ELECTRON-BEAM SIZE MEASUREMENT WITH A BEAM PROFILE MONITOR USING FRESNEL ZONE PLATES

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Abstract

We have designed and constructed a non-destructive and real-time beam profile monitor in the KEK-ATF damping ring to measure the extremely small electron-beam size. The monitor has a microscopic structure where two Fresnel zone plates (FZPs) constitute an x-ray imaging optics. In the monitor system, synchrotron radiation from an electron beam is monochromatized by a silicon crystal and the transverse electron-beam image is twenty-times magnified by the two FZP and detected on the x-ray CCD camera. With this monitor, we have succeeded in obtaining a clear electron-beam image and measuring the electron-beam size less than 10 μm. The measured magnification of the imaging optics was in good agreement with the design value.

INTRODUCTION

A beam profile monitor with an x-ray imaging optics for synchrotron radiation (SR) is expected to measure the electron-beam size with a high spatial resolution in a non-destructive manner. Fresnel zone plates (FZPs) begin to be used as x-ray imaging lenses with advance of x-ray mask fabrication technologies. The spatial resolution, which depends on the outermost-zone width of FZPs, is capable of being less than 100 nm. A real-time beam profile monitor based on FZPs was already proposed and designed for the Super-SOR light source [1]. We have recently constructed the same type of beam profile monitor in the KEK-ATF damping ring [2] with a natural emittance of about 1 nm to study the feasibility of the monitor. In this paper, the new beam profile monitor using FZPs and the results of the beam size measurement will be presented.

IMAGING OPTICS

The x-ray imaging optics of the beam profile monitor consists of two FZPs, the condenser zone plate (CZP) and the micro zone plate (MZP), and it has a microscopic structure, as shown in Fig. 1. The magnification M of the imaging optics is given by $M = M_{CZP}\ M_{MZP}$, where M_{CZP} and M_{MZP} are the magnifications of the CZP and MZP.

The spatial resolution of the CZP, δ_{CZP}, is given by

$$\delta_{CZP} = 1.22\,\Delta r_{N,C} = 0.61\,\lambda f_C / r_{N,C}\ . \qquad (1)$$

Here, f_C is the focal length of the CZP for the wavelength λ and $r_{N,C}$ and $\Delta r_{N,C}$ are the radius and the width of the outermost zone of the CZP. The spatial resolution of the MZP, δ_{MZP}, is similarly expressed. The spatial resolution of each FZP corresponds to the distance between the center and first-zero positions of the diffraction pattern. The spatial resolution at the SR source point, δ_0, is given by

$$\delta_0 = \delta_{CZP} / M_{CZP} = 0.61\,\frac{\lambda f_C}{r_{N,C} M_{CZP}}\ . \qquad (2)$$

This is equal to the spatial resolution of the imaging optics if the condition of $\delta_{CZP} > \delta_{MZP} / M_{MZP}$ is satisfied.

The radius of the CZP, $r_{N,C}$, should be $L_{C1}\sigma_{SR}$ or less so that the SR uniformly irradiates the CZP. Here L_{C1} and σ_{SR} are the distance from the source point to the CZP and the SR angular divergence. On the condition of $r_{N,C} = L_{C1}\sigma_{SR}$, the spatial resolution δ_0 [μm] is approximately expressed by the following equation:

$$\delta_0 = \frac{2.62\,\varepsilon_{ph}^{-0.575}\varepsilon_c^{-0.425} E_e}{1 + M_{CZP}}\ , \qquad (3)$$

where E_e [GeV], ε_c [keV] and ε_{ph} [keV] are the electron beam energy, the critical photon energy and the photon energy corresponding to the wavelength λ. The critical photon energy ε_c [keV] and the SR angular divergence σ_{SR} [rad] from a bending magnet (BM) is given by

$$\varepsilon_c = 0.665\,E_e^{\,2} B \qquad (4)$$

$$\sigma_{SR} = 0.289 \times 10^{-3}\ \left(\varepsilon_{ph} / \varepsilon_c\right)^{0.425} \Big/ E_e\ , \qquad (5)$$

where B[T] is the magnetic field at the BM. Here the angular divergence of the electron beam is assumed to be negligibly small as compared with that of the photon.

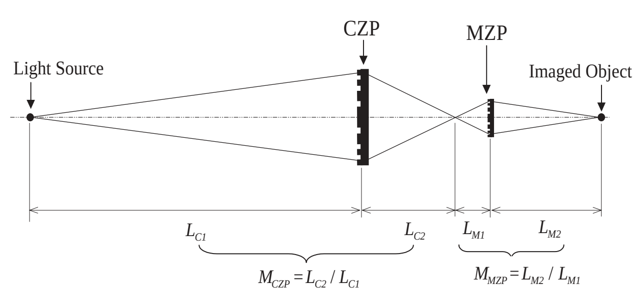

Figure 1: Imaging optics of the beam profile monitor.

MONITOR SYSTEM

Figure 2 shows the layout of the beam profile monitor system, which extracts the SR from the BM in the KEK-

ATF damping ring. The magnetic field of the BM is 0.748 T for E_e = 1.28 GeV and the critical photon energy is 0.816 keV. This system mainly consists of a Si crystal monochromator, two FZPs (CZP and MZP) and an x-ray CCD camera. The specifications of the optical elements are summarized in Table 1.

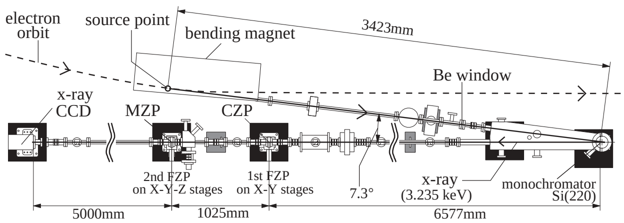

Figure 2: Layout of the beam profile monitor system.

Table 1. Specifications of optical elements

Fresnel zone plate	CZP	MZP
Total number of zones	6444	146
Radius	1.5 (1.26[a]) mm	37.3 μm
Outermost zone width	116 (138[b]) nm	128 nm
Focal length	0.91 m	24.9 mm
Magnification	M_{CZP}=0.1	M_{MZP}=200
Monochromator		
Spectral resolution	5.6×10^{-5}	
Crystal lattice plane	Si(220)	
Lattice spacing	0.192 nm	
Bragg angle θ_B	86.35°	
X-ray CCD camera		
Quantum efficiency	> 90 % @ 3.235keV	
Effective area	12.29 × 12.29 mm	
No. of pixels	512 × 512	
Pixel size	24 μm × 24 μm	

[a] The effective radius of the CZP defined by $L_{C1}\sigma_{SR}$.
[b] The zone width at the effective radius of the CZP.

The FZPs are formed by 0.8-μm-thick Ta absorber on 0.2-μm-thick SiN membrane. The magnifications of the FZPs, M_{CZP} and M_{MZP}, are 1/10 and 200 and hence the 20-times magnified image of the electron-beam can be obtained on the x-ray CCD camera. We selected the x-ray energy of 3.235 keV, considering the spatial resolution of the monitor, the energy dependence of the photon flux and some spatial restrictions of the ring facility. For the selected energy, the spatial resolution of the monitor calculated from Eq. (3) is 1.7 μm. Each FZP is mounted on the holder inserted between two bellow ducts. In order to align the two FZPs, both holders can be moved in the horizontal (x) and vertical (y) directions by motorized linear stages. The MZP holder can also be moved in the longitudinal (z) direction to match the focal plane to the CCD screen.

In order to avoid the effect of the energy aberration, the SR should be monochromatized before it arrives at the CZP. The required energy bandwidth $\Delta E/E$ is given by

$$\Delta E/E \leq 2\sigma_{eb} M_{CZP} / r_{N,C} \ , \qquad (6)$$

where σ_{eb} is the size of the electron beam [3]. For the minimum size of the electron beam in the ATF damping ring (> 5 μm), the spectral resolution of less than 8.0×10^{-4} is needed. In the system, a Si(220) crystal is used to deflect the extracted x-ray beam from the bending magnet with the Bragg angle $\theta_B = 86.35°$. The spectral resolution of this monochromator is 5.6×10^{-5} and it fully satisfies the required condition of (6). The Si crystal can be rotated around the x- and y-axis for adjustment of the horizontal and vertical angles of the x-ray beam.

The x-ray CCD camera (HAMAMATSU C4880-21) is a direct incident type with a back-thinned illuminated CCD, which offers high quantum efficiency, more than 90 % for the x-ray energy of 3.235 keV. The pixel size is 24 μm and less than twenty times the spatial resolution of the imaging optics δ_0. The minimum exposure time is 20 ms and the maximum frame rate is 7 frames/s. The CCD is a full-frame transfer type and an x-ray shutter made of 50-μm-thick beryllium copper is installed before the CCD camera to cut off the x-ray irradiation during the readout.

MEASUREMENT

After adjusting the angles of the Si crystal and the horizontal and vertical positions of the FZPs, an electron-beam image was clearly observed on the CCD. The background mainly consisted of the readout noise and the x-rays transmitted through the FZPs and their count rates were much lower than that of the peak signal. However we subtracted these background components from the CCD data as possible. The position of the electron-beam image is more sensitive to the position change of the MZP by a factor of 200 than those of the transmitted x-rays. By changing the MZP position by few tens microns, which corresponds to only the size of one or two CCD pixels, the electron-beam image was moved out of the CCD frame while the background components were almost unchanged in position and intensity. The CCD data without the electron-beam image was used as the background data. Figure 3 shows an electron-beam image on the x-ray CCD after the background subtraction.

The horizontal and vertical profiles of the beam image were obtained by projecting the 2-dimensional intensity distribution on the horizontal and vertical axes and the horizontal and vertical image sizes by fitting the horizontal and vertical image profiles to gaussian curves. The longitudinal position of the MZP was scanned for searching the minimum image sizes, which suggested that the focal point of the MZP was on the x-ray CCD. The real beam sizes at the source point were obtained by dividing the minimum image sizes by the magnification of the imaging optics, which was measured by the method described later. The horizontal and vertical beam profiles and their fitted curves are shown in Fig. 4, where the axes of abscissas reflect the dimension at the source point. The beam sizes were measured on five different days with different beam currents and tuning conditions of the ring. The measurement results were summarized in Table 2. The measured horizontal and vertical beam sizes were 36 – 44 μm and 9.4 – 9.7 μm in 2002/05/30-06/07 and 37.6 μm and 6.9 – 7.5 μm in 2002/12/06-07.

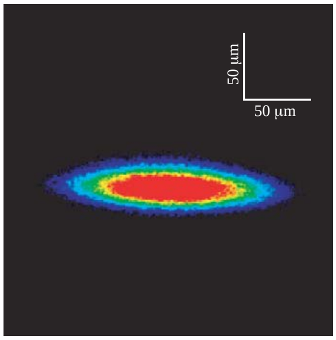

Figure 3: Electron beam image obtained by the beam profile monitor. The length of the horizontal and vertical white bars corresponds to 50 µm at the SR source point.

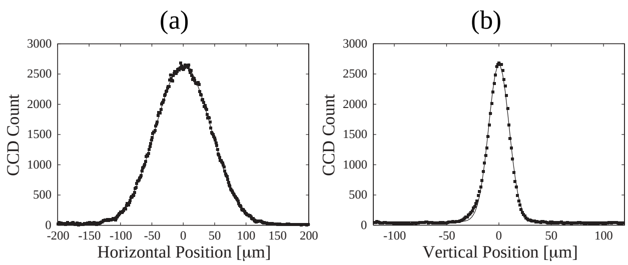

Figure 4: (a) horizontal and (b) vertical beam profiles with their fitted gaussian curves. Data from 2002/06/06.

Table 2: Summary of beam-size measurements

Date[a]	Beam size σ_x[µm], σ_y[µm]	Magnification
2002/05/30	38.1 ± 1.4, 9.52 ± 0.35	M=20.53 ± 0.76
2002/06/06	44.2 ± 1.6, 9.70 ± 0.36	M_{MZP}=204.8 ± 1.5
2002/06/07	36.3 ± 1.3, 9.38 ± 0.35	M_{CZP}=0.1002 ± 0.0038
2002/12/06	37.6 ± 2.0, 6.93 ± 0.37	M=21.08 ± 1.26[b]
2002/12/07	37.6 ± 2.0, 7.45 ± 0.39	

[a] The total beam currents were and 0.27, 2.5 and 0.5 mA in single-bunch mode for 2002/05/30, 2002/06/06 and 2002/06/07 and 3 mA in three-bunch mode for the two dates of 2002/12/06-07.
[b] The magnification of M_{MZP} was not measured for 2002/12/06-07.

The magnification of the imaging optics, $M=M_{CZP}M_{MZP}$, was obtained by measuring the horizontal beam position at the source point, x, and the horizontal position of the beam image on the CCD, X, at the same time. The variation of the beam image position ΔX is related to the variations of the horizontal beam position Δx by

$$\Delta X = M\Delta x = -M\,\frac{\eta_x}{\alpha}\,\frac{\Delta f_{rf}}{f_{rf}}, \tag{7}$$

where η_x, α, f_{rf} and Δf_{rf} are the dispersion function at the SR source point, the momentum compaction factor, the rf frequency and its variation. The beam image position X was measured as function of Δf_{rf} and fitted to a straight line. The magnification was obtained from the slope of the fitted line and the ring parameters f_{rf}, η_x and α. Figure 5 shows the relation between the beam image position X and the horizontal beam position x. As shown in Table 2, the obtained magnification values of the imaging optics were almost equal to the design value of 20.

The magnification of the MZP was also evaluated by utilizing the fact that the ratio of the position change of the beam image to the position change of the MZP is equal to the magnification plus one. The center position of the beam image was measured with changing the MZP position. The obtained data were well fitted by a straight line and the magnification of the MZP was obtained. The magnification of the CZP was determined by the measured values of M and M_{MZP}. The measurement result agrees well with the design values of M_{MZP} and M_{CZP} , as shown in Table 2.

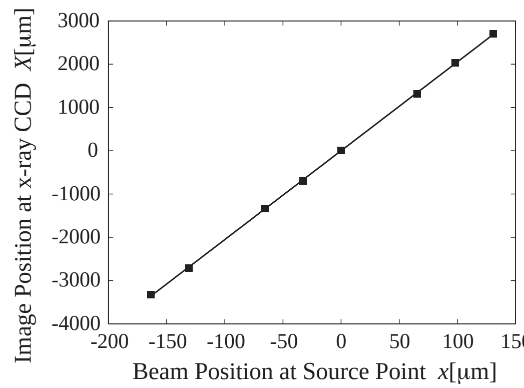

Figure 5: Relation between the horizontal beam position at the SR source point and the horizontal position of the beam image on the x-ray CCD. Data from 2002/05/30 - 06/07.

CONCLUSIONS

The FZP-based beam profile monitor was developed for measuring the extremely small size of the electron beam in the KEK-ATF damping ring. It is a real-time and non-destructive monitor with a high spatial resolution and consists of a silicon crystal monochromator, two FZPs (CZP and MZP) and an x-ray CCD camera. With this monitor, we directly obtained the transverse image of the electron beam and then measured the horizontal and vertical beam sizes. The horizontal beam sizes were about 40 µm and the vertical beam sizes 7 – 10 µm for five different days. The magnification was also measured and was in good agreement with the design value. The good performance and prospects of the monitor were confirmed in the experiments. Further measurements of the beam sizes will be carried out more systematically.

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