechanics. The horizontal focus mirror (HFM) is located equidistant between the source and image for one-to-one imaging, meanwhile the magnification of vertical focus mirror (VFM) is 1.1. Detailed parameters of K-B mirrors are discussed in the next part. 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.

To obtain the two dimensional image of beam profile, a scintillator screen based x-ray camera is placed at the end of the beamline. The scintilator is a $10\times0.005\text{mm}^2$ LuAG:Ce glued on quartz substrate which is produced by Crytur. The scintillator converts x-ray into visible light, a microscope connecting with a CCD camera is used to view the image on the scintilator. In order to prevent hard x-rays from impinging on the CCD camera, visible light is reflect 45^o by a flat mirror. The CCD camera (Kodak Full frame KAF-8300) has a pixel size and special resolution of 5.4µm, while the total number of pixels is 3358× 2536, although only a small part of the pixels would be used. With 20x magnification microscope objectives, the effective pixel size is 0.27µm. Both slanted edge and Jima x-ray test by Crytur proved a very good performance that the special resolution was better than 1.5µm.

Table 1: Design Parameters of K-B Mirrors

Mirror	VFM	HFM
Shape	spherical cylinder	spherical cylinder
Radius of Curvature	2.57km	2.57km
Grazing angle	3mrad	3mrad
Substrate	Silicon	Silicon
Coating	Rh	Rh
Acceptance angle	122µrad	117µrad
Size L ×W× H	$320\times40\times40\text{ mm}^3$	$320\times40\times40\text{mm}^3$
Clear Aperture L×W	$300\times10\text{ mm}^3$	$300\times10\text{ mm}^3$
Roughness RMS	<0.2nm	<0.2nm
Slope error RMS	<0.3urad	<0.3urad
Distance to source	7.36m	7.72m
Distance to image	8.08m	7.72m
Magnification	1.1	1
Heat load	Hitting 1.083W@ Absorbed 0.832W	Hitting 0.251W@ Absorbed 0.058W

OPTICAL DESIGN

Kirkpatrick Baez Mirror System

In 1948, Kirkpatrick and Baez [11] first designed a two crossed spherical mirrors method to eliminate the astigmatism of a single mirror used at glancing incidence. This method essentially eliminates the astigmatism, and would eliminate coma by using of 1:1 imaging system. Since then, K-B mirrors were widely used as x-ray focusing device in synchrotron radiation beamline.

For measuring ALS storage ring beam profile, a K-B mirror diagnostic system was designed in soft x-ray region for the first time in 1996 [12,13]. 53µm horizontal by 25µm vertical beam size was obtained in single bunch mode, where the spatial resolution is approximately 10µm.

To achieve better spatial resolution, we set our K-B mirrors working in hard x-ray region to decrease the diffraction. The targeting source size is vertical 20µm and horizontal 78µm. Vertical and horizontal focusing mirrors are located at 7.36m and 7.72m from the source point to make an image at 15.44m from the source. The substrate is Silicon, coated with Rh. Both mirrors are manufactured by SESO, have a 3mrad gracing incidence angle, most of the hard x-ray above 23.5keV is absorbed by the first mirror. The slope error is less than 0.3µrad in tangential direction and less than 5µrad in sagittal direction. With V122µrad × H117µrad acceptance angle limited by entrance slits, the heat load at the first mirror is 1.083W at 300mA beam current, 0.832W is absorbed and would be taken away by water cooling, 0.251W is reflected to the second mirror,. Table 1 lists more detailed parameters of the K-B mirrors.

Fig.2 shows the spectrum of SR after filtered by Al window and limited by aperture slits, the SR has a spectrum from approximately 12 keV to above 60 keV and peak around 24keV. After VFM and HFM, the narrowed spectrum is from 12keV to 23.5keV and peak around 20keV.

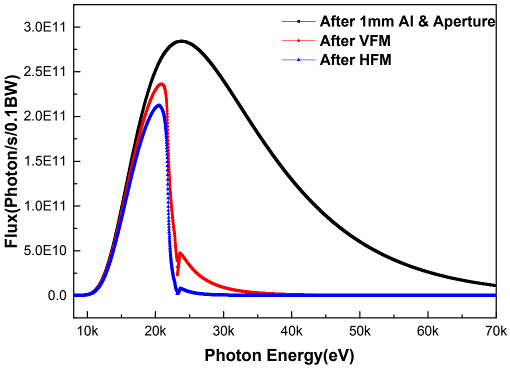

Figure 2: (Color) Spectrum of the synchrotron radiation filtered by Al window, entrance slits, VFM and HFM.

Optical Aberrations

Because of reflective optics design, there is no chromatic aberration in K-B optics. According to the analysis by Jean Susini [14], third-order spherical aberration, first-order coma and third-order coma are the main aberrations contributing to focus broaden. For purely geometrical consideration, the spot size can be express as follows:

$$F = \frac{3}{16} L^2 \frac{\theta_i}{p} \frac{1-M^2}{M} + S_Z M + S_Z (\mathrm{M}+1) \frac{L}{4p}, \tag{1}$$

where F is the FWHM focus size, L is illuminated length on the mirror, $M=q/p$ the magnification, θ_i the gracing angle, S_z the vertical source size; p and q are the source-mirror and mirror-focus distances, respectively. The first term corresponds to the third order spherical aberration and the two other terms of Eq. (1) are related to the first-order coma and third-order coma. As $M \approx 1$ in our case, there is no spherical aberration. Coma becomes the major part which can also be ignored after calculation, because it's no more than 2% broaden to the FWHM focus size. So the optical aberrations are not included in PSF consideration in next section.

Point Spread Function Calculation (PSF)

The performance of the K-B monitor is decided by the rms Point spread function (PSF). The obtained image on the camera is the convolution of the source profile with the PSF of the whole system, including several independent terms: the PSF of the diffraction, the PSF of the x-ray camera, and the image blur caused by mirror slope error. We can't experimentally measure the PSF of our system, so 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:

$$\begin{aligned} \Sigma^2 &= (\sigma \times M)^2 + S^2{}_{diff} + S^2{}_{slope} + S^2{}_{camera} \\ &= (\sigma \times M)^2 + S^2{}_{sys} \end{aligned} \tag{2}$$

where S is the rms size of the image of the photon source at the bending magnet, M is the magnification of K-B mirrors, S_{diff} is the diffraction introduced by the mirror 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.

As there is small difference between VFM and HFM in magnification and aperture, we only discuss VFM for ~20µm vertical beam size measurement here. So $\sigma \approx$ 20µm, M=1.1.

The diffraction limit S_{diff} in FWHM is:

$$S_{diff}^{FWHM} = \frac{0.88\lambda}{2NA} \tag{3}$$

$$NA = \frac{OA}{2q} \tag{4}$$

$$OA = L \times \theta_c \tag{5}$$

NA is numerical aperture specify the "light-gathering power" of the imaging system; λ is the wavelength of x-ray, we use 0.1nm (12keV) here for calculation; OA is the optical aperture for VFM; q=*8.08m* is the distance from VFM to the image; L=*300mm* is the mirror effective length and θ_c =3mrad is the grazing incidence angle of VFM. After dividing FWHM $\mathrm{S_{diff}}$ by 2.35, we obtain the rms S_{diff}=0.34µm.

Surface waviness can be amplified by mirror-to-image distance q when x-ray is reflected away from the surface. We use $S_{slope}=2\times\sigma_{slope}\times q$ to calculate the rms slope error distribution, where σ_{slope}=0.3urad, q=8.08m, then S_{slope}=4.8µm.

The spatial resolution of x-ray camera is S_{camera}=1.5µm has already been test by Crytur. Total effective PSF of K-B system S_{sys} is calculated by using the quadratic sum of each terms to be 5.0µm, where S_{slope} is the dominant item contributing the biggest part to image extension. Then deconvolution can easily be done with quadratic subtraction as given by the expression (2). In order to obtain the image size with the error under 10 percent, distortion S_{sys} should be under the half of vertical beam size, hence for our system beam size ~10µm can be accurate measured directly.

Ray Tracing

Ray tracing of K-B imaging optics was performed with the SHADOW [15] program. SSRF bending magnet source was modeled assuming random distributions in both real and momentum space using Monte Carlo method. The input optical elements were two K-B mirrors arranged sequentially. Slope error was 0.3µrad and was modeled using PreProcessors. Wavefront distortion or the image diffuse error by the Al window, two vacuum vessel windows made by Beryllium(Be) and the scintillation plate were not considered in the ray tracing. Cross section of the synchrotron radiation source and the image plane computed by ray tracing program were shown in figure 3. Comparing the two images, we confirmed that the resulting aberrations are small and the image quality is acceptable.

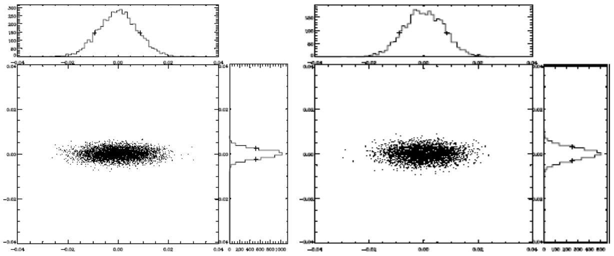

Figure 3: Ray tracing of K-B mirrors system. Left: source, Right: image

CONCLUSION

An x-ray imaging diagnostic monitor based on Kirkpatrick-Baez mirrors has been designed in hard x-ray region. The new monitor will be installed at summer shutdown at SSRF in 2016. We have evaluated the PSF of the K-B monitor, the effective PSF is 5.0µm, in which mirror slope error induced image blur is the major contribution. Beam-based calibration experiment will be done to determine the PSF in the future. Vertical beam size ~20µm and horizontal ~78µm would be achieved by x-ray camera.

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