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Author
Kincaid, B.M.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

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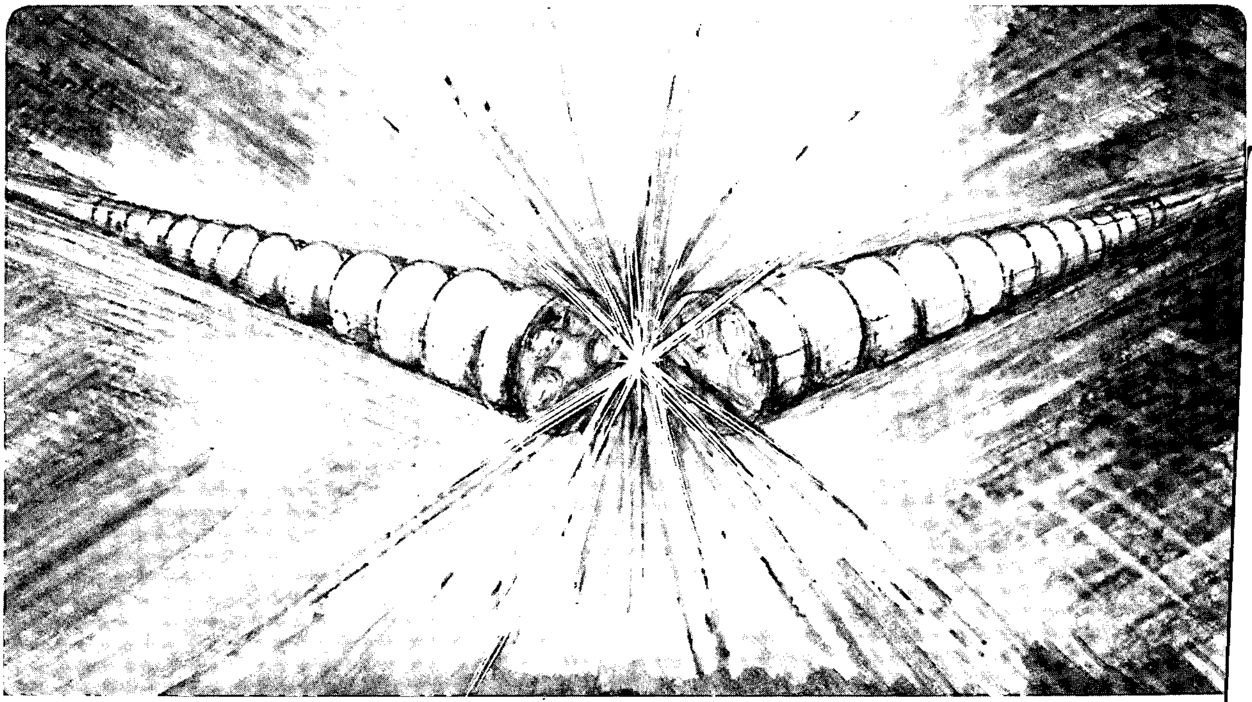

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Real World Issues for the New Soft X-Ray Synchrotron Sources[†]

Brian M. Kincaid

Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road, Berkeley, CA 94720

Abstract

A new generation of synchrotron radiation light sources covering the VUV, soft x-ray and hard x-ray spectral regions is under construction in several countries. They are designed specifically to use periodic magnetic undulators and low-emittance electron or positron beams to produce high-brightness near-diffraction-limited synchrotron radiation beams. An introduction to the properties of undulator radiation is followed by a discussion of some of the challenges to be faced at the new facilities. Examples of predicted undulator output from the Advanced Light Source, a third generation 1–2 GeV storage ring optimized for undulator use, are used to highlight differences from present synchrotron radiation sources, including high beam power, partial coherence, harmonics, and other unusual spectral and angular properties of undulator radiation.

Introduction

The properties of undulator radiation and undulator magnets dominate the design of the electron storage ring and the experimental apparatus planned for the new synchrotron light sources.

In a typical undulator magnet, the magnetic field on-axis can be written as $B_y(z) = B_0 \cos kz$, where $k = 2\pi/\lambda_u$. For permanent magnet systems, B_0 is proportional to the magnetization strength of the polarized magnetic material, and can be as high as 2 Tesla. An electron of energy $E = \gamma m_0 c^2$ has a sinusoidal trajectory given by $x(z) = a \cos kz$, where $a = K\lambda_u/2\pi\gamma$. The maximum deflection angle K/γ. The undulator parameter K is $\lambda_u e B_0/2\pi m_0 c^2$, having the value $0.934\, B_0(T)\lambda_u(cm)$, usually of the order of unity. For the ALS, $\gamma \simeq 3000$, so a is of the order of 10μ, which is much smaller than the electron beam dimensions of $\sigma_x = 330\mu$ and $\sigma_y = 63\mu$.

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The radiation produced by a single electron is essentially that of a moving dipole. The Doppler effect for such a moving source results in an angle dependent observed wavelength, given by $\lambda = \lambda_u(1-\beta_z \cos\theta)$. Here β_z is v_z/c, with v_z being the electron's average velocity in the z direction. The speed of the electron is constant travelling through the undulator magnetic field, so the transverse deflection of the trajectory results in a slowing down of the average z motion. This can be expressed as a reduced γ, given by $\gamma^* = \gamma/(1+K^2/2)^{\frac{1}{2}}$. The radiation pattern is strongly peaked in the forward direction, with an opening angle of the order of $1/\gamma$, about 0.3 milliradians for the ALS. The small angle approximation may therefore be used, resulting in $\lambda = \lambda_u(1+K^2/2+\gamma^2\theta^2)/2\gamma^2$. Hence, the shortest wavelengths are radiated in the forward direction, with longer wavelengths radiated off-axis.

For an undulator of length $L = N\lambda_u$, the electron radiates a Doppler-compressed wave train of length $N\lambda$, resulting in a transform limited sinc^2 spectrum, with fractional linewidth $1/N$. For undulators at the new light sources, $N \simeq 100$, resulting in a one percent spectral bandwidth for each observation angle. Near the forward direction, energy within this bandwidth is radiated into a central cone with an opening angle of $\theta = 1/\gamma^*\sqrt{N} = (1+K^2/2)^{\frac{1}{2}}/\gamma\sqrt{N}$, a small fraction of $1/\gamma$, approximately 0.1 milliradian for the ALS. This is the same as the diffraction limited angular width of the radiation pattern from a line source of length L, given by $\theta \simeq (\lambda/L)^{\frac{1}{2}}$. This is because, classically, a single electron radiates a completely deterministic coherent wave field, which must obey the rules of diffraction. The peak intensity, or energy/unit solid angle, in the forward direction scales as N^2. The total energy radiated into the central cone therefore goes as N, resulting in roughly N times more spectral flux than from a bend magnet source.

If an optical system is used to form an image of the source of the central cone radiation, the diffraction limited 1-σ source size and angular divergence are $\sigma_r = \sqrt{\lambda L}/4\pi$ and $\sigma_{r'} = \sqrt{\lambda/L}$, resulting in a phase space (emittance) of $\lambda^2/4$. This is the same expression as for a single Gaussian laser mode[1]. These properties are in marked contrast to the broad spectral and angular features of bend magnet radiation.

Brightness, Flux, and Coherence

Brightness. Higher source brightness is the major performance improvement for the new light sources. Brightness is defined as source photon flux divided by the product of source area and emission solid angle[2]. It is the figure of merit for microimaging systems since it determines how much flux can be focussed onto a small target. Using a high-brightness light source, the entire central-cone undulator output can be focussed through a small entrance slit into a high-resolution grating monochromator, something not possible using present day sources. The source brightness is significantly higher for the new sources because of the small beam emittance (about a factor of ten) and the use of undulators (about another factor of N).

Flux. The total power radiated by the electron beam is proportional to $B^2\gamma^2 IL$. B is dependent on magnet technology, and is about the same for all synchrotron radiation sources. Since storage ring beam emittance grows with increasing γ, the electron beam energy must be kept relatively low (1–2 GeV) to achieve the small emittance and energy spread necessary for high brightness undulator sources. Beam current is limited by the low beam energy and the small beam size. This means that the new light sources will produce about the same flux as present sources.

Coherence. Some of the work at the forefront of x-ray optics involves the use of Fresnel zone plate lenses for microscopy and the use of the coherence of present day undulator sources for x-ray holography[3][4]. Both these techniques depend on spatial and temporal coherence. One of the major benefits expected from the new light sources is an increase in the amount of spatially coherent light, and hence an improvement in performance.

The random distribution of electrons within a stored bunch of electrons results in classical, non-laserlike, chaotic light [5]. The angular and energy spreads of the electron beam broaden the radiated spectrum. The non-zero electron beam size further reduces the brightness of the source. Spatial coherence is produced by the small electron beam, combined with the intrinsic properties of undulator radiation. Temporal coherence is strictly first order[5], determined by the combination of beam emittance, energy spread, and $1/N$.

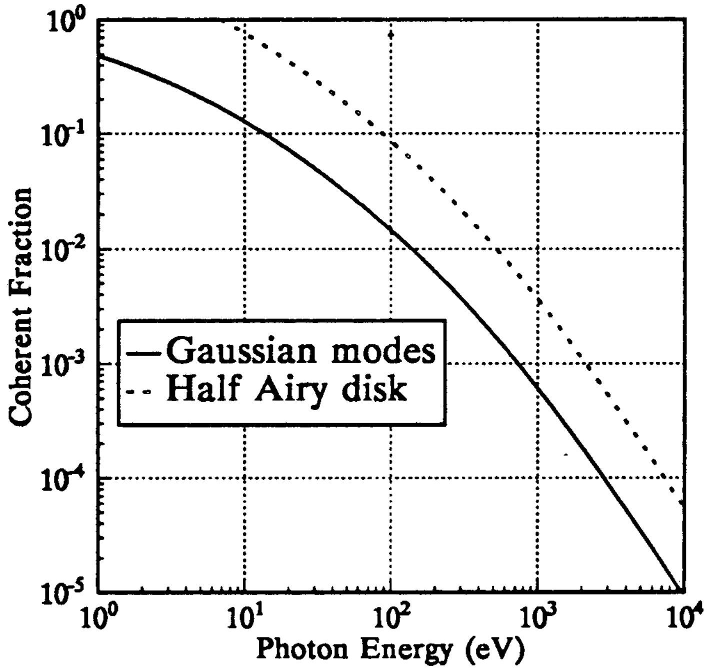

Figure 1. The coherent fraction f.

The amount of spatially coherent light is proportional to source brightness[1]. The fraction of the central-cone radiation that is spatially coherent (i.e. within a single gaussian mode) is given by[1] $f = (\lambda/4\pi)^2/\sigma_{Tx}\sigma_{Ty}\sigma_{Tx'}\sigma_{Ty'}$. Here $\sigma_{Tx} = (\sigma_x^2 + \sigma_r^2)^{\frac{1}{2}}$, $\sigma_{Ty} = (\sigma_y^2 + \sigma_r^2)^{\frac{1}{2}}$, $\sigma_{Tx'} = (\sigma_{x'}^2 + \sigma_{r'}^2)^{\frac{1}{2}}$, and $\sigma_{Ty'} = (\sigma_{y'}^2 + \sigma_{r'}^2)^{\frac{1}{2}}$. For the ALS, $\sigma_x = 330\mu$, $\sigma_y = 63\mu$, $\sigma_{x'} = 30\mu rad$, and $\sigma_{y'} = 16\mu rad$. This ratio involves only the photon wavelength, the electron beam emittance, and the undulator length. For practical optical systems using the coherence properties of the light, it is possible to use several radiation modes without significantly losing resolution, as reflected in the half-Airy-disk criterion [6]. This allows the acceptance of about six times more flux than the Gaussian mode criterion, although, at the diffraction-limited end of the spectrum it becomes unphysical, allowing more than 100% of the radiation to be coherent.

Consequences of Large K.

High Power Loading. To maximize light source performance, the longest possible straight sections and the largest N should be used, since both flux and brightness increase with N. Usually the size and number of straights in the machine are fixed, and hence the length L of the undulator. This means λ_u must decrease for N to increase. For a fixed machine energy (γ) and operating wavelength λ, this means K must increase, requiring an increase in B. A large value of K_{max} means that a single undulator can cover a large tuning range by varying K, a desirable feature. Unfortunately, this also drives up the total power that must be handled by the first optical element in the beam line. For the ALS this can be several kW.

Harmonics. The undulator spectrum is rich in harmonics, with even harmonics forbidden by symmetry on-axis[1]. The number of significant harmonics is $n_c = (3/4)K(1 + K^2/2)$, increasing as K^3 for large K, and, the fraction of total radiated power in the first harmonic is $P_1/P_{tot} = 1/(1 + K^2/2)^2$. The maximum useful harmonic limited by undulator quality and the electron beam emittance and energy spread, so the higher harmonics are just extra heat to deal with. In addition, harmonics can pass through grating monochromator systems and show up in the output beam, and may have to be filtered out. For the ALS, undulators have been designed to produce useful output up to the 5^{th} harmonic. So, the optimization of undulator performance can lead to difficult optical engineering problems: how to remove extra heat with thermal distortions kept to a minimum to preserve brightness

Optics Contamination. The extra power produced when central brightness and flux are maximized can pose a serious mirror contamination problem. Synchrotron radiation hitting mirror surfaces generates an intense photoelectron flux, which can lead to deposition of carbonaceous contamination, reducing the mirror reflectivity. The contamination deposition rate may be reduced by improved vacuum, but, in-situ cleaning systems probably will be necessary.

Effects on the Storage Ring. In an undulator magnet the peak mid-plane field depends on the gap between pole tips or magnet blocks, $B_y \simeq \exp(-\pi g/\lambda_u)$[7]. If the λ_u is decreased, as desired, g must decreased also to increase B and K. This means that the electron beam must pass through an increasingly long and narrow vacuum chamber. Such a small gap may make it difficult or impossible to inject beam into the storage ring or have a long stored beam lifetime.

Strong undulator fields, combined with the relatively low energy of the electron beam required, result in significant electron beam focussing effects, making it necessary to re-tune the machine when the undulator gap is varied. This may have an adverse effect on electron beam lifetime, position, or size around the ring.

Off-axis Radiation. The potential problems arising from changing the undulator gap may make it seem more practical to use off-axis radiation, using the Doppler shift to vary the wavelength rather than the undulator gap. This approach, while tempting, is fraught with difficulties. As L and N are increased, the fact that the observer of the undulator output is not infinitely far away becomes increasingly important. Typical undulator to experiment distances are of the order of 10 meters, while L can be as large as 5 meters. This places the experiment in the Fresnel region, where the variation of observation angle θ from one end of the undulator to the other results in a chirped radiation pulse. Furthermore, since the upstream end of the undulator is farther away from the observer than the downstream end, the inverse square law results in significant amplitude modulation of the chirped wave. An analysis leads to the result that if the off-axis observation angle α is greater than $\sigma_{r'}\sqrt{D/L}$, then the chirp effect broadens the narrow undulator spectral peaks[8]. For larger off-axis angles, the broadening is large enough to overlap different harmonics, and all the spectral advantages of using undulators are lost. The apparent source size $\Delta x = L \sin \alpha$ increases off-axis, decreasing source brightness. These effects might be useful, however, in lithographic imaging, where too much spatial coherence causes speckle. A better method of broadening the undulator peaks to avoid gap adjustments is to taper the undulator gap, again producing a chirped wave, but without as serious a brightness penalty.

Tuning for Spatial Coherence.

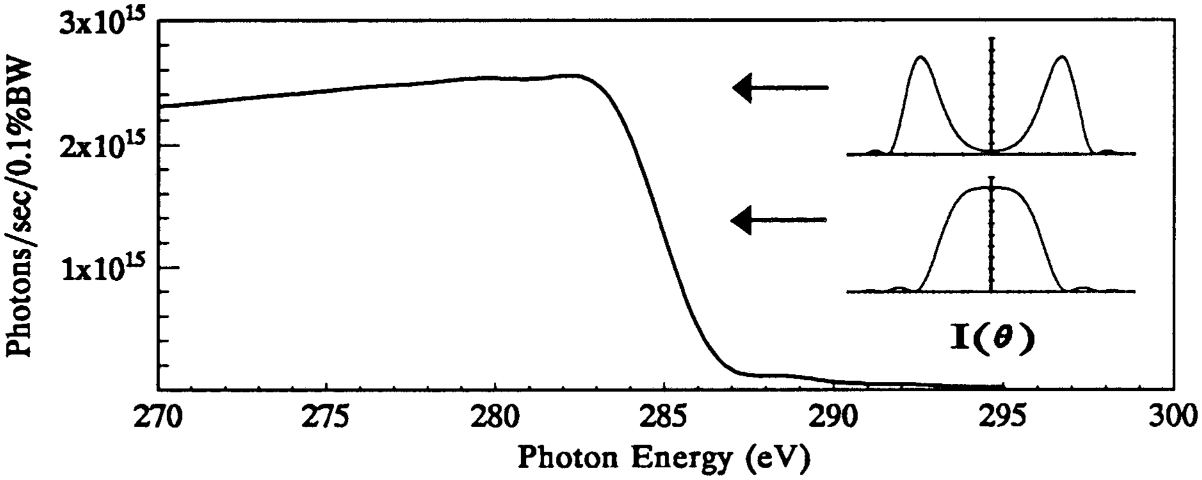

Figure 2.

The amount of spatial coherence is a sensitive function of wavelength. Figure 2. shows the angle integrated spectrum for the first harmonic of ALS undulator U5 with $K = 1$, for photon energies near the carbon K-edge. This spectrum is what might be observed after opening up the entrance slits of a high-resolution monochromator in an attempt to coordinate the undulator gap, the beam position, and the monochromator setting to maximize spatially coherent light output. The best spatially coherent flux is produced at the exact fundamental photon energy, indicated by the lower arrow. Even though the total flux is greater at the peak of the curve at slightly lower photon energy, the radiation pattern has a hole in the center, and a larger total opening angle, certainly not well described by a Gaussian mode. This results in a significantly smaller coherence fraction.

More work is needed in the area of imaging undulator radiation and the spatial coherence of undulator radiation. The theory of brightness propagation using Wigner distributions in principle includes all of above, but the theory has not been developed beyond its initial formulation[1].

Conclusions

To make use of the improved performance promised for the new light sources, users needing spatially coherent light must have adjustable gap, long length, short period undulators. This leads to the requirement for high quality, high heat load optics, and for the control of surface contamination. Beam position stability is a must, and beam position feedback and thermal stability systems should be built in from the outset. To be able to adjust a beam line for desired coherence properties, the user must have control of electron beam position and angle in the undulator, as well as the alignment of optical elements in the beam line. Accurate and reproducible calibration of both the undulator and monochromator is mandatory Techniques must be developed for dealing with small, high-power beams of invisible radiation. The use of off-axis radiation to avoid changing the undulator gap should be eschewed, although undulatory tapering may have its uses. These requirements will have a major impact on the design and operation of the new soft x-ray light sources.

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