A Wedged Pole Hybrid Type Undulator as a Synchrotron Radiation Source

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Abstract

An undulator of wedged-pole-hybrid type has been constructed. This undulator was designed as a prototype undulator for the SPring-8 Project. The magnetic period of this device is 33 mm, and the number of period is 61.5. It generates 0.59 T for the maximum magnetic field at the minimum gap width (13.5mm). This device is expected to generate brilliant photon beams of energy ranges around 10 keV by installing into the low emittance high energy storage ring such as the SPring-8.

I. INTRODUCTION

The third generation synchrotron radiation source in the x-ray regime is now under construction in Japan as well as in USA and Europe. The aim of this project, which is called the SPring-8 Project, is to construct a large synchrotron radiation facility to provide highly brilliant x-ray beams for synchrotron radiation users. The 8 GeV SPring-8 storage ring has 44 straight sections including 4 long (30 m) sections. Most of all straight sections, except the injection section and the RF–cavity sections, are expected to be used for insertion devices. The length of normal straight section is longer than 6 m. However, at present, the length of insertion device is planned not to exceed 4 m because both upper and downstream parts of vacuum chambers are occupied by electron beam position monitors, tapered sections, valves and flanges.

We have constructed an undulator of wedged-pole-hybrid type as a prototype but a half length version for the SPring-8 insertion device. In this paper, the magnetic characteristics of this undulator is described, and the Halbach type semi-empirical equation for WPH undulator is proposed. Also included are expected spectral characteristics of the undulator radiation.

II. UNDULATOR

The characteristics of the undulator radiation depends on the peak magnetic field, the magnetic period length of undulator and the electron energy of the storage ring. Since changing the electron energy is not plausible during the dedicated run for synchrotron radiation user's experiments, the magnetic field of insertion device required to be changed widely in order to obtain a wide range of tunability of photon energy. Usually, the magnet gap width is controllable for changing the magnetic field. Smaller gap width gives larger magnetic field providing lower photon energy for the fundamental peak of undulator radiation. The fundamental energy on the beam axis is given by;

$$\varepsilon[\mathrm{keV}] = \frac{0.950E^2[\mathrm{GeV}]^2}{\{\lambda_u[\mathrm{cm}](1+K^2/2)\}},$$

where E is the electron energy, λ_u is the magnetic period and K is the deflection parameter described as follows by using the peak magnetic field B_0;

$$K = 0.934 B_0[\mathrm{T}]\lambda_u[\mathrm{cm}].$$

In order to meet the synchrotron radiation users' needs, the strongest magnetic field at minimum magnet gap is desirable.

The permanent magnet hybrid undulator was proposed by Halbach for obtaining higher on-axis magnetic field compared with pure magnet undulator [1]. Lately, a wedged-pole hybrid undulator was proposed by Quimby [2]. The wedged-pole configuration is expected to generate the strongest on-axis field. It softens a trade-off relation between the physical aperture of electron beam and the tunability of photon energy to some extent. Therefore, we chose a wedge-pole configuration for the prototype undulator. Table 1 shows the undulator parameters. The design parameters of this device is quite similar to the APS prototype undulator except the magnet design [3].

Table 1
Parameters of a wedged-pole hybrid undulator.

Magnet material,	Nd-Fe-B
Undulator period, λ_u(cm)	3.3
Magnet gap range (cm)	1.35-30
Maximum peak field on-axis, B_0(T)	0.59
Deflection parameter range, K	≤1.8
Peak field error, $\Delta B/B$(%)	0.4
Transverse rolloff at ±1 cm (%)	≤0.09
Total steering error (G-cm)	-11
Number of periods	61.5

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This undulator was built by Spectra Technology Inc. Figure 1 shows the whole view of this device with the magnetic measurement system.

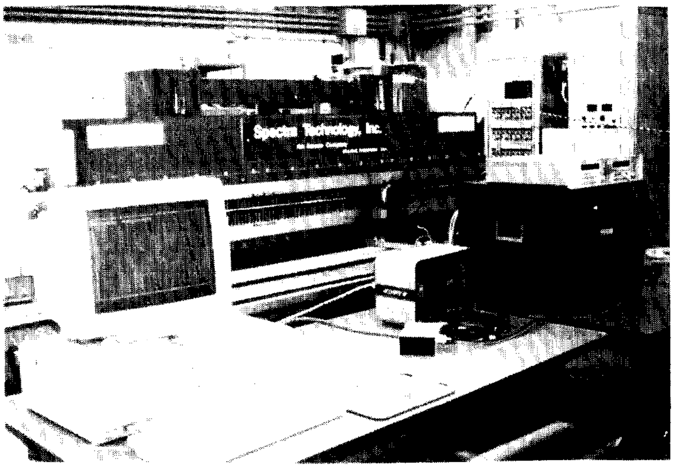

Figure 1. The prototype undulator under the magnetic measurement. The wedged-pole hybrid undulator was built by Spectra Technology Inc.

III. MAGNETIC MEASUREMENTS

The precise magnetic measurements at minimum gap was carried out before shipping to Japan. The measured on-axis peak magnetic field was in good agreement with the design value. The integrated steering errors measured along the beam axis -11 Gauss-cm, which is extremely good compared with the design value (<100 G-cm), was achieved by the shimming technique [4]. The transverse field rolloff at ± 1.0 cm from the centerline was less than 0.09 %. All these measurements were confirmed after the device was installed at JAERI site.

A series of measurements of the magnetic field was carried out on the magnet at various gap settings using a Hall probe magnetic measurement system. Hall probe output voltages were converted to digital data using 16 bit A/D board and acquired in a 32 bit personal computer as a function of Hall probe position. The position measurements were carried out using an optical linear encoder with the resolution of 10 μm. The average peak field value, B_0, was calculated for the central periods excluding 3 poles values of each end of undulator.

Figure 2 shows the measured peak field on-axis as a function of magnet gap. The results can be well represented by the Halbach type equation as follows;

$$B_0 = 2.87\exp\left\{ -\frac{g}{\lambda_u}\left(4.12-0.63\frac{g}{\lambda_u}\right) \right\},$$

where g is the magnet gap width. This equation seems to be valid within the range of gap to period ratio, g/λ_u, less than 0.7.

Originally, above equation was proposed by Halbach for Sm-Co hybrid undulator and modified for Nd-Fe-B hybrid undulator by himself [5, 6]. Only the difference between original Halbach equations and the present equation is the numerical constants. These constants were determined from the measured magnetic peak fields for this particular device. The calculated result using above equation is also shown in

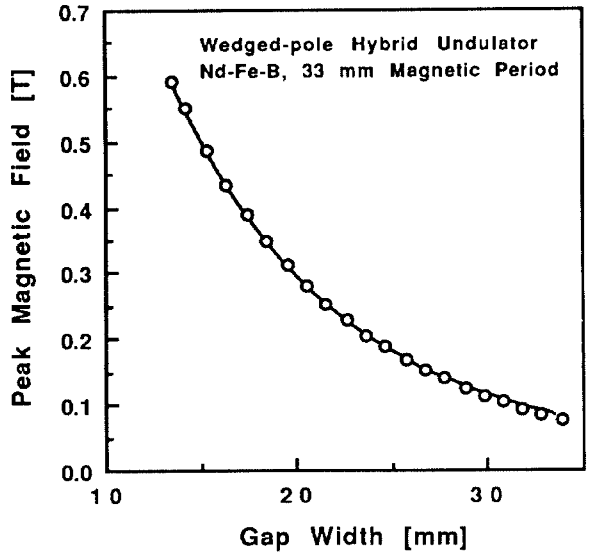

Figure 2. Maximum peak magnetic field on-axis as a function of magnet gap. Measured data (open circle), and calculated values (solid line) are presented.

figure 2 (solid line). Furthermore, it may worth noting that the measured peak field data are in good agreement with the computed values using 2D-finite-element method [7].

IV. EFFECT ON ELECTRON BEAM

The undulator introduces some vertical focusing effect on the electron beam when it is installed in the storage ring, and therefore changes the vertical tune slightly. This tune shift is given simply by the following equation [8];

$$\Delta Q = \frac{1}{4\pi}\beta_y\left(\frac{0.3}{E}\right)^2\frac{B_0^2 L_u}{2},$$

where β_y is the betatron function of undulator straight section in m, E is the electron energy in GeV, B_0 is the peak magnetic field in T and L_u is the length of the undulator in m. For the SPring-8 storage ring, the electron energy is 8 GeV, the β_y of undulator straight section is 10.0 m and the maximum peak field of undulator is 0.59 T. Therefore, the above equation gives a tune shift of 3.9×10^{-4}. Tune shifts of this magnitude can be easily corrected by the quadrupole trim coil windings.

One of the other effects on the electron beam due to the undulator installation might be a reduction of the beam lifetime. Although the vertical physical aperture is limited around 10 mm or so by the undulator vacuum chamber, the physical aperture of this order would not affect the lifetime because the vertical electron electron beam size is small enough in the low-emittance storage ring such as the SPring-8 storage ring. Only the problem that would be happen is the reduction of dynamic aperture due to the destruction of the lattice symmetry. However, solving this problem is not the case in this paper, and the similar problem was already solved elsewhere [9].

V. UNDULATOR SPECTRUM

The expected spectral brightness of the undulator radiation was calculated. Figure 3 shows the on-axis spectral brightness of the prototype undulator installed in the symmetry straight section in the PEP storage ring at the Stanford Linear Accelerator Center. For the calculation, PEP was assumed to be operated 8 GeV, 50 mA low-emittance mode. The machine parameters for the low-emittance operation are listed elsewhere [10].

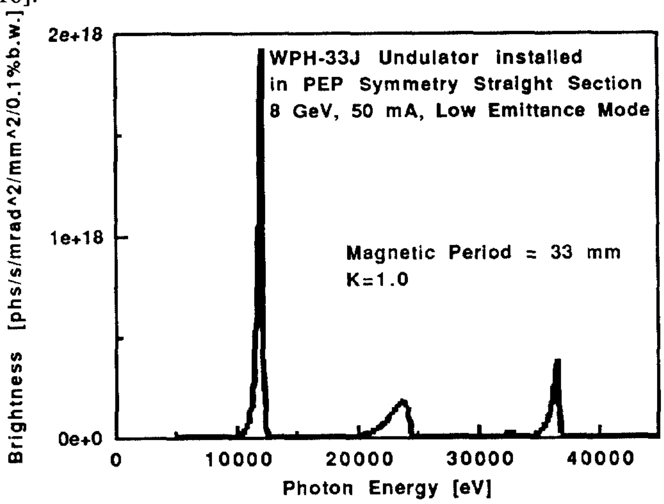

Figure 3. Spectral brightness of wedged-pole hybrid undulator installed in PEP, 8 GeV, low-emittance mode operation.

Figure 4 also shows the on-axis spectral brightness of the undulator installed in SPring-8. An undulator of 3.3 cm magnetic period at 8 GeV operation energy of SPring-8 provides first harmonic radiation within the energy between 7 keV and 16 keV while changing the deflection parameter K from 1.8 to 0.5. The expected brightnesses of the first-harmonic radiations are of the order of 10^{18} photons/s/mm^2 /mrad^2/0.1%b.w. Vertical and horizontal emittance coupling in SPring-8 is assumed to be 10 % for the calculation.

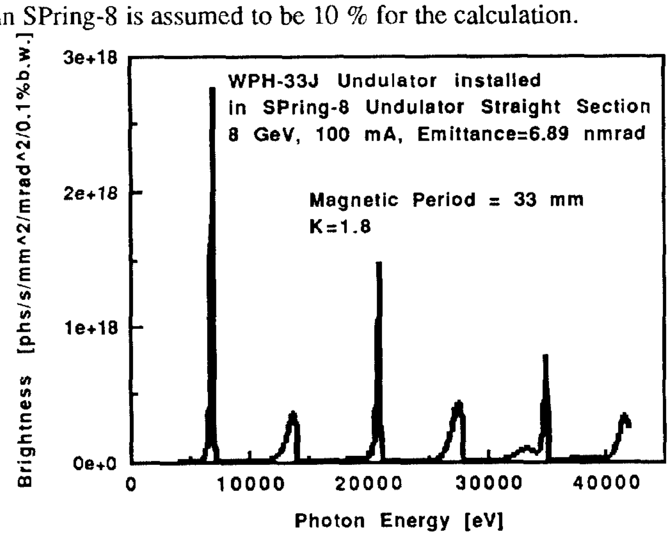

Figure 4. Spectral brightness of wedged-pole hybrid undulator installed in SPring-8. K=1.8 correspond to the minimum gap.

As is shown in figure 3, PEP has an excellent capability if it is operated in low-emittance mode and the undulator is installed at a symmetry straight section. The calculated brightness shows that PEP is comparable with the other so-called "the third generation" synchrotron radiation sources. Looking forward to the future, ESRF will be commissioned in three years, APS in five years and SPring-8 in seven years. In all these rings, it seems that the wedged-pole hybrid permanent magnet undulator would be one of the standard insertion device for obtaining a wide tunability of photon energy.

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