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20-keV Undulators for a 6-GeV Storage Ring*

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Abstract The main goal of the future 6-GeV electron storage ring is to provide 20-keV fundamental harmonic radiations from insertion devices. Parameter restrictions of REC-vanadium permendur hybrid undulators have been examined. The critical factor is the achieveable minimum gap of the undulator. Variations of the spectral brilliance for different beam parameters are also shown.

Introduction

A 6-GeV electron or positron storage ring, which is under consideration of conceptual design studies, would be a "next generation" source of synchrotron radiation in the x-ray regime. The principal technical goal of the machine is to provide highly brilliant photon beams of energies up to 20 keV at the fundamental harmonic of undulator radiations. The purpose of this paper is to discuss the restrictions of the undulator parameters for the 20-keV photon radiation and to study the expected spectral brilliance of the undulators.

The fundamental photon energy, E_1(keV), radiated from an undulator in the forward direction is given by

$$E_1 = \frac{0.95\ E^2}{\lambda_u(1 + K^2/2)}, \tag{1}$$

where E(GeV) is the electron energy in the storage ring and λ_u(cm) the undulator period. The undulator deflection parameter, K, is defined as

$$K = 0.934\ B_o\lambda_u. \tag{2}$$

Here B_o(T) is the peak magnetic field along the undulator axis.

In the forward direction of a parallel electron beam, the brightness of the photon beam, $dn(\omega)/d\Omega$ (photons/s/(mrad)^2), is given by[1]

$$\frac{dn(\omega)}{d\Omega} = 1.75 \times 10^{17}\ \frac{\Delta\omega}{\omega}\ E^2 I\ N^2\ F_\nu(K)\ \left(\frac{\sin N\pi\nu}{2N\cos\frac{\pi\nu}{2}}\right)^2, \tag{3}$$

where $\nu = \omega/\omega_1$ and ω_1 is the fundamental harmonic, N the number of undulator periods, and I(A) the electron beam current. The function

$$F_\nu(K) = \left(\frac{\nu K}{1 + K^2/2}\right)^2 \left[J_{\frac{\nu-1}{2}}(q) - J_{\frac{\nu+1}{2}}(q)\right]^2, \tag{4}$$

$$\left(q = \frac{\nu K^2/4}{1 + K^2/2}\right)$$

is a monotonously varying function of K for K < 1. In the region of 0.3 < K < 0.6, one can obtain an optimum quasi-monochromatic photon beam of the fundamental harmonic. For K < 0.3, the photon flux decreases rapidly, and for K > 0.6, on the other hand, higher harmonics start to appear.

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Magnetic Field

For undulators of relatively short periods and K < 1, designs of only permanent magnets are feasible in a practical sense. Several permanent magnet undulators have been designed utilizing commercially available rare-earth cobalt (REC) of $SmCo_5$.[2] The undulator magnet consists of two parallel arrays of periodically magnetized REC blocks. It generates a transverse field on the median plane of the undulator.

In a two-dimensional approximation of pure REC, the peak field is given by[3]

$$B_o = 1.8\ B_r\ (1 - e^{-2\pi h/\lambda_u})e^{-\pi g/\lambda_u}, \tag{5}$$

where B_r is the remnant field of the REC, h the height of the magnet blocks, and g the undulator gap. In Fig. 1, the peak fields for h/λ_u = 0.25 and 1.0 are plotted as curves A and B, respectively, with B_r = 0.9 T. By increasing the height of the blocks, the peak field could be increased by about 20%.

In the case of hybrid configuration, Holbach has obtained a semi-empirical relation,[4]

$$B_o = 3.33\ e^{-\frac{g}{\lambda_u}(5.47 - 1.8\ g/\lambda_u)}, \tag{6}$$

which is valid for $0.07 < g/\lambda_u < 0.7$. Equation (6) is an optimized result assuming $SmCo_5$ material with B_r = 0.9 T and a high grade vanadium permendur pole plates are used.

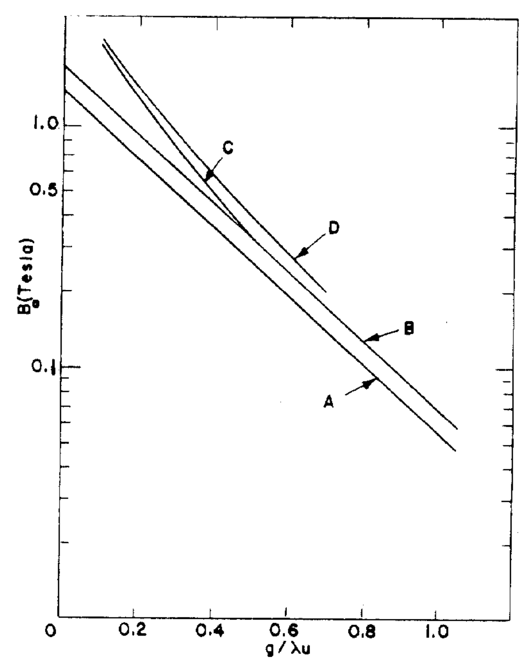

Fig. 1 Peak magnetic field in the midplane of an undulator gap as a function of the ratio of the undulator gap and the period. A (h/λ_u = 1/4): $SmCo_5$, B (h/λ_u = 1): $SmCo_5$, C: $SmCo_5$ Hybrid, D: NdFeB Hybrid.

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A new magnet material of neodymium-iron-boron is under development,[5] and using it approximately 20% higher magnetic field of

$$B_o = 3.44\ e^{-\frac{g}{\lambda_u}\left(5.08 - 1.54\ g/\lambda_u\right)} \qquad (7)$$

could be achieveable.[6] Equations (6) and (7) are plotted in Fig. 1 as curves C and D. For conservative estimates, magnetic field of Eq. (6) is assumed in this study.

Minimum Undulator Gap

As seen from Eqs. (5)--(7), the ratio of the undulator gap and the period is the critical factor determining the peak field and the deflection parameter. The minimum gap is determined depending on the consideration of the beam stability and lifetime, and the efficiency of the beam injection. For β = 16 m, $\varepsilon_x = \varepsilon_y = 5 \times 10^{-8}$ for booster, $5\sigma_y$ = 0.45 cm, for example, one obtains better than 95% of injection efficiency by choosing the minimum aperture of 0.6 cm. If the thickness of the vacuum chamber wall is 0.1 cm and its vertical aperture is adjustable, a minimum gap of 0.9 cm is quite possible.

In Fig. 2, variations of the deflection parameter vs undulator gap are plotted for various values of the period. and their corresponding photon energies at the fundamental harmonics are shown in Fig. 3. For K > 0.4, one could choose undulator period and gap for 20-keV photons 1.55~1.6 cm and 0.8~0.9 cm, respectively. A conservative minimum gap may be about 1.2 cm, at which the photon energy is in the range of 15 ~ 18 keV depending on the choice of the undulator period.

In order to achieve a gap of 0.8 cm or less, design of the vacuum chamber with variable vertical aperture should be considered. Reducing the minimum gap from 1.2 cm to 0.8 cm will widen the tunability range of an undulator considerably. For an undulator of λ_u = 2.5 cm, for example, the fundamental harmonic photon energy will be 7.0 ~ 12.3 keV instead of 10.0 ~ 12.5 keV.

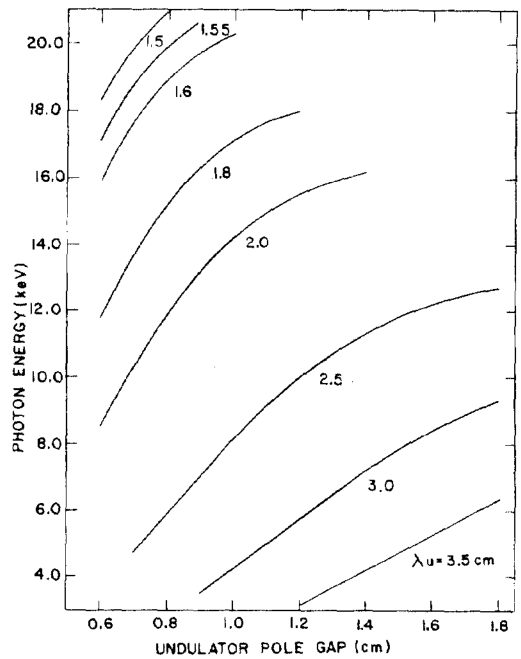

Fig. 3 Variation of the photon energy at the fundamental harmonic as a function of the gap.

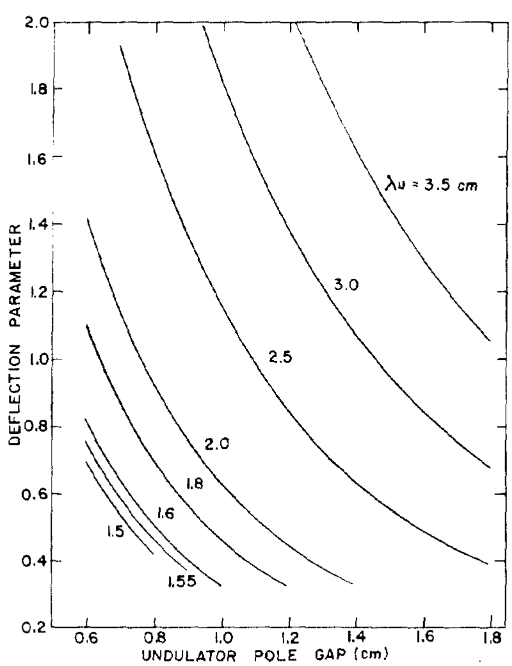

Fig. 2 Undulator deflection parameter vs gap for various undulator periods.

Undulator Spectrum

The peak brightness of Eq. (3), which is for a perfectly parallel electron beam, may be reduced slightly due to the broadening of the line width. Finite size and emittance of the electron beam are the main causes of the broadening for an ideal undulator. Actual brightness of the photon spectrum is an average value within the beam emittance angle.

Figure 4 compares the first three harmonics of the spectral brilliance of a 200-period undulator with

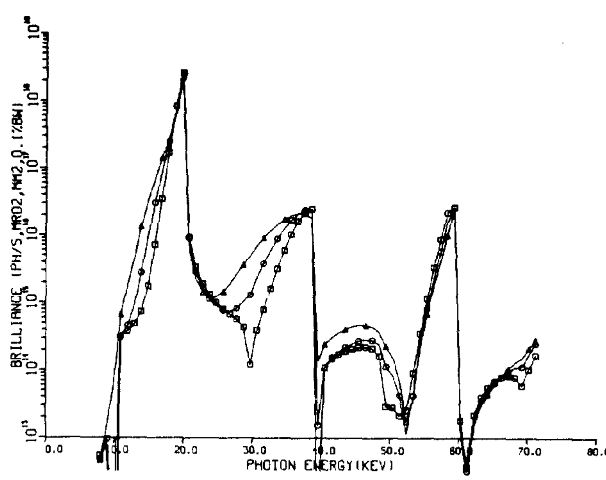

Fig. 4 Spectral brilliance of an undulator with N = 200, I = 0.2 A, λ_u = 1.6 cm, g = 0.9 cm, K = 0.405, and ε_{xo} = 0.65 x 10^{-8} m-rad. Squares: β_x = 34 m, β_y = 10 m, circles: $\beta_x = \beta_y$ = 21 m, triangles: β_x = 13 m, β_y = 46 m.

three different sets of β functions. The spectral brilliance is defined as the brightness divided by the effective source size. Variations of the peak values of the harmonics are within 5% for the cases of $\beta_x >> \beta_y$, $\beta_x = \beta_y$, and $\beta_x << \beta_y$. Corresponding spectral brightness has shown similar results.

Figure 5 is an example of the brilliance from a 2.5 cm-period tunable undulator. Between the gap of 0.9 ~ 1.6 cm, the fundamental photon energy varies from 7.0 keV to 12.3 keV. The deflection parameter of 1.37 at the gap of 0.9 cm contributes the strong peak of the 21-keV third harmonic.

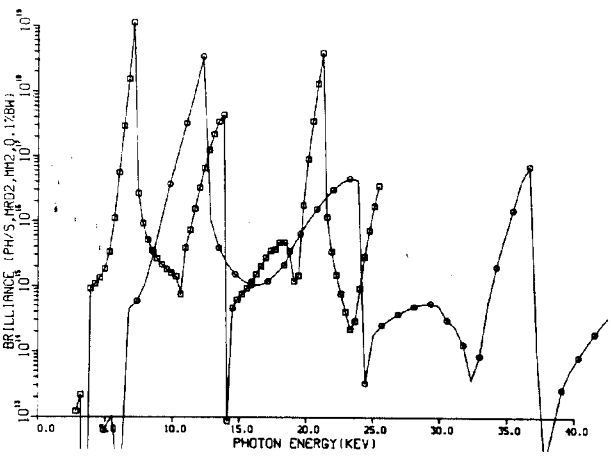

Fig. 5 Spectral brilliance of an undulator with N = 200, I = 0.2 A, $\beta_x = \beta_y$ = 21 m, and ε_{xo} = 0.65 x 10^{-8} m-rad. Squares: K = 1.37, g = 0.9 cm, circles: K = 0.49, g = 1.6 cm.

Another concern is the number of undulator periods. Equation (3) shows that the brightness from a parallel beam is proportional to N^2. The brightness or brilliance from a beam with a finite size and emittance, however, is obtained by dividing the rms solid angle or source area from the total flux.

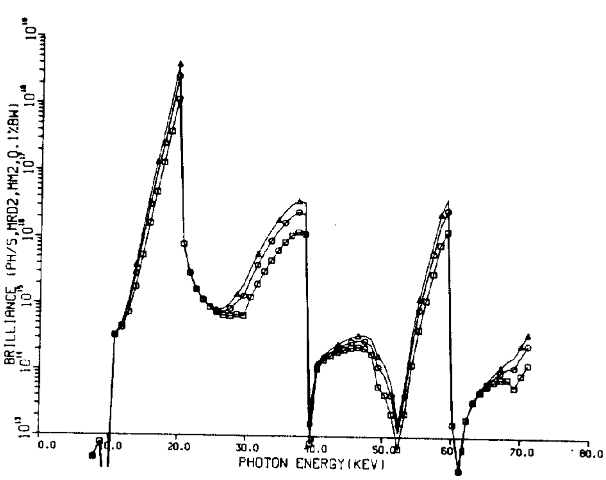

Fig. 6 Spectral brilliance of an undulator with I = 0.2 A, λ_u = 1.6 cm, g = 0.9 cm, K = 0.405, $\beta_x = \beta_y$ = 21 m, and ε_{xo} = 0.65 x 10^{-8} m-rad. Squares: N = 100, circles: N = 200, triangles: N = 300.

Therefore, the brightness or brilliance is proportional to N. Figure 6 shows the dependence of the brilliance on the number of periods. The peak values at the fundamental harmonic are proportional to N within 10%.

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