Current and Future Light Sources

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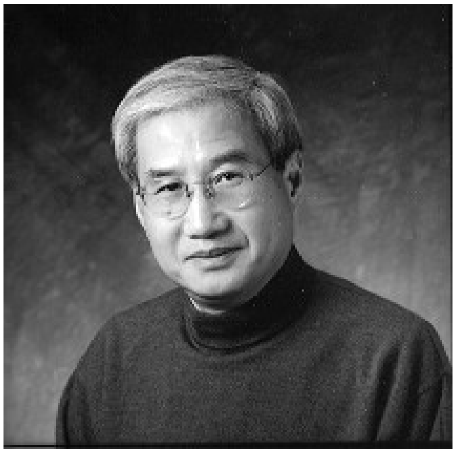

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Abstract: We review the development of the synchrotron radiation sources from the current, third-generation devices based on undulators in electron storage rings to the future devices based on high-gain free-electron lasers in electron linacs.

I. Introduction

Third-generation synchrotron radiation facilities have been highly successful with respect to both machine operations and scientific output. Their success derives from the high brightness of the spontaneous emission from undulators in the straight sections of optimized electron storage rings.

Among several possibilities for next-generation light sources, the most exciting is the one based on self-amplified spontaneous emission (SASE). SASE is intense, coherent radiation generated by amplifying the initial spontaneous emission via an extremely high-gain free-electron laser (FEL) process. SASE in the x-ray region will be possible with a system composed of a photocathode rf gun, a bunch compressor, a high-energy linear accelerator (linac), and a long undulator. The Linac Coherent Light Source (LCLS) is a demonstration project for production and use of SASE at 1 Å using the Stanford Linear Accelerator Center linac [1]. The peak brightness of the x-ray beam from the LCLS is projected to be ten orders of magnitude larger than that of third-generation sources. Given the positive experience from the LCLS, we may conceive a "fourth-generation" user facility employing a superconducting linear accelerator, such as the one proposed by the group at Deutsches Elektronen-Synchrotron (DESY) [2]. The R&D preparing for the conceptual design of the LCLS was recently endorsed by the Basic Energy Sciences Advisory Committee on Novel Coherent Light Sources [3].

II. Undulator Radiation from Third-Generation Synchrotron Radiation Facilities

Undulator radiation is the radiation emitted by a relativistic beam of particles as it passes a periodic magnetic structure (called undulators) [4], as shown in figure 1. Undulators placed in straight sections of low-emittance, high-current electron storage rings are the basis for the so-called third-generation light source facilities. The radiation brightness—photon flux per unit phase space area—from undulators in the third-generation light sources is typically about 10^{20} photons/(sec)(mm)^2 (mrad)^2, which is about five to six orders of magnitude higher than the synchrotron radiation from bending magnets, which in turn is higher by another six orders of magnitude than the brightness of x-ray tubes. Recognition of the power of undulator radiation in studying the structure of atoms and molecules and their arrangement in organic and inorganic materials, with its far-reaching implications in the basic sciences and industries, has led to competition in recent years among countries around the world to construct third-generation synchrotron radiation facilities.

Undulator radiation from an electron beam is an incoherent sum of radiation from individual electrons. The total radiation phase space is therefore given by a convolution of the coherent radiation phase space of individual electrons and the electron beam phase space. Since the electron beam phase space area is characterized by the rms emittance ε_x, and the corresponding quantity for coherent radiation is $\lambda/4\pi$, where λ is the radiation wavelength, undulator radiation becomes maximally bright when $\varepsilon_x \leq \lambda/4\pi$ [5]. In this case the undulator radiation becomes transversely coherent, thus permitting interference techniques such as holography. For a typical third-generation light source, the horizontal (vertical) rms emittance $\varepsilon_x(\varepsilon_y)$ is about 10^{-9} (10^{-11}) m-rad. Therefore, the coherence condition is satisfied for UV radiation with the wavelength ≥ 100 Å. Even for wavelengths down to tens of Å or shorter, the coherent fraction is substantial. These values of emittances, together with hundreds of milliamps of the ring current, and the undulator periods of about 100, are the reasons why the brightness of the third-generation synchrotron radiation source is so high.

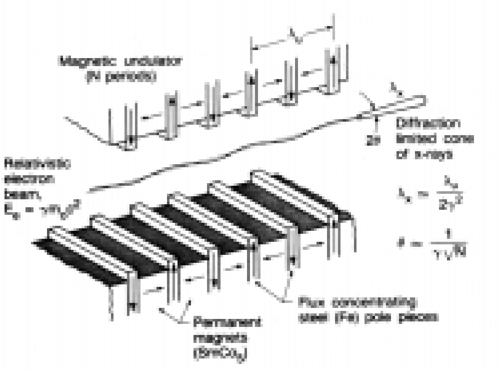

FIG. 1. Schematic of a periodic magnetic structure (an undulator) of period λ_u and with a number of periods, N. The structure is based on permanent magnets.

III. Free-Electron Lasers

Imagine now that the undulator radiation generated by an electron bunch is trapped between two mirrors at both ends of the undulator. If the distance between the mirror pair, which forms an optical resonator, is properly chosen, then the radiation pulse generated from one electron pulse can be made to return and travel together with the next electron bunch in the undulator. In that case, the interaction between the radiation pulse and electron beam is such that it causes periodic density modulation of the electron beam, with the period equal to the radiation wavelength. A density-modulated electron beam radiates more strongly than an electron beam with random electron distribution. The stronger radiation pulse in turn leads to higher density modulation. This process, which is essentially the same as in conventional laser oscillators, continues until the intracavity radiation intensity reaches a saturation level. Such an arrangement, referred to as a free-electron laser (FEL), produces highly coherent radiation beams of spectral brightness many orders of magnitude higher than that of undulator radiation [6].

The advantage of FELs over conventional lasers is that the wavelength can be chosen arbitrarily if electron beams of suitable energy and beam brightness and high reflectivity mirrors are available. To date, the shortest wavelength record of free-electron lasers has been 2400Å from a storage-ring-based free-electron laser in Novosibirsk [7]. The wavelength limit here was due to the mirror availability.

IV. Self-Amplified Spontaneous Emission as a Future Light Source

In the above, we have described the FEL oscillators based on use of a mirror pair. As in conventional lasers, FELs can also be used as an amplifier if seed lasers are available. An amplifier has the advantage that it does not require mirrors. For a sufficiently high electron beam brightness, and for a sufficiently long undulator, the gain in a single pass could be so high that the spontaneous undulator radiation emitted in the beginning part of the undulator could be amplified to an intense, quasi-coherent radiation, the so-called self-amplified spontaneous emission (SASE) [8]. Seed lasers are not necessary in this case. The reason why SASE has attracted so much attention recently as the basis for the “fourth-generation” light source is because it is currently the only known approach for obtaining tunable, coherent radiation down to the x-ray wavelength region with brightness significantly higher than that available from current generation synchrotron radiation facilities.

Various performance characteristics of SASE can be expressed by a single dimensionless parameter ρ: the power e-folding length (gain length) is about $1/1\pi\rho$ undulator periods, the SASE saturates in about $1/\rho$ undulator periods, and the saturation power is about ρ times the electron beam power. In order to limit the number of periods to less than 1000, the ρ parameter should be less than 10^{-3}. For x-ray wavelengths in the range 10 to 1 Å, this requires a peak current of several kiloamps; an invariant emittance $\gamma\varepsilon_x \leq 10^{-6}$ m-rad, where γ is the Lorentz factor, $\gamma \approx 2 - 3 \times 10^4$; and an energy spread $\Delta\gamma/\gamma \leq 10^{-3}$.

The temporal coherence of SASE radiation at saturation is very similar to that of undulator radiation of period $N = 1/\rho$; the SASE consists of random superposition of N_e wavetrains, where N_e = total number of electrons, each wavetrain being of about $1/\rho$ cycles. In the frequency domain, the radiation has a spectral width $\Delta\omega/\omega \sim \rho$ that specifies the first-order coherence. The radiation intensity at a given frequency or time fluctuates 100%; i.e., the SASE belongs to the class of light referred to as “chaotic light.” The fluctuation can be reduced if the detector has a finite resolution so that the intensity is averaged over a finite resolution either in the frequency domain or the time domain. In the case of standard undulator radiation, the reduction factor is large due to long electron bunches and short radiation wavetrains. Therefore, the fluctuation is hardly observable. In the case of SASE, the electron bunches are shorter and the radiation wavetrains longer, so that the intensity fluctuation could be 10-20%.

In contrast to temporal coherence, SASE is quite different from undulators as far as the transverse coherence is concerned: the latter is partially coherent, while the former is fully coherent. The transverse coherence of SASE arises mathematically from the dominance of a single growing mode as a solution of the coupled Vlasov-Maxwell equation describing the high-gain FEL system [9]. Intuitively, it may be understood as follows. The angular divergence of undulator radiation is an incoherent sum of the angular divergence of individual undulator radiation, which is coherent, and the electron beam angular divergence. On the other hand, the electron beam develops density modulation in the case of SASE. The radiation angular divergence from each slice of the electron beam in which the electrons are bunched is the diffraction-limited angular divergence determined by the transverse size of the electron beam, implying that the radiation is fully coherent transversely [5].

The bunching in SASE is not complete because the temporal coherence is chaotic. Nevertheless, the SASE is dominated by the bunched part, and the radiation from that part is transversely coherent.

V. Storage Ring or Linac?

Let us now go back to the accelerators. The third-generation synchrotron radiation facilities, whose capabilities we already have emphasized, are all based on storage rings. However, we will see that linacs are better suited than storage rings for driving a SASE FEL for x-rays.

Storage rings provide high brightness electron beams, the brightest electron beams until recently. This is due to the inherent radiation damping taking place in storage ring bending magnets. By taking maximum advantage of the damping, and at the same time minimizing the emittance dilution due to quantum excitation by a proper magnetic lattice, it was possible to design high brightness storage rings for third-generation light sources. By the same token, however, the brightness achievable in storage rings is limited by the inherent beam dynamics phenomena of storage rings; quantum excitation, Touschek scattering, microwave instabilities, etc. Considering impedance control and current reasonable and feasible limitations on the size of storage rings, the electron beam emittance is limited to about 10^{-9} m-rad, a bunch length of about 10 ps, with a charge of about 1 nC.

For a linac, however, the beam parameters are more or less determined by the gun. With the recent development of the rf photocathode gun [10] with the emittance correction technique [11], linacs have become a very promising option for driving SASE at x-ray wavelengths: the state-of-the-art rf gun technology could produce 1-nC electron bunches of invariance emittance $\gamma\varepsilon_x \approx 10^{-6}$ m-rad in a pulse length of about 10 ps. After acceleration, pulse compression, and further acceleration, electron beams with 15 GeV of energy, pulse length of 200 fs, peak current of 5 kA, and emittance of $\varepsilon_x \approx 0.3 \times 10^{-10}$ m-rad can be prepared, which are adequate for producing SASE radiation at ≥ 1 Å in a 200-fs pulse length. The SLAC linac is uniquely suited for this purpose, as was first emphasized by C. Pellegrini [12].

VI. Factors Enabling Linac-Based SASE

There are basically three factors that enable the realization of 1-Å SASE based on linacs. The first is the development of the rf photocathode gun as was already mentioned in the previous section. The second is the preservation of beam qualities through bunch compression and acceleration processes. The third is the development of precision undulator magnets.

For SASE at x-ray wavelength, it is important that the already low emittance from an rf photocathode be further reduced by an emittance compensation scheme [11]. The emittance from an rf photocathode gun is due mainly to the space charge effect [13], which causes the beam to expand with a different rate along the axial length of the bunch, stronger at the beam center and weaker at the ends. In the phase space picture, the emittance ellipses at different longitudinal positions “rotate” with different rates, causing an increase in overall emittance compared to the slice emittance. The emittance compensation scheme consists of reversing the beam expansion in a solenoidal focusing element and realigning different slice ellipses in the drift section. The phenomenon here is very much analogous to the spin echo.

The beam generated by the rf photocathode gun needs to be compressed by a factor of 100 and accelerated to 10-20 GeV before it is ready for a SASE undulator at x-ray wavelength. Avoiding the emittance dilution due to single particle effects (focusing mismatch, dispersive and chromatic effect, etc.) and beam instabilities is a nontrivial problem considering the small emittance, high current beam under consideration. The R&D on this topic was studied extensively both numerically and experimentally in connection with the linear collider design efforts. Experimentally, the increase in the invariant, vertical emittance, which is about 1.5 mm-mrad in the SLAC linac, can be controlled to less than 50% through the 3-km-long linac in which the beam is accelerated to 50 GeV [14]. This is the level of control necessary for an x-ray SASE.

The x-ray SASE requires a long linac, typically about 100 m long with about 1000 periods. The undulator can be divided into several segments, with an interruption between the adjacent segments, without degrading the exponential gain in the undulator [15]. The magnetic field tolerance of each segment is tight, but within the current state-of-the-art, due to the recent development in undulator construction spurred by the needs of the third-generation synchrotron radiation facilities. These interruptions between segments can be used for focusing the electron beam and for installing diagnostic equipment. All segments must be aligned to within an accuracy of a few microns.

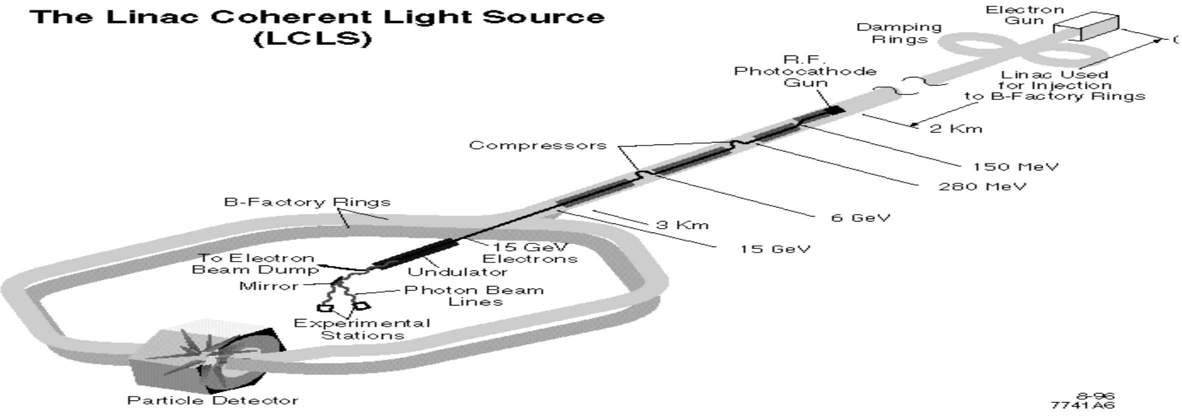

FIG. 2. Layout of the LCLS.

VII. SASE Projects

Several experimental projects are either in progress or being planned in several laboratories around The proof-of-principle experiments for wavelengths longer than 1 µ have already achieved a significant level of single pass gain [16-19]. The experiments at the Advanced Photon Source [20], Brookhaven National Laboratory [21], and DESY [22], at wavelengths from visible to about 1000 Å, will be carried out within one to two years. Eventually the goal is to achieve SASE at x-ray wavelengths, for which the only linac available to date is the Stanford Linear Accelerator Center (SLAC) linac.

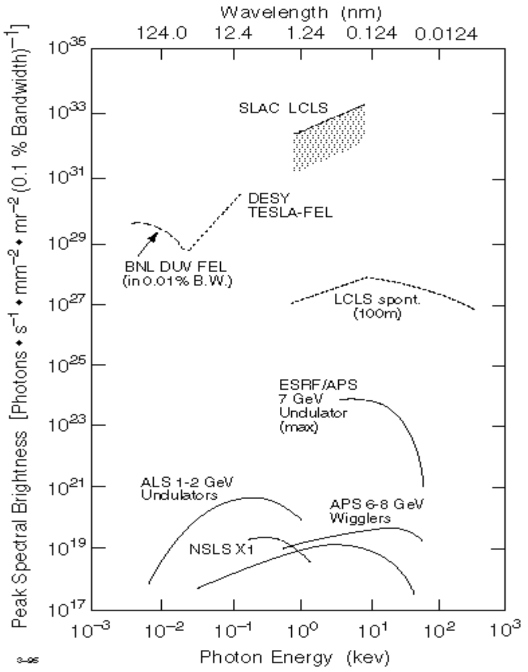

FIG. 3. Peak spectral brightness.

Figure 2 shows the layout of the x-ray SASE project using the SLAC linac, called the Linear Coherent Light Source (figure 2) [1]. It uses about one third of the existing SLAC linac, but the beam will be generated by a new rf photocathode gun. The evolution of the e-beam parameters from the gun to the entrance of the undulator is indicated in the figure.

The performance in the peak (during the 100-fs pulse length) spectral brightness of the LCLS is compared with other synchrotron radiation and FEL sources in figure 3, and comparisons of time-averaged brightness are given in figure 4. Note that the peak spectral brightness of the LCLS is more than ten orders of magnitude higher than the undulator radiation from third generation synchrotron radiation sources. In addition, the pulse length is about 100 times shorter, thereby improving the time resolution by the same factor.

The enhancement in the average brightness is much less than that in the peak brightness, due to the smaller repetition rate of the linac. However, the average spectral brightness of LCLS is still three to four orders of magnitude higher than the undulator sources. The average brightness can be increased further by increasing the bunch repetition rate if a superconducting linac is used, as is planned at DESY [2].

VIII. Summary and Conclusion

We have reviewed the capabilities of the current status of third-generation synchrotron radiation sources and future development exploiting the free-electron lasers. The enormous increase in the brightness of the future light sources will present scientific opportunities that are not possible or even imaginable at the present time [23].

IX. Acknowledgments

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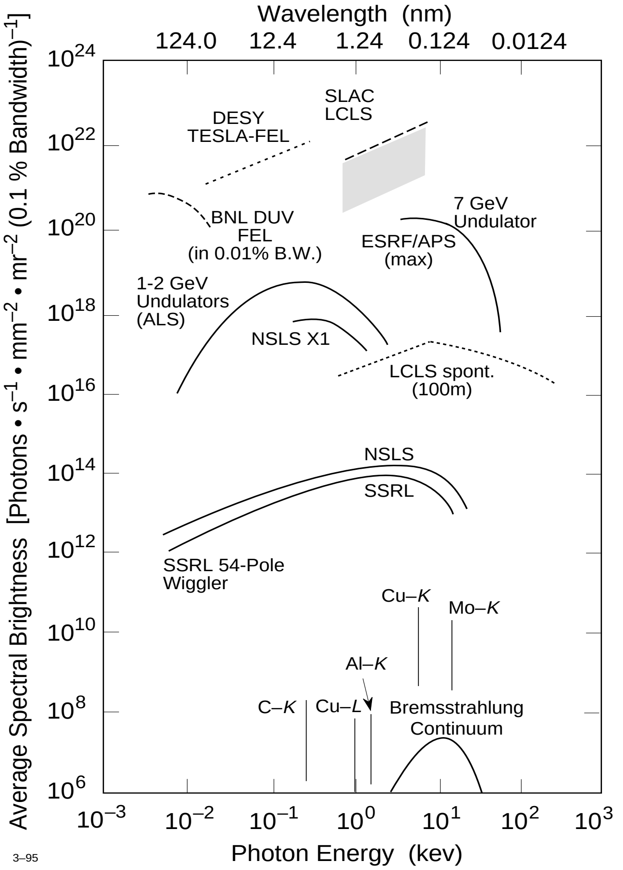

FIG. 4. Average spectral brightness.

References

[1] LCLS Design Study Report, SLAC-R-51 (April 1998).

[2] Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-Ray Facility, DESY 1997-048 (May 1997).

[3] Report of Panel on Novel Coherent Light Sources for DOE, Basic Energy Sciences Advisory Committee (February 1999).

[4] For a review, see K.-J. Kim, “Physics of Particle Accelerators,” *AIP Conf. Proc.* **184**, edited by M. Month and M. Dienes (AIP, 1989), page 565.

[5] K.-J. Kim, “Emittance in Particle and Radiation Beam Techniques,” *AIP Conf. Proc.* **398**, 243 (1996).

[6] J.M.J. Madey, *J. Appl. Phys.* **42**, 1906 (1971).

[7] I.B. Drobyazko *et al., Nucl. Instrum. Methods A* **282**, 424 (1989).

[8] R. Bonifacio, C. Pellegrini, L.M. Narducci, *Opt. Commun.* **50**, 6 (1985); K.-J. Kim, *Phys. Rev. Lett.* **57**, 1871 (1986); J.-M. Wang and L.-H. Yu, *Nucl. Instr. Methods A* **250**, 396 (1986).

[9] M. Xie, to be published.

[10] R.L. Sheffield, *Physics of Particle Accelerators,* AIP **184**, edited by M. Month and M. Dienes, 1500 (1989).

[11] B. Carlsten, *Nucl. Instrum. Methods A* **285**, 313 (1989).

[12] C. Pellegrini, Proc. of Workshop on 4th Generation Light Sources, edited by M. Cornacchia and H. Winick, SSRL Report 92/02 (1992).

[13] K.-J. Kim, *Nucl. Instrum. Methods A* **239**, 127 (1985).

[14] T.O. Raubenheimer, *Nucl. Instrum. Methods A* **358**, 40 (1995).

[15] K.-J. Kim, “Undulator Interruption in High-Gain Free Electron Lasers,” to be published in *Proc. of FEL’97,* (Beijing, China, August 1997).

[16] M. Hogan et al., *Phys. Rev. Lett.* **80**, 289 (1998).

[17] D.C. Nguyen et al., *Phys. Rev. Lett.* **81**, 810 (1998).

[18] M.J. Hogan et al., *Phys. Rev. Lett.* **81**, 4867 (1998).

[19] M. Babzien et al., *Phys. Rev. E* **57**, 6093 (1998).

[20] S.V. Milton, SPIE Proceedings, **3614**, 86 (1999).

[21] The VISA Collaboration Report (April 1998).

[22] J. Rossbach, Proc. of the XIX International Linac Conference, ANL-98/28, **2**, 1048-1051 (1999).

[23] D. Moncton, Proc. of the XIX International Linac Conference, ANL-98/28, **1**, 357-361 (1999).