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Applicability of a double-undulator configuration

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ABSTRACT

The applicability of the double-undulator concept for an electron storage ring of 3-GeV class is evaluated based on the parameters of Taiwan Photon Source. In the soft X-ray case, the fundamental harmonic is mainly used, the interference effect is preserved at some level, which means that the brilliance from a double-undulator is expected to be much greater than that of a single undulator. In the hard X-ray case, harmonics number greater than five are generally used, the interference effect cannot, however, be preserved, which means that a double undulator configuration can be assumed to comprise two independent and uncorrelated sources. The total coherent flux obtained from a double-undulator configuration is found to be much less than twice that of a single undulator. The double-undulator concept is hence inapplicable in the hard X-ray region from the viewpoint of high coherent flux performance.

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1. Introduction

As is well known, an increased number of undulator periods is a straightforward approach to increase the brilliance of radiation from an undulator, which implies an increased length of an undulator. An effective example is an undulator of length 25 m [1] that provides X-rays in SPring8 with average brilliance of order 10^{20} (photons/s/mm^2/mrad^2 in 0.1% b.w.) in the photon energy range 7.4–50 keV. Particularly in the production of X-rays, a short undulator period length and a small magnetic gap favor a generation of highly brilliant radiation, but the operation of a long undulator with a small gap in a straight section is limited according to the vertical betatron function. This function increases quadratically along the longitudinal direction and is subject to an obstacle from a small magnet gap at the end of an undulator. The long undulator must thus be operated with a large gap to avoid beam loss [2], which leads to a loss of the tunability of an undulator. To solve this dilemma, a double mini-β-Y (DMBy) [3] or a triple mini-β-Y [4] lattice has been specially designed to provide two or three sections with small values of the vertical betatron function through an installation of additional quadrupole magnets.

A long undulator can hence be divided into two or three segmented undulators, and accommodated in the minimum vertical betatron function of each section to maintain an acceptable beam lifetime. If constructive interference is to be preserved between two wave packets of undulator radiation, the brilliance of a double collinear undulator configuration might be enhanced relative to a single undulator. A successful example of an intensity gain are demonstrated for soft X-ray radiation, and the intensity relative to that of a single undulator can be more than doubled [5] through an interference effect on superposition of radiation cones. In the case of hard X-ray radiation, such an interference effect might, however, be degraded due to a finite energy spread of the electron beam.

Our aim in this paper is to estimate the applicability of a double collinear undulator configuration. The influence of the quality of an electron beam and of the triplet quadrupole magnet kick on the interference effect of two wave packets of radiation is discussed. Some examples discussed in this paper are based on the parameters of undulators at Taiwan Photon Source (TPS).

2. Spectral degradation due to a finite energy spread

The angular flux density of radiation obtained from a single undulator with N periods is given by

$$P_{\text{single}}(\omega,\theta) = P_0(\omega,\theta)\frac{\sin^2\left(\pi N \frac{\omega}{\omega_{n,\theta}}\right)}{\sin^2\left(\pi \frac{\omega}{\omega_{n,\theta}}\right)}. \tag{1}$$

$$\omega_{n,\theta} = \frac{4\pi c n \gamma^2}{\lambda_u\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)}. \tag{2}$$

In these equations, ω denotes the frequency; θ, observation angle; γ, Lorentz factor; n, harmonic order; c, speed of light; λ_μ,

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undulator period; K, undulator deflection parameter, and $P_0(\omega,\theta)$, the contribution from a single period. In the relativistic case, as radiation is propagating forward, $P_0(\omega,\theta)$ can be approximated as $A\exp(-\gamma^2\theta^2/2)$. In Eq. (1), the squared sine terms represent a Laue interference function having interference fringes as shown in Fig. 1, for which the undulator parameters at TPS, shown in Table 1, are used.

The distribution of natural divergence of undulator radiation is generally approximated with a Gaussian form, $\sigma_{r'} = \sqrt{\lambda/L_u}$ (Gaussian approx. 1) or $\sigma_{r'} = \sqrt{\lambda/2L_u}$ (Gaussian approx. 2), where λ denotes the wavelength of radiation and L_u the undulator length. To estimate the source brilliance, this approximation, appearing somewhat crude in Fig. 1, is essential. As a result, the natural source size, $\sigma_r = \sqrt{\lambda L_u}/4\pi$ or $\sqrt{2\lambda L_u}/4\pi$, is obtainable algebraically from the photon emittance, $\sigma_r\sigma_{r'} = \lambda/4\pi$ only under a Gaussian beam approximation. In addition, various parameters of the electron beam follow a Gaussian distribution because the photon emission occurs as a quantum process. The average brilliance in the case of zero energy spread is obtainable via a convolution method,

$$B_{ro} = \frac{F_n}{4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}}. \tag{3}$$

$$\Sigma_{x,y} = \sqrt{{\sigma_r}^2 + {\sigma_{x,y}}^2},\ \Sigma_{x',y'} = \sqrt{{\sigma_{r'}}^2 + {\sigma_{x',y'}}^2}. \tag{4}$$

where $\sigma_{x/y}$ or $\sigma_{x'/y'}$ denotes the horizontal/vertical electron beam size or the horizontal/vertical electron beam divergence, respectively. In Eq. (3), F_n is the natural photon flux given by

$$F_n = 1.431\times10^{14} I_b N K^2 \xi \left[J_{(n-1)/2}\left(K^2\xi/4\right) - J_{(n+1)/2}\left(K^2\xi/4\right)\right]^2. \tag{5}$$

$$\xi = n/\left(1+K^2/2\right). \tag{6}$$

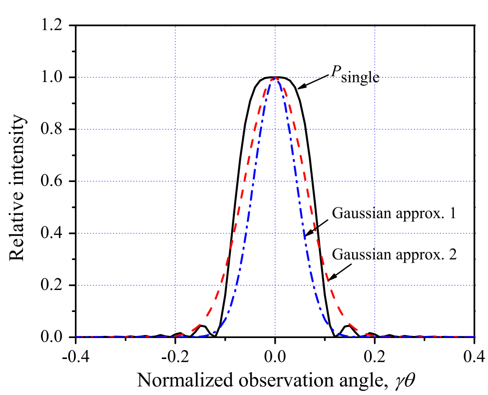

Fig. 1. Example of spatial profile of single-undulator radiation from a single electron.

where I_b denotes the beam current. This approximation for brilliance is valid for the case of only a single undulator.

In the natural spectral profile of undulator radiation, interference fringes can be observed. As is well known that the spectral width of N-period undulator for n-th harmonic is approximated by $1/nN$. It is very convenient if the profile is approximated with a Gaussian form as is the case of the natural divergence. The natural RMS spectral width of the undulator radiation is estimated by APS [6] and expressed as

$$\left[\frac{\sigma_\omega}{\omega}\right]_{n,N} \approx \frac{0.4}{nN}. \tag{7}$$

In a third-generation storage ring, the emittance can be minimized to 10^{-9} m · rad, nevertheless, many ultimate or diffraction-limited storage rings (MAX IV [7], Sirius [8]) are being commissioning or construction to achieve a much smaller emittance. Therefore, the broadening of the spectral width due to finite emittance can be reduced. In contrast, the energy spread still remains around 10^{-3}. So, the spectral broadening due to finite energy spread is unavoidable. When an undulator having infinite number of periods is assumed, the spectral profile seems to have many spectral lines with zero width. When finite energy spread is assumed, however, each spectral line has finite width. From Eq. (2), therefore, the RMS spectral width derived from the energy spread, σ_γ/γ, is given by

$$\left[\frac{\sigma_\omega}{\omega}\right]_{Esp} = \frac{2\sigma_\gamma}{\gamma}. \tag{8}$$

The ultimate brilliance in the single-electron approximation is given from Eq. (3) by

$$B_{ru,n} = \frac{F_n}{4\pi^2 {\sigma_r}^2 {\sigma_{r'}}^2} = \left(\frac{2}{\lambda_n}\right)^2 F_n. \tag{9}$$

It shall be noted that $B_{ru,n}$ is proportional to N. Here, from Eqs. (7) and (8), the critical number of undulator periods and the critical undulator length are defined as

$$N_{c,n} = \frac{1}{5n}\left(\frac{\sigma_\gamma}{\gamma}\right)^{-1}. \tag{10}$$

$$L_{c,n} = N_{c,n}\lambda_u. \tag{11}$$

When the number of undulator periods equals to $N_{c,n}$, spectral width broadening by the energy spread (Eq. 8) becomes equal to that the intrinsic spectral width (Eq. 7). Therefore, $N_{c,n}$ is regarded as a guide value for qualitative determination of the spectral property of undulator radiation. If $N_{c,n}$ is smaller than the number of undulator periods, the natural spectral width becomes larger with degradation of interference effect. To preserve an interference effect, $N_{c,n}$ must be sufficiently larger than the number of undulator periods, N. As a matter of course, the interference effect is much degraded due to the finite emittance of an electron beam.

Table 1
Parameters of a double mini-β Y straight section and undulators.

			Hard X-ray (IU)	Soft X-ray (EPU)
Beam energy, E_{GeV}	3 GeV	**Period length, λ_u**	22 mm	48 mm
Beam current, I_b	500 mA	**Minimum gap, G_{min}**	7 mm	13 mm
Emittance, ε_x	1.6×10^{-9} m · rad	**Undulator length, L_u**	2×3.12 m	2×3.22 m
Emittance coupling, κ_{em}	0.1%[a]	**Number of periods, N**	142	67
Energy spread, σ_γ/γ	8.86×10^{-4}	**Maximum K_y / K_x**	1.48/–	3.72/2.46
Beta-value, β_x/β_y	10.45/1.79 m	**Length of drift space, L_{DS}**[b]	3.99 m	3.38 m
Dispersion, η_x/η_y	0.011/0 m	**Critical number of periods, $N_{c,n}$**	45 (n=5)	226 (n=1)
		Effective number of periods, N_{ep}	340–460	150–210

[a] emittance coupling has been obtained as 0.04% [10].
[b] including a quadrupole set.

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