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SCIENTIFIC OPPORTUNITIES AT THE PROPOSED 6-7 GeV ADVANCED PHOTON SOURCE*

G. K. Shenoy and P. J. Viccaro
Argonne National Laboratory
Argonne, IL 60439

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1 Introduction

Historically, synchrotron radiation (SR) has been obtained primarily from bending-magnet (BM) sources from storage rings dedicated to high energy physics (1). These continuous sources of electromagnetic radiation contributed in a major way in the use of synchrotron radiation in understanding the structure and dynamics of biological, chemical and material systems (2). During the past few years, newer dedicated sources of SR have been built delivering primarily BM radiation. In addition, sophisticated periodic magnetic structures, called insertion devices (IDs) (3), have been tested on such storage rings. These sources are very versatile probes in scientific and technological research and are far superior in many cases to BM sources.

Two different types of IDs--undulators and wigglers--have been developed to satisfy the many present and future requirements of various investigations. These requirements include the need for radiation with specific polarization characteristics, tunability of the energy of the radiation, ultrahigh spectral brilliance covering an x-ray energy range from soft to hard, and a matching of the radiation characteristics with those of the x-ray optical elements for maximum utilization of the potential of such sources. All these will be achieved by the proposed 6-7 GeV Advanced Photon Source (APS) at Argonne (4) by a proper match between the characteristics of the storage ring and the ID characteristics (5). The low emittance of this storage ring will

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provide radiation sources which are only tens of micron in size and with extremely low photon beam divergence. In this article, we briefly summarize the characteristics of the radiation from the Advanced Photon Source at Argonne and its possible applications.

2. Insertion Device Sources

Electrons or positrons traveling along the length of either a wiggler or undulator ID experience transverse motion due to periodic magnetic fields that alternate in their polarity (3). The distinction between wigglers and undulators is determined by the value of the so-called deflection parameter K which is related to the maximum deflection angle of the particle beam velocity. If the motion of the particle in a transverse ID is sinusoidal, then K is given by

$$K = 0.934\ B_o\ \lambda_o, \tag{1}$$

where B_o is the peak magnetic field in tesla and λ_o is the spatial period of the magnetic structure in centimeters.

When $K > 10$, the device is called a wiggler which provide nearly continuous distribtion of energy spectrum similar to BM radiation sources. The number of poles (or magnetic periods) in such a "multipole wiggler" determines the degree to which the photon intensity (or total flux) is enhanced. The horizontal spacial distribution of intensity is narrower than that from a BM. One can also shift the critical energy of photon spectrum from such a device by changing the value of B_o. For example, the photon critical energy, E_c, for a 6 GeV synchrotron ring is given by

$$E_c\ (\text{keV}) = 23.95\ B_o. \tag{2}$$

Different types of wigglers include those consisting of a single magnetic period with a large magnetic field B_o usually referred to as an "energyshifter". On the other hand, there are situations where higher photon harmonics and detrimental to the experiment and one would prefer to have a high-flux wiggler with a low value of E_c. This "low-E_c" wiggler utilizes poles with low B_o values.

Undulators are IDs with $K < 1$ in which the radiation from the poles shows constructive interference effects and the radiated energy is compressed into narrow peaks called harmonics of the device. This quasi-monochromatic property of undulators should be contrasted with the radiation from wigglers or BMs, in which a large percentage of unwanted radiation is presented in their continuous spectral distributions. The unwanted radiation can form a large heat load on the first optical element and hence complicate its design. This situation is alleviated by the use of undulator radiation in which large fluxes are provided in select narrow energy bands.

The IDs are designed so that the total magnetic field integral over their length is zero, and hence their influence on the particle closed orbit trajectory is much less severe than that from BMs. This provides an unprecedented flexibility to incorporate IDs with different radiation characteristics without a detailed reevaluation of the storage ring performance.

3. Source Size and Brilliance

For a low emittance lattice such as the APS, at Argonne, the spectral "brilliance" which characterize the radiated photon beam is of the utmost importance. This quantity depends on both the source size and divergence. Specifically, it is the spectral intensity emitted per unit source phase space volume and has the units of photons/sec/0.1%BW/mrad^2/mm^2.

The phase space volume is a function of the emittance and the magnetic lattice betratron function, β. The expected emittances in the horizontal (x) a and verticle (y) direction are given by (4,5)

$$\varepsilon_x = 7.2\text{x}10^{-9} \text{ m}\cdot\text{rad};\ \varepsilon_y = 7.3\text{x}10^{-10} \text{ m}\cdot\text{rad} \qquad (3)$$

In a straight section containing an undulator, for example, the effective size and the divergence of the source, Σ_i and Σ_i' (i=x,y), are given by

$$\Sigma_i = (\sigma_R^2 + \sigma_i^2)^{1/2};\ \Sigma_i' = (\sigma_R'^2 + \sigma_i'^2)^{1/2}. \qquad (4)$$

Here $\sigma_i = \sqrt{\varepsilon_i \beta_i}$ and $\sigma_i' = \sqrt{\varepsilon_i / \beta_i}$ (i=x,y) are the particle beam size and divergence, respectively. The diffraction-limited source size and divergence are given by

$$\sigma_R = \frac{1}{4\pi}\sqrt{\lambda L}\ ;\ \sigma_R' = \frac{\lambda}{L}\ . \qquad (5)$$

The average brilliance is obtained by dividing the flux of photons by $4\pi^2\Sigma_x\Sigma_y\Sigma'_x\Sigma'_y$.

It is clear that the effective phase-space volume is dependent on the betatron functions for a device of fixed length. This dependence is rather insensitive at short (<10Å) photon wavelengths of photons and for betatron functions larger than the device length. In situations where one desires low photon-beam divergence, however, one should maximize β_x and/or β_y as much as the lattice operation will permit. For example, undulators should be low-divergence devices whereas the wigglers could be optimized for small effective source size. On the basis of these general guidelines, the values of β_x and β_y in various parts of the Advanced Photon Source lattice can be selected and a typical set is presented in Table 1 along with the positron beam size, and beam divergence in various parts of the lattice. It is important to note that in the case of APS the positron beam divergence and its size govern the spectral characteristics of the source.

4. Spectral Character and Applications of Wiggler and Undulator Sources

The photon energy (in keV) of the nth harmonic of an undulator at an observation angle θ (in radians) relative to the undulator axis is given by (3)

$$E_n = \frac{0.949\ E_R^2 n}{\lambda_o(1 + K^2/2 + \gamma^2\theta^2)} , \qquad (6)$$

E_R is the ring energy in GeV, and λ_o is the undulator period in cm. On axis ($\theta = 0$), only the odd harmonics are present. However, one will observe the even harmonics of radiation even along the axis since the particle beam has a finite size and divergence.

The minimum achievable period of an undulator magnetic structure with modern-day magnet technology is about 1.6 cm. Thus, the highest first-harmonic energy that one can realize from an undulator on a 6 to 7 GeV, storage ring is about 20 keV which is about 7 times larger than current sources. Thus, at 6 to 7 GeV, the APS has the unique capability in providing undulator radiation in the hard x-ray range.

The average spectral brilliance or the flux from an undulator can be calculated to various degrees of precision using a method based on numerical integration procedures (5,6). In this method, the Lienard-Wiechert potential is integrated over the charged particle trajectory over the undulator length. In general, these procedures demand considerable computational time.

Figure 1 shows the on axis spectral brilliance for a typical 6 GeV undulator with a first-harmonic peak energy of ~11 keV compared to a BM and wiggler source. These calculations include with the size and the divergence of the positron beam. The undulator is based on $SmCo_5$ permanent magnets and vanadium permendur pole-tips (7) and has a period of 2.4 cm and length of 5m.

In general, the on-axis brilliance of an undulator increases with increasing K (Fig. 1), as expected from simple undulator theory and small values of K suppress the higher harmonics. For most APS undulators, the second and third harmonic brilliance will be higher than that for a BM. The finite size of the positron beam results in the fairly large contribution to the second harmonic brilliance along the undulator axis. The finite emittance of the stored beam also gives rise to a broadening of the radiation peaks. Changing the magnetic gap changes or tunes the first harmonic energy (Fig. 1). The tunability range expected for the proposed APS is 5 to 20 keV.

High brilliance pseudomonochromatic undulator sources are suitable for many applications. They include:

- Ultra-resolution inelastic scattering, ($\delta E/E \sim 1\text{-}5\times10^{-7}$) to study, for example, photon excitations.
- Intermediate-resolution inelastic scattering ($\delta E/E \sim 10^{-4}$) to study, for example, charge density waves.
- High-momentum-resolution scattering ($\Delta k \sim 1\text{-}^{-4}$ Å^{-1}) to study, for example, surface diffraction and long-wavelength magnetic modulations.
- Small-angle scattering.
- High-resolution monochromatic topography.
- Elastic magnetic scattering.
- Nuclear resonant diffraction for coherent x-ray radiation.
- Anomalous scattering.
- Soft x-ray application.
- X-ray microprobe and fluorescence analysis.

Several based beamlines proposed for the Advanced Photon Source are discussed in Ref. 8.

As mentioned earlier, wigglers IDs have K values larger than about 10, which results in an approximately continuous photon energy spectrum. Large K-values are achieved by having either large B_o and/or large λ_o. In principle, a multipole wiggler can supply the same number of photons per second in the same bandwidth as a comparable undulator. However, both the vertical and horizontal opening angles of radiation are considerably larger than those of an undulator and consequently the spectral brilliance is lower.

The flux of radiation from a multipole wiggler can be obtained from the expression for the flux from a BM, and the central brilliance can also be calculated in a fashion similar to the BM case, if one is careful to use the proper source size and numer of periods, N. In Fig. 1, the central brilliance is plotted as a function of photon energy for a wiggler with parameters: $B_o = 1.2$ T, $\lambda_o = 20$ cm, N = 10, and K = 22. The brilliance is also compared with that of the undulator discussed above, and with BM radiation for the proposed Advanced Photon Source. This wiggler using permanent-magnet technology is adequate for a large number of experiments requiring photon energies up to about 100 keV ($E_c \sim 29$ keV). In general, wigglers based on complex superconducting-magnet technology, will not be necessary for the Advanced Photon Source.

The brilliance of wigglers proposed for the Advanced Photon Source at 6 GeV are compared to those operating or planned at other storage rings in Fig. 2. The parameters are given in Ref. 5.

Applications of wiggler devices are extensive and cover the spectral energy range of 1 keV to 100 keV for the Advanced Photon Source (8).

A few of the applications include:

- Compton scattering: charge
- SEXAFS, surface diffraction, standing-wave applications
- Conventional diffraction to study micrometer-sized single crystals
- Protein crystallography
- Time resolved topography

- X-ray absorption spectroscopy (dispersive and time resolved)
- Angiography/microradiography (time resolved)
- Low-energy photon sources (for XPS or for higher harmonic rejection)

Several beamlines for the above applications are described in Ref. 8. Both undulators and wigglers on the proposed Advanced Photon Source will provide electromagnetic radiation whose characteristics are unique and unprecedented in the hard x-ray region. The spectral quality of the sources over the accessible energy range will provide avenues to new and exciting science in the coming decade.

Table 1

Betatron Functions, Positron Beam Size, and Positron Beam Divergence in Different Parts of a 6 GeV Advanced Photon Source Lattice

	Undulator	Wiggler
β_x (m)	22.5	1.37
β_y (m)	13.15	1.24
σ_x (μm)	405	100
σ_y (μm)	98	30
σ'_x (μrad)	18	73
σ'_y (μrad)	7	24

References

(1) For a recent review see: E. E. Koch, D. E. Eastman and Y. Farge, in: Handbook on Synchrotron Radiation, ed., E. E. Koch (North Holland, Amsterdam 1983).

(2) For a review of applications see: Synchrotron Radiation Research, Eds., H. Winick and S. Doniak (Plenum Press, New York, 1980).

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(4) Conceptual Design Report of 6 GeV Synchrotron X-Ray Source, Argonne National Laboratory, March 1986.

(5) Conceptual Design Report of a 6-GeV Synchrotron X-Ray Source: Supplement A, Argonne National Labortory Light Source Document: LS-52, March 1986.

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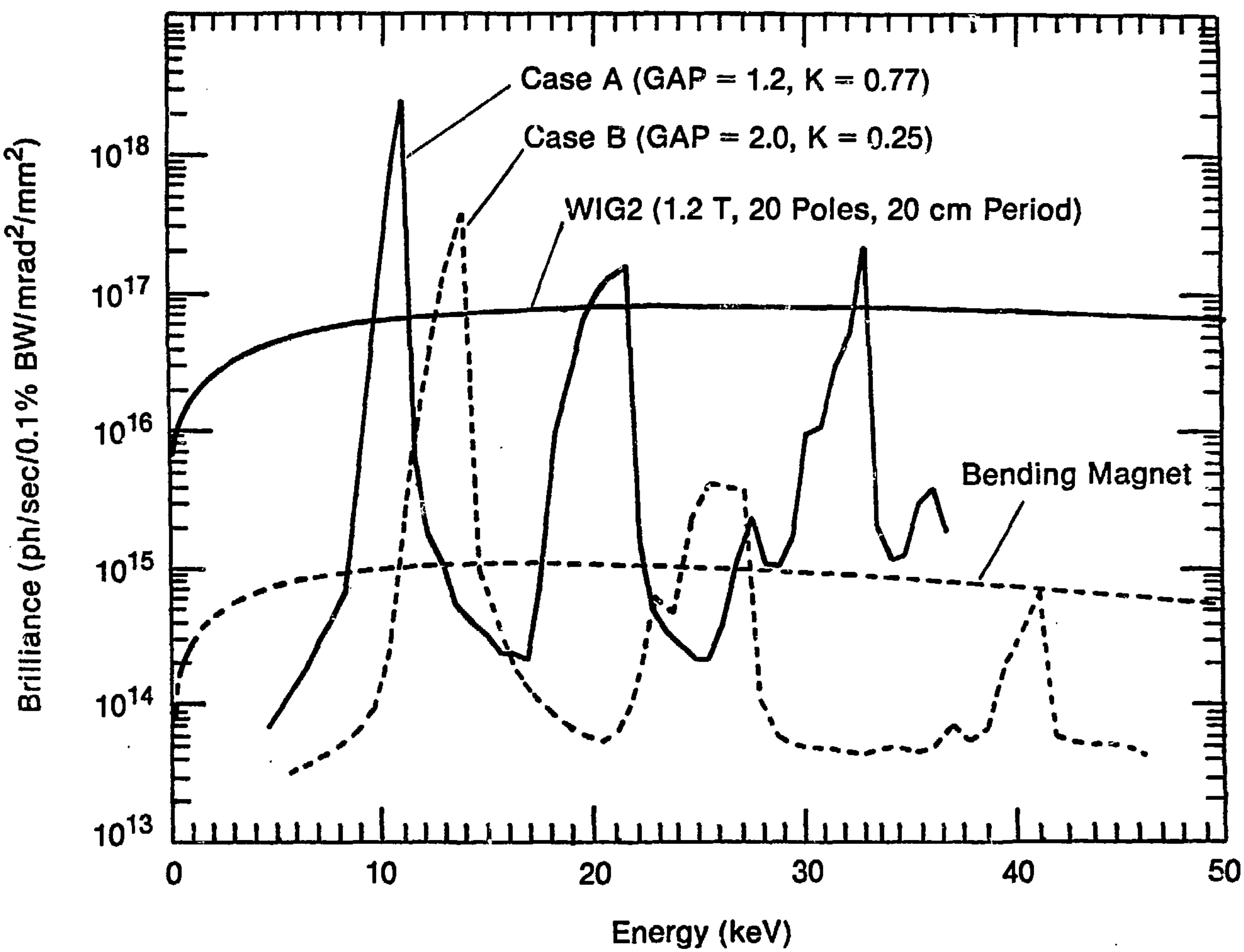
(7) K. Halbach, J. Appl. Phys. 57 (1985) 3605 and references therein.

(8) Conceptual Design Report of a 6-GeV Synchrotron X-ray Source: Supplement B, Argonne National Laboratory Light Source Document: LS-51, March 1986.

Figure Captions

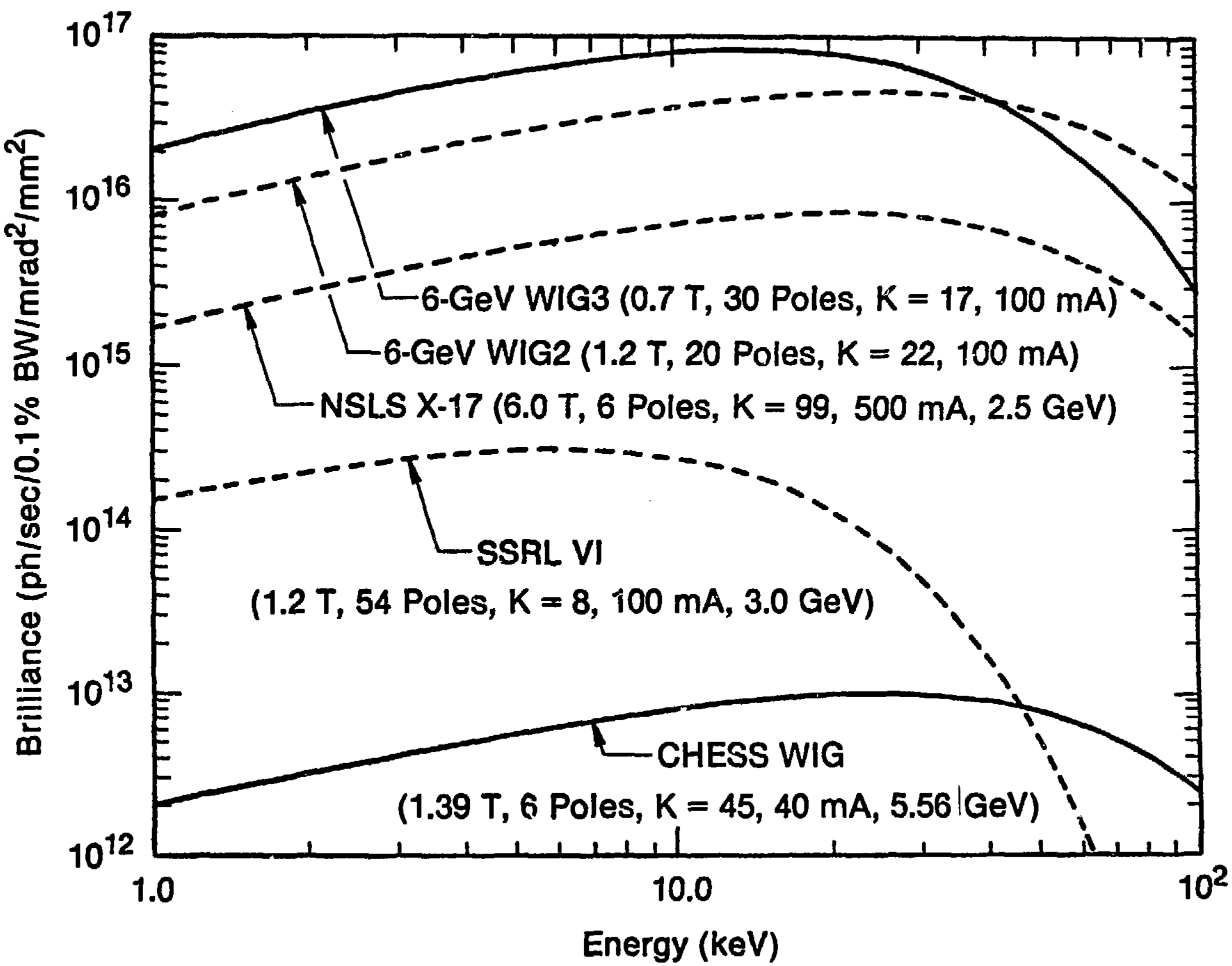
Fig. 1 Brilliance from an undulator assuming the two different magnetic gaps indicated compared with that from a wiggler and a BM (E_c = 19.2 keV) on a 6 GeV (100 mA) synchrotron.

Fig. 2 Brilliance from wigglers on a 6 GeV (100 mA) storage ring, compared with those from wigglers on other synchrotron sources.



Case A (GAP = 1.2, K = 0.77)
Case B (GAP = 2.0, K = 0.25)
WIG2 (1.2 T, 20 Poles, 20 cm Period)
Bending Magnet
Brilliance (ph/sec/0.1% BW/mrad²/mm²)
10^18
10^17
10^16
10^15
10^14
10^13
0
10
20
30
40
50
Energy (keV)

Fig 1



10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
Brilliance (ph/sec/0.1% BW/mrad^2/mm^2)
6-GeV WIG3 (0.7 T, 30 Poles, K = 17, 100 mA)
6-GeV WIG2 (1.2 T, 20 Poles, K = 22, 100 mA)
NSLS X-17 (6.0 T, 6 Poles, K = 99, 500 mA, 2.5 GeV)
SSRL VI
(1.2 T, 54 Poles, K = 8, 100 mA, 3.0 GeV)
CHESS WIG
(1.39 T, 6 Poles, K = 45, 40 mA, 5.56 GeV)
1.0
10.0
10^2
Energy (keV)