SPECTRAL CHARACTER OF OPTIMIZED UNDULATOR INSERTION DEVICES FOR THE SYNCHROTRON X-RAY SOURCE AT ARGONNE

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Introduction

Two general types of undulator x-ray sources are planned for the Advanced Photon Source (APS) to be built at Argonne. One is to provide first harmonic radiation tunable over the interval of 7 to 14 keV during the initial phase of operation of the storage ring. This tunability range will increase for the same device to approximately 4.7 to 14 keV during the mature phase of operation. The larger tunability interval corresponds to a smaller vertical stay free clearance expected for the final operating conditions of the ring. This allows for a smaller undulator magnetic gap and hence lower energy first harmonic radiation [1]. By using the higher harmonics of this device, considerable intensity will be available at 20 keV and above.

A second device with a smaller period is planned for those cases where the intensity of the third harmonic radiation from the above device is not sufficient. In this case, the undulator will provide 20 keV radiation in the first harmonic.

The magnetic design of both devices will be a hybrid type [2] which uses the Nd-Fe-B alloy as the permanent magnet material and vanadium permendur as the pole-tip. As part of the optimization scheme, the magnetic field calculations have been carried out using a version of the two dimensional field code PANDIRA [3]. In this approximation, the width of the undulator is assumed to be infinite. Three dimensional effects associated to finite pole widths have been estimated using experimental results of single pole measurements for a 7 cm period device [4].

In additional, numerical calculations of the spectral characteristics have been done using the magnetic design parameters and taking into account the emittance expected for the APS. On-axis brilliance results as well as expected spectral power densities have been determined.

Analysis

The required tunability range and maximum photon energy coupled with the ring energy, along gap and smallest acceptable K-value, determine the period of an undulator [1]. For the case of the APS storage ring operating at 7 GeV, the minimum gap is expected to be approximately 10 mm. Under these conditions, a 14 keV device with period close to 3.3 cm has an acceptable tunability range for the case of Nd-Fe-B alloy permanent magnet material and vanadium permendur pole tips. The peak on axis magnetic field for this type of device is given by [2]:

$$B(T) = 0.95 \times 3.44 \exp(-R(5.08-1.54R)$$

where the factor 0.95 represents a filling factor due to packing losses of permanent magnet material, and R is the rates of the magnet gap to the undulator period.

Given the peak field, the deflection parameter or K-value is determined from

$$K = 0.934\ B(T)\ \lambda(\mathrm{cm}).$$

As is known, the photon intensity from an undulator is governed by the value of K. Small K-values correspond to small intensities. At the closed gap position for the 14 keV undulator, the K-value at the minimum gap is near 2.5. Under these conditions, as will be shown below, the third harmonic will contain a significant amount of intensity. In this case, the actual tunable range of the device is extended well beyond 20 keV by using the third harmonic.

The undulator which will provide 20 keV in the first harmonic has a more limited tunability range and as mentioned, is intended for those cases where the flux from the 14 keV device is not adequate at these energies.

In the actual design of the undulators, the pole overhang, width, thickness and height must be determined as well as the equivalent permanent magnet dimensions. The field quality along the undulator axes (z) as well as in the horizontal direction (x) depend on the geometrical arrangement of the poles and permanent magnetets and their dimensions. The peak value of the field depends in much the same way on these parameters.

In a hybrid configuration, the magnetic field strength and distribution depend on the geometry of pole-tips. The field quality is much less dependent on the magnetic and geometric quality of permanent magnet material. In the optimization procedure, the various geometrical parameters of the structure were varied and the two-dimensional flux lines were computed iteratively in the yz plane. From this calculation, both the peak field and field quality in the z direction can be determined. In the optimization, an attempt was made to obtain the highest peak field consistent with the best sine-like variation of the field along the particle beam trajectory.

As mentioned, this procedure assumes an infinite width for the device. As has been shown experimetally [4], a finite pole width affects both the field quality (roll-off) in the horizontal direction and the peak field intensity. For the latter, a two dimensional code tends to overestimate the peak magnitude on axes. Through a direct scaling with the experimental results, the minimum widths given in Table 1 were obtained. Other relevant parameters of the 3.3 cm period device are also shown in the Table.

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Table 1

Parameters for the 14 keV Undulator

Period (cm)	3.3
Number of Periods	151
Length (m)	4.95
Minimum Gap (cm)	1.0
Pole Pieces:	
Width (mm)	48
Height (mm)	35
Thickness (mm)	6.2
Overhang (mm)	~1
Permanent Magnet:	
Width (mm)	64
Height (mm)	42
Thickness (mm)	10.3

Fig. 1 shows the optimized two-dimensional magnetic flux lines of a 1/4 period of the 3.3 cm-undulator at a minimum gap for a 1.4 cm. The shapes of the vanadium permendur pole-tip and the Nd-Fe-B permanent magnet shown in the insert in the figure. This geometry produces sinusoidal field variation along the undulator with less than 2% of higher moments present. It also avoids flux saturation at the corners of the pole tip as well as demagnetization of the permanent magnet. For gap values ranging between 1.4 and 2.2 cm, the field increase at 1 mm above or below the midplane is 2%.

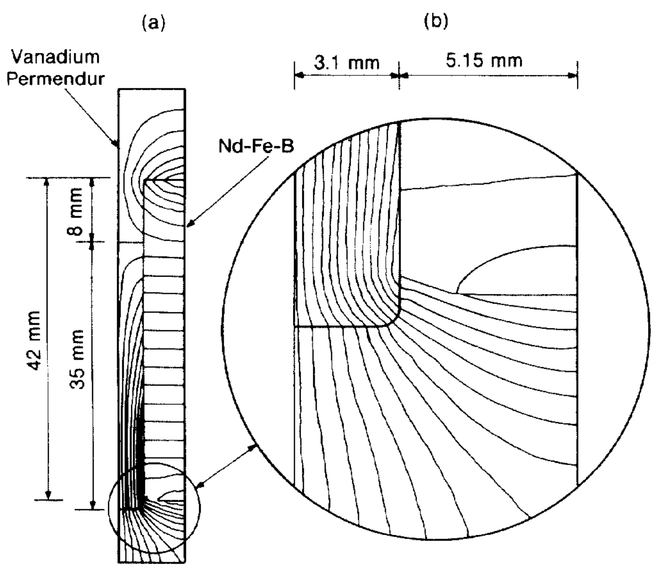

Fig. 1 Magnetic fields lines for a quarter period of a 3.3 cm device. The inset shows details of pole and permanent magnet shaping to reduce saturation and demagnatization effects.

The maximum widths of the pole-tips and the permanent magnet blocks in Table 1 are wide enough to consider the undulator field configuration as a two-dimensional model to a good approximation. If an additional tolerance in the horizontal direction is desired, the pole width and magnet width could be increased. The widths shown are consistent with a field roll-off of less than 1% over a distance of ±1 cm in the horizontal direction.

An estimate of the dimensional tolerance was obtained using the same procedure. Reducing the pole overhang, for example, from 1.0 mm to 0.5 mm increases the peak field by 1.4%. Increasing the thickness of the permanent magnet by 2 mm and simultaneously reducing the thickness of the pole by 2 mm also increases the peak field by 2.5%. From the above exercise, the following required dimensional tolerances can be estimate:

- Thickness tolerance ±0.05 mm (±2 mil)
- Height tolerance ±0.25 mm (±10 mil)
- Width tolerance ±0.25 mm (±10 mil)

An equivalent analysis was performed for the 20 keV device. The period in this case is 2.2 cm with 227 periods. The pole width is 4 mm and the permanent magnet thickness is 7 mm. The K-values are never larger than 1 for this undulator. This implies that the undulator will have a limited tunability range involving the first harmonic.

The spectral characteristic such as on-axis brilliance etc. usually calculated for a single particle are unrealistic since the particle beam has a non-zero phase space volume. In order to estimate these effects for the above undulators, numerical simulation were done which take the non-zero source size and divergence properties into account. For the APS ring, the typical source size and divergence in the x and y planes are given below. The values of $\beta_x = 20$ m and $\beta_y = 10$ m were used along with expected emittance of the APS storage ring.

- $\sigma_x = 364\ \mu m$ $\sigma_y = 82\ \mu m$
- $\sigma'_x = 19\ \mu rad$ $\sigma'_y = 9\ \mu rad$

The simulation is one which involves a numerical integration over the path of the particles through the undulators. The magnetic field was assumed to have a sinusoidal variation along the length of the device with no field errors present. An example of the results of a calculation of on-axis brilliance for a range of gap settings are shown in Fig. 2 for the first device. The stored energy of the particle beam was assumed to be 7 GeV with 100 mA current and source

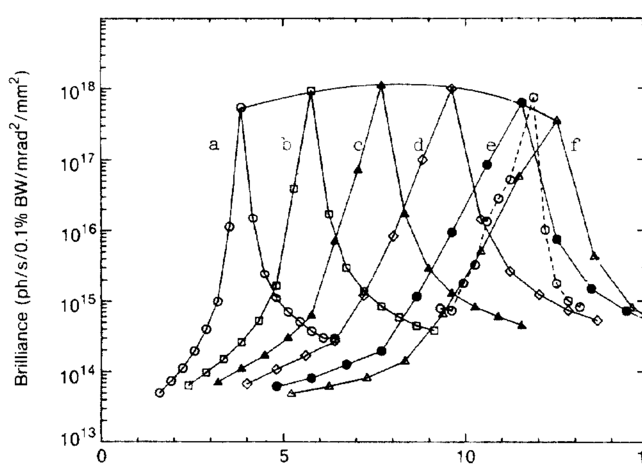

Fig. 2 The spectral on-axis brilliance for the 3.3 cm device with 148 periods. The solid lines are the first harmonic for gaps of a) 11.2, b) 13.9, c) 16.5, d) 19.7, e) 24.7, and f) 30.1 mm. The dashed curve is the third harmonic for gap of a).

sizes given earlier. The first harmonic radiation at a gap of approximately 11 mm is near 4.7 keV. As can be seen, the third harmonic has appreciable intensity at the smallest gap. Fig. 3 shows the simulations for two gap settings in which both the second and third harmonics are present. As can be seen, the second harmonic appears on-axis with appreciable intensity because of the finite source size.

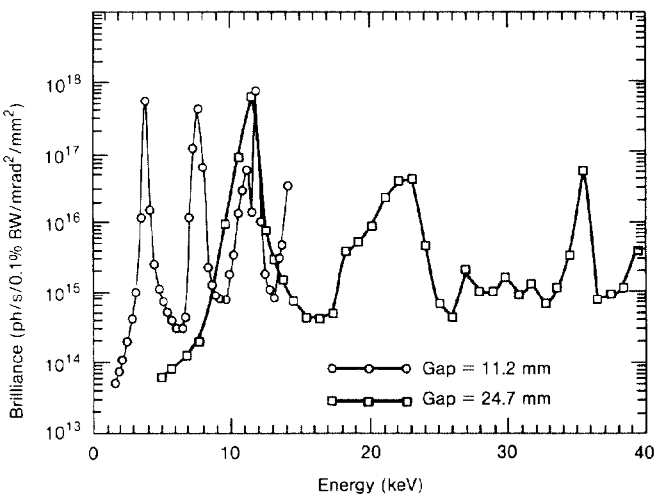

Fig. 3 The spectral on axis brilliance for the 3.3 cm device at the gaps indicated.

Some of the relevant spectral parameters are summarized in Table 2 and 3. As is evident, both devices appear to have large on-axis brilliance over the whole range of tunability. Only for the case of the 3.3 cm device is the brilliance appreciably smaller above 13.5 keV. However, a slight decrease in the period by approximately 0.1 cm is sufficient to raise the tunability interval from 3.5 to 4.7 keV at the lower end and approximately 13.6 to above 14 keV at the higher end.

Table 2

Undulator Spectral Properties
3.3 cm period, 151 periods

Gap (cm)	1.0	3.25
K	2.46	0.296
B(T)	0.81	0.098
El(keV)	3.5	13.5
Brilliance*	7.08	0.87
Total Power(W)	10000	150
Power Density (kW/mrad^2)	298	9.5

Table 3

Undulator Spectral Parameters
2.2 cm period, 227 periods

Gap (cm)	1.0	1.7
K	0.92	0.34
B(T)	0.450	0.165
El(keV)	14.9	20.
Brilliance*	7.99	1.7
Total Power (W)	3100	420
Power Density (kW/mrad^2)	250	64

*Brilliance x10^{18} in units of (ph/s/0.1%BN/mrad^2/mm^2)

A second property of both devices is the large peak on-axis power density, at the closed gap position. The photon heat load at these gaps is an area which will require innovative heat transfer solutions.

Both devices will provide ample flux over a relatively large range of x-rays energies and will allow for a host of new and interesting experiments.

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References

[1] P. J. Viccaro and G. K. Shenoy, "Undulator Tunability and Synchrotron Ring Energy", these proceedings.

[2] K. Halbach, "Application of Permanent Magneto in Accelerators and Electron Storage Ring", J. Appl. Phys. 57, 3605 (1985) and references therein.

[3] PANDIRA is an improved version of Poisson developed by K. Halbach. See reference [4].

[4] K. Halbach, E. Hoyer, S. Marks, D. Plate, and D. Shuman, "CSEM-Steel Hybrid Wiggler/Undulator Magnetic Field Studies", IEEE Trans. on Nucl. Science, NS-32, 3240 (1985).