BEAM SIZE MEASUREMENT OF THE SPRING-8 STORAGE RING BY TWO-DIMENSIONAL INTERFEROMETER

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Abstract

Two-dimensional interferometer using visible synchrotron radiation was developed in order to measure beam sizes at a source point in a bending magnet of the SPring-8 storage ring. The theoretical background of this method is described in the framework of wave-optics. Assuming designed optics parameters, transverse emittance was evaluated from measured beam size.

1 INTRODUCTION

Electron beam imaging using visible synchrotron radiation (SR) is a conventional method of beam size measurement. In the case of SPring-8 storage ring, the resolution of vertical beam imaging is limited by diffraction effect [1] due to collimation of SR in a narrow vertical divergence angle. Interferometric technique has superior resolution than beam imaging. A visible SR interferometer with a double slit was first applied to KEK-PF and a small vertical beam size was successfully measured [2]. The similar technique was applied to the SPring-8 storage ring in order to measure the vertical beam size [3]. As an improvement of the interferometer, we newly developed a two-dimensional interferometer with a quad slit having four apertures, which has an advantage that horizontal and vertical beam sizes can be simultaneously measured by observing visibility of a two-dimensional interference pattern.

2 TWO-DIMENSIONAL SR INTERFEROMETER

2.1 Principle

When a monochromatic light is diffracted by a quad slit with four apertures located rectangularly, a two-dimensional interference pattern appears on an observation screen. The interference pattern of a spherical wave from a point source can be calculated by Rayleigh-Sommerfeld diffraction formula using a paraxial approximation. If the source is a group of incoherent point sources distributed in Gaussian shape with width σ_x and σ_y (1σ), the interference pattern is expressed as,

$$I(x_s, y_s) = I_0 \left[\frac{\sin\left(\frac{\pi x_s a}{2\lambda L}\right)}{\frac{\pi x_s a}{2\lambda L}}\right]^2 \left[\frac{\sin\left(\frac{\pi y_s b}{2\lambda L}\right)}{\frac{\pi y_s b}{2\lambda L}}\right]^2 \left[1 + V_x \cos\left(\frac{4\pi x_a x_s}{\lambda L}\right)\right]\left[1 + V_y \cos\left(\frac{4\pi y_a y_s}{\lambda L}\right)\right] \quad (1)$$

where L, a, b and λ are distance from the source to quad-slit, horizontal and vertical slit aperture sizes and wavelength of light, respectively. Parameters V_x and V_y are called as visibility. We have approximated that a are Gaussian convolution integral of envelope expressed by a sinc function can be neglected when the envelope width becomes far larger than the light source size by the use of a quad-slit with small aperture sizes. The relationships between the source size, namely electron beam size, and the visibility expressed by,

$$\sigma_x = \frac{\lambda}{2\pi\theta_x}\sqrt{-2\ln\left(V_x\right)}, \quad \sigma_y = \frac{\lambda}{2\pi\theta_y}\sqrt{-2\ln\left(V_y\right)} \quad . \quad (2)$$

2.2 Effect of aspherical features of SR wavefront

The wavefront of SR from an orbiting electron is not spherical in a strict sense. The relative phase relation of SR at each aperture of the quad-slit depends on the electron orbit angle, and an interference fringe shifts with respect to the overall envelope depending on the orbit angle. Therefore, a visibility generally depends not only on electron beam size but also on beam angular divergence. Deviation of SR phase from that of spherical wave on the transverse plane of the quad-slit of the SPring-8 interferometer is shown in Fig.1, which was calculated by Fourier transforming a radiation field derived from Lienard-Wiechart potentials of an electron orbiting in a bending magnet [1]. Wavelength λ is 441.6nm. The aspherical feature of SR is apparent in the horizontal direction, however the deviation of SR phase

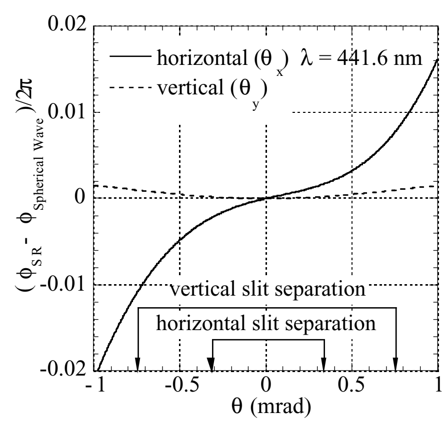

Figure 1:Difference of phase distributions between an ideal spherical wave and realistic radiation field derived from Lienard-Wiechart potentials of an electron orbiting in a bending magnet. Wavelength is 441.6nm.

from that of spherical wave is at most λ/500 at the apertures of the quad-slit, and spherical wavefront is still a good approximation to SR. The horizontal and vertical angular divergences of the electron beam at the source point are about 100μrad and 0.5μrad, respectively. By convolution of beam divergence, the degradation of visibility is evaluated to amount to resolution of 1.4μm and 0.013μm in horizontal and vertical directions, respectively.

2.3 Optimization of interferometer

It is advisable to measure a beam size in condition of visibility range that an accuracy of the measurement is tolerable to various instrumental errors. If we consider a simplified case in which a slit size is zero, visibility V and average intensity I of an interference fringe are expressed by the peak I_{max} and the bottom I_{min} intensity as follows,

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \qquad I = \frac{I_{max} + I_{min}}{2}. \qquad (3)$$

If we assume that fluctuations of I_{max} and I_{min} are $\Delta I_{max} = \Delta I_{min} = \Delta I$, from error propagation using equations 2 and 3, the error of beam size becomes as,

$$\frac{\Delta\sigma}{\sigma} = -\frac{\sqrt{1 + V^2}}{2\sqrt{2}\, V \ln(V)} \frac{\Delta I}{I}. \qquad (4)$$

Fig.2 shows that the error of measured beam size is insensitive to the intensity error ΔI in the range of visibility from 0.1 to 0.6. It is necessary to optimize the wavelength and the slit separation in order to measure in condition of the suitable visibility. Fig.3 shows relationships between the wavelength and the slit angular separation giving visibility 0.6 for specified beam sizes. The vertical slit separation is limited by finite extent of SR. In the case of our interferometer, a narrow aperture of photon beam transport line prevents us from selecting the appropriate vertical slit separation.

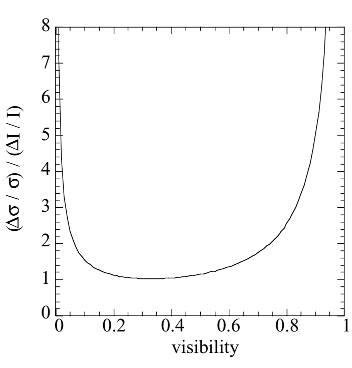

Figure 2: Visibility dependence of beam size error. Curve is $\Delta\sigma/\sigma$ normarized by $\Delta I/I$. It is advisable to measure beam size in condition of visibility range from 0.1~0.6.

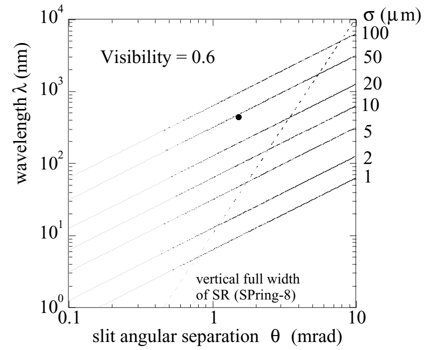

Figure 3:Solid lines show relations between wavelength and slit angular separation giving visibility 0.6 for various beam sizes. Broken line shows full width of vertical divergence of SR from SPring-8 bending magnet. Dot shows combination of θy and λ of interferometer of SPring-8.

3 EXPERIMENT

An experimental set-up of the two-dimensional interferometer of the SPring-8 storage ring is shown in Fig.4. All the instruments are installed in the accelerator tunnel. Visible SR is steered to the optical system of interferometer by two plane mirrors. The 1st mirror is located in vacuum at 18m downstream from the source point. X-ray heat load is protected by water-cooled x-ray absorber in front of the 1st mirror. A quad slit is located at 19.6m downstream from the source point. The size of each square aperture is 3mm*3mm and the horizontal and vertical angular separations are 0.65mrad and 1.51mrad, respectively. The position accuracy of each aperture is about ±0.2mm, which corresponds to the ambiguity of angular separation of about ±0.02mrad. Two-dimensional interference pattern is imaged on a CCD camera with pixel size 7.6μm*7.6μm by two achromatic doublet lenses behind the quad slit. The magnification is adjusted to one by moving the 2nd lens and the CCD camera axially. The CCD camera has electrical shutter and the exposure time is adjustable from 0.06ms to 31.7ms. Typical exposure time is 1.71ms. A polarizer with extinction ratio $5*10^{-4}$ is located in front of the camera in order to select σ-polarization. Center wavelength and bandwidth of a bandpass filter are 441.6nm and 10nm(FWHM), respectively. It is attached to the camera.

The interference pattern observed by the CCD camera is captured into a picture processing system. The captured data is analysed by making horizontal and vertical projections after subtracting the background which is measured by closing a photon shutter located at the photon beam transport line. A typical measured two-dimensional interference pattern is shown in Fig.5. A following model function is fitted to the projected data corrected for linearity of the CCD camera,

$$f(z) = I_0 \left[\frac{\sin\left(a\left[z - z_0\right]\right)}{a\left[z - z_0\right]} \right]^2 \left[1 + V \cos\left(kz + \phi\right) \right] \qquad (5)$$

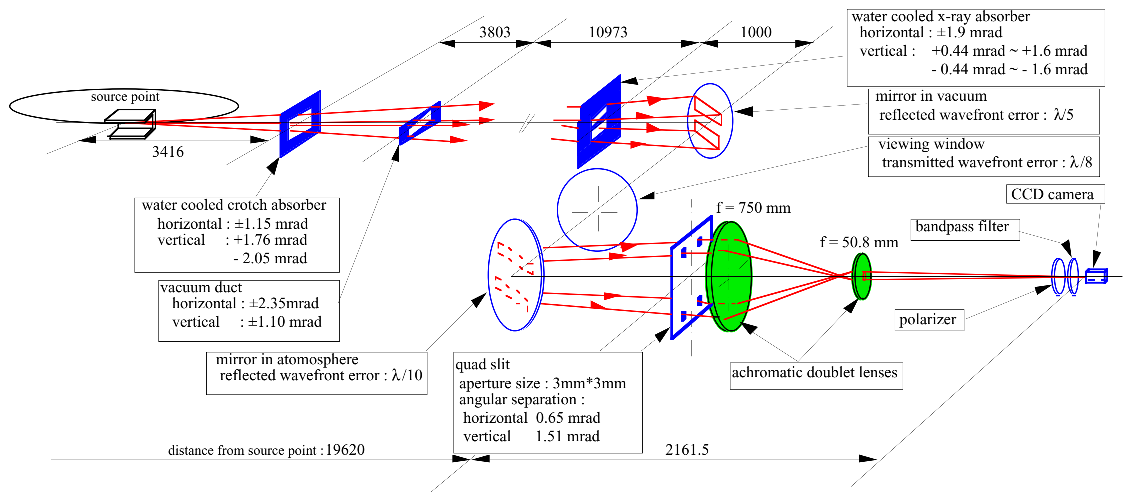

Figure 4 Experimental setup of two-dimensional interferometer of the SPring-8 storage ring

where I_0, a, z_0, V, k and ϕ are free parameters.

It is necessary to deconvolute the instrumental resolutions from the measured values in order to obtain real beam sizes. We evaluated as 7.4µm in the both horizontal and vertical directions by taking into account the effects of following instrumental factors on visibility.

- Imbalance of photon intensity among four apertures of quad slit
- Wavefront distortion by optical components
- Electron beam angular divergence
- Bandwidth of bandpass filter
- Extinction ratio of polarizer
- Pixel size of CCD camera

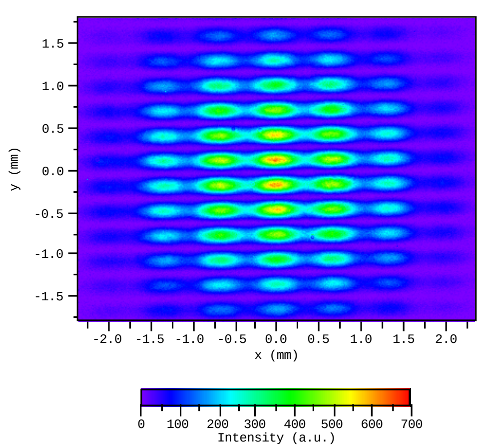

Figure 5: Typical two-dimensional interference pattern observed.

4 RESULTS

We measured beam sizes after improvement of the storage ring with four magnet-free 30m-long straight sections. Beam conditions of the storage ring are as follows, betatron tunes of the operating point are ν_x= 40.142 and ν_y= 18.359 which are used in ordinary user time operations, distribution of the vertical dispersion along the circumference of the ring is corrected as small as 1.2mm (r.m.s.), stored beam current is 100mA, gaps of all insertion devices are completely opened. We obtained the beam sizes as,

horizontal beam size (1σ) : 153.7±5.1 µm

vertical beam size (1σ) : 19.5±1.8 µm.

The beam size errors caused by ambiguity of slit angular separations are ±4.0µm and ±0.3µm in the horizontal and vertical directions, respectively. The accuracy of linearity correction of the CCD camera introduces errors of ±0.4µm (horizontal) and ±1.1µm (vertical). The statistical errors are estimated as ±0.7µm (horizontal) and ±0.4µm (vertical).

If we assume designed values of optics parameters at the source point and beam energy spread, the horizontal and vertical emittance ε_x, ε_y and the coupling ratio κ are evaluated as follows,

$$\varepsilon_x = 7.3 \pm 0.8 \text{ (nm•rad)}$$

$$\varepsilon_y = 14.2 \pm 2.7 \text{ (pm•rad)}$$

$$\kappa = \varepsilon_y / \varepsilon_x = 0.0019 \pm 0.0006.$$

The estimated transverse emittance of the storage ring is consistent with the designed value of 6.6 (nm•rad) within the error. It is necessary to estimate various systematic errors carefully in order to obtain an absolute beam size with higher accuracy. We consider that the resolution of the present interferometer is limited by using visible light in principle. It is planned to use X-ray in order to measure beam size with the resolution of 1µm.

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