CONCEPTUAL DESIGN OF AN INSERTION DEVICE FOR NON-DESTRUCTIVE BEAM DIAGNOSTICS OF A LOW-EMITTANCE SYNCHROTRON LIGHT SOURCE

M. Masaki *

JASRI/SPring-8, 1-1-1 Kouto, Mikazuki, Sayo, Hyogo, 679-5198, Japan

Abstract

An insertion device (ID) is proposed to measure small vertical angular divergence and relative energy spread of electron beam in a low-emittance synchrotron light source. It was numerically studied that the vertical angular divergence in the sub-μrad range and the relative energy spread of the 10^{-3} order could be measured.

INTRODUCTION

Non-destructive diagnostics of electron beam is essentially important for a low-emittance synchrotron light source. In the SPring-8 storage ring, two-dimensional visible light interferometer [1] and x-ray beam imager using a single Fresnel zone plate [2] have been developed for transversal profiling of electron beam. For diagnostics of longitudinal beam characterization, single bunch impurity and bunch length have been measured by a gated photon counting method [3] and a streak camera, respectively. All of these beam diagnoses have utilized bending magnet radiation.

The accelerator diagnostics beamline #2 (BL05SS)[4] is under construction at the SPring-8 storage ring. The beamline has a straight section of the storage ring, where IDs for light sources can be installed. An ID was devised as one of the candidates of light sources for the beam diagnostics at this beamline. The aim of the devised ID is to measure the vertical angular divergence in the sub-μrad range and the relative energy spread of the 10^{-3} order, which cannot be measured using bending magnet radiation. The measurement targets were decided based on the electron beam performance of the SPring-8 storage ring [5].

THEORETICAL BACKGROUND

In the synchrotron light source operated on small emittance-coupling ratio such as the SPring-8 storage ring, vertical divergence of spectral photon flux produced by electron beam in a conventional undulator of several meters long will be dominated by natural angular divergence of the undulator radiation. Therefore, the divergence of spectral photon flux is not useful for the diagnostics of the small vertical divergence of electron beam. For the energy spread measurement, x-ray emission in harmonics higher than the 10th order at least should be observed in order to measure on sufficient sensitivity. The emission in such a high harmonics cannot be generated from an undulator with small deflection parameter.

* masaki@spring8.or.jp

As shown in Fig.1, the proposed ID consists of several short planar undulators as x-ray radiators cascaded through vertical deflective sections to make a half-period cosine-like electron trajectory. Two radiation parts of the upper and lower sides are formed due to up-and-down electron orbit by the deflective sections. X-rays emitted from the two radiation parts generate an interference pattern at observation plane far from the ID.

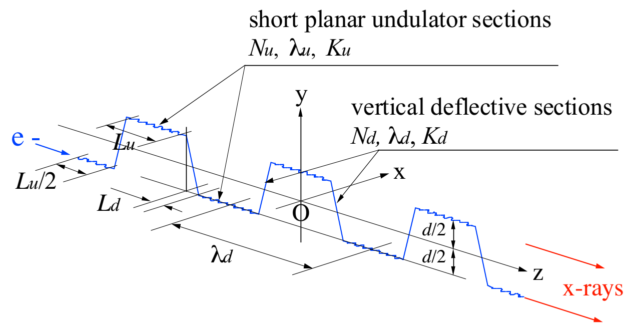

Figure 1: Schematic view of the trajectory (blue line) of an electron moving in the ID.

Emission intensity of σ-polarized component observed at the distant place is expressed as follows,

$$I(x_s, y_s, \lambda; x'_e, y'_e, \gamma) \propto A \cdot B \cdot C, \quad (1)$$

where functions A, B and C are

$$A = \frac{\sin^2\left[\pi N_u\left(1 - \frac{\lambda_1}{\lambda}\right)\right]}{\sin^2\left[\pi\left(1 - \frac{\lambda_1}{\lambda}\right)\right]}, \quad (2)$$

$$B = \frac{\sin^2 N_d \phi}{\sin^2 \phi}, \quad (3)$$

$$C = 1 - \frac{1}{2}\sin^2\phi + \cos\phi \cdot \cos\left[\frac{2\pi d}{\lambda}\left(\frac{y_s}{L} - y'_e\right)\right]. \quad (4)$$

λ is the observing wavelength. The function A denotes radiation intensity of the 1st harmonics from each planar undulator, where the resonant wavelength of the 1st harmonics $\lambda_1 = (\lambda_u/2\gamma^2)(1+K_u^2/2+\gamma^2\theta^2)$. The parameters N_u, λ_u and K_u are period number, period length and deflection parameter of the planar undulators, respectively. γ is

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energy of an electron divided by mc^2, where m is mass of electron and c is speed of light. The angle θ is given by $\{(x_s/L - x'_e)^2 + (y_s/L - y'_e)^2\}^{1/2}$. The coordinate (x_s, y_s) denotes a point on the observation plane and L is the distance from the center of the ID to the observation plane. An electron is injected off-axis to the ID at horizontal and vertical angles x'_e and y'_e, respectively. Effect of transverse position of an electron is negligible, when the observing point is far from the ID enough. The function B denotes emission intensity from a phased array radiator consisting of N_d elements with a phase difference 2ϕ between adjacent elements, which is similar to a diffraction pattern formed by a multi-slit. The element described here is one period of the vertical deflective motion having period length λ_d shown in Fig.1. The parameter ϕ means the phase slip per half period length $\lambda_d/2$, and it is expressed as a following formula,

$$\phi = \frac{\pi}{\lambda} \cdot \frac{1}{2\gamma^2}\left[2L_u\left(1+\frac{K_u^2}{2}\right) + 2L_d\left(1+\frac{K_d^2}{2}\right) + \lambda_d\gamma^2\theta^2\right], \quad (5)$$

where L_u, is total length $N_u\lambda_u$ of each planar undulator section, L_d and K_d are length and deflection parameter of each vertical deflective section, respectively. The function C denotes effect of interference between radiations from adjacent planar undulators. The parameter d is height gap between the upper and the lower electron orbits.

The emission intensity from a single electron given by Eq.1 is shown on y_s-E_p plane in Fig.2, assuming the ID parameters as N_u=6, λ_u=44(mm), K_u=1.5, N_d=3, λ_d=936(mm), L_d=110(mm), K_d=7.7, and the injected angles and energy of an electron as $x'_e = y'_e = 0$, γ=15656 (8GeV), and the distance to the observation plane as L=65(m). E_p denotes observing photon energy. Energy spectrum has many narrow peaks (FWHM ~ 20eV) in wide envelope given by the function A. For on-axis (θ=0) emission, the resonant photon energy of harmonics corresponding to each narrow peak is determined by a condition $\phi = 2n\pi$ (n=integer) which emissions from all the undulator sections contribute in phase to the intensity. The order of the harmonics is very high from 30 to 50.

Taking into account horizontal and vertical divergences σ'_x, σ'_y and energy spread σ_γ of electron beam with an elliptical Gaussian distribution, the observed intensity distribution is given by a following formula,

$$\tilde{I}(x_s, y_s, \lambda) = \frac{1}{2\pi\sigma'_x\sigma'_y\sigma_\gamma}\int_{-\infty}^{\infty} I(x_s, y_s, \lambda; x'_e, y'_e, \gamma) \times \exp\left(-\frac{x'^2_e}{2\sigma'^2_x} - \frac{y'^2_e}{2\sigma'^2_y} - \frac{(\gamma-\gamma_0)^2}{2\sigma_\gamma^2}\right) dx'_e dy'_e d\gamma, \quad (6)$$

where γ_0 is the center energy of electron beam divided by mc^2. Effect of σ'_y will contribute to vertical visibility of an interference pattern observed at the fixed photon energy satisfying the condition $\phi = 2n\pi$. The energy spread σ_γ will have an effect on envelope width of the observed interference pattern in the vertical. The envelope width in the horizontal will be dominated by effect of σ'_x.

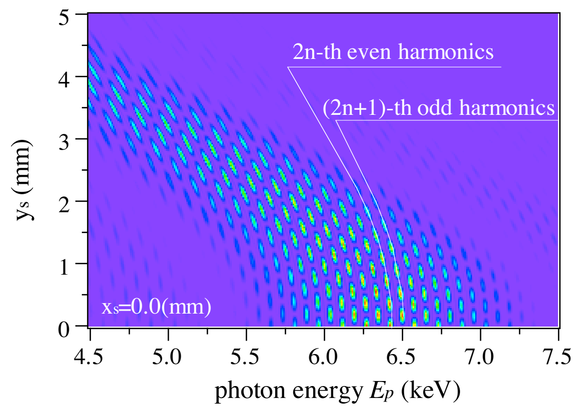

Figure 2: Emission intensity at x_s=0.0(mm) on y_s-E_p plane. Two white curves are connecting emission spots in even (2n) and odd (2n+1) harmonics, respectively.

The even (2n-th) harmonics with energy higher than center of the spectrum envelope given by the function A should be chosen from many harmonics as the observing photon energy. If the harmonics with energy lower than the center is chosen, the vertical visibility will be very degraded by contamination from off-axis emission in the next odd (2n+1)-th harmonics whose interference pattern has a phase shift π from the one of the even harmonics as shown in the function C. The contamination appears on the y_s-axis (x_s=0.0) with the assistance of the horizontal beam divergence. The contamination can be suppressed by choosing the harmonics on the high-energy side described above, where the emission intensity is weaker at the (2n+1)-th order than the 2n-th one.

NUMERICAL STUDIES

Magnetic field of the ID, which realizes the values of the ID parameters described in the previous section, was calculated based on an integral method (e.g. [6]). The magnetic field is created by an ensemble of parallelepiped permanent magnet blocks with remanent field of 1.3T, which magnetization was assumed to be uniform over the whole volume. The calculated magnetic field and electron orbit in the field are shown in Fig.3. The height gap d between the upper and the lower electron orbits is about 35μm. Using the electron orbit, radiation field at the observation point far from the ID was numerically computed from the Lienard-Wiechert potentials.

The calculated energy spectra of the on-axis emission are shown in Fig.4 from both a single electron and an electron beam with σ'_x =16(μrad) and σ_γ/γ_0=0.0011. Their electron beam parameters are based on the designed values of optics parameters, natural emittance and energy spread of the SPring-8 storage ring. In the case convoluted by the beam distribution, the photon energy giving peak value of each harmonics is detuned to the low-energy side, for example, from 7.001 (keV) to 6.994(keV) as shown in Fig.4.

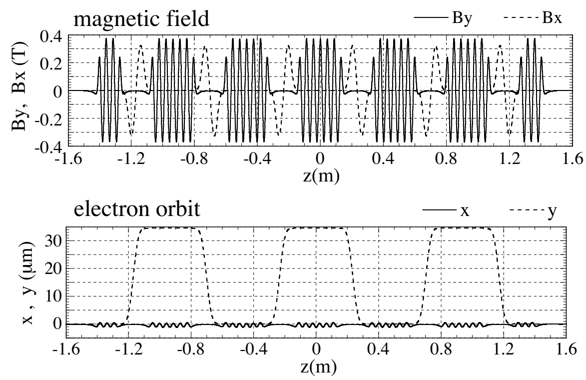

Figure 3: The horizontal and vertical magnetic field of the ID and electron orbit in the field.

The energy detune depends on the horizontal divergence σ'_x. In order to tune the observing photon energy to the peak of the harmonics for a single electron, the horizontal divergence should be evaluated experimentally by horizontal width of the interference pattern etc.

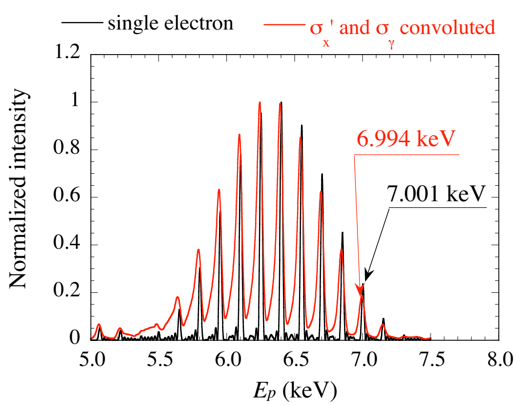

Figure 4: Calculated energy spectra of the on-axis emission. The black and red lines show the spectra from a single electron and an electron beam with the parameters described in the text.

2D-image of an interference pattern generated from a single electron was calculated at the photon energy E_p=7.001(keV) (Fig.5). Since E_p=7.001(keV) is in the high-energy side described in the previous section, the off-axis emissions in the odd harmonics are suppressed.

Vertical interference patterns on the y_s-axis were computed by taking into account the horizontal and vertical divergences σ'_x, σ'_y and the relative energy spread σ_γ/γ_0 (Fig.6), where σ'_y=1.0(μrad) based on the designed optics parameters and the vertical emittance [5] of the SPring-8 storage ring. Other two beam parameters are the same as values described above. The visibility of the interference pattern becomes about 0.5 due to the effect of the vertical divergence σ'_y (see blue line in Fig.6). The relative energy spread σ_γ/γ_0 broadens the envelope width about 15%. Owing to the broadening, the further fringes appear in the both sides of the original interference pattern (see green line in Fig.6). The horizontal divergence σ'_x has a little effect on the visibility and the envelope width (see red line in Fig.6). They should be corrected based on the horizontal divergence evaluated experimentally.

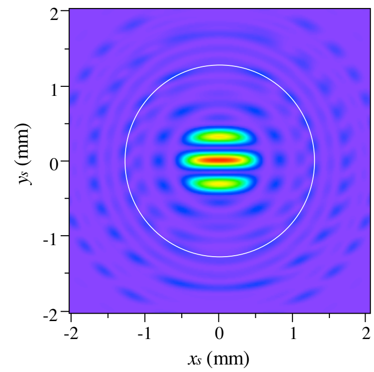

Figure 5: 2D-image of an interference pattern from a single electron calculated at E_p=7.001(keV). The off-axis emission in the next odd harmonics shown with a white circle is successfully suppressed.

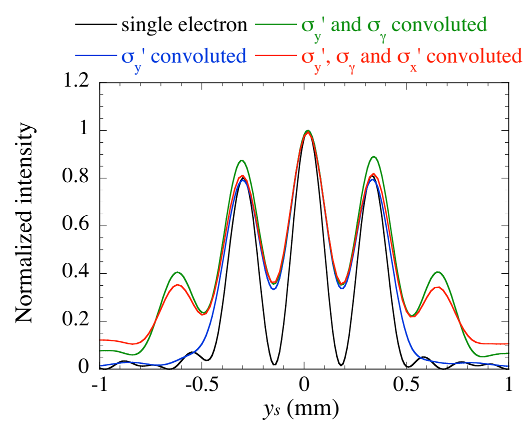

Figure 6: Vertical interference patterns calculated at E_p=7.001(keV) and x_s=0.0(mm). The black and other colored lines show the patterns from a single electron and an electron beam with the parameters described in the text.

CONCLUSION

The exotic ID was proposed for beam diagnostics of a low-emittance synchrotron light source. The results of the numerical studies show that the small vertical divergence and relative energy spread of electron beam could be measured using the ID. It will be necessary to estimate allowable errors of the magnetic field and to make a prototype of the ID for a feasibility study.

REFERENCES

[1] M.Masaki, et al., J. Synchrotron Rad. (2003) **10**, p.295.
[2] S.Takano, et al., Nucl. Instr. and Meth. to be published.
[3] K.Tamura, et al., Proceeding of 1st Annual Meeting of Particle Accelerator Society of Japan 2004, p.581.
[4] SPring-8 Research Frontiers 2003, p.135.
[5] H.Ohkuma, et al., Proceedings of the 2003 PAC, p.881.
[6] Undulators,Wigglers and Their Applications edited by H. Onuki and P. Elleaume (2003), p.161.

0-7803-8859-3/05/$20.00