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**Linac-Based, Intense, Coherent
X-Ray Source Using Self-Amplified
Spontaneous Emission**

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ABSTRACT

We discuss the principles and properties of SASE radiation, and the reason why the SLAC linac is uniquely suited for the SASE generation of x-rays.

I. INTRODUCTION

The SLAC linac, built some thirty plus years ago by R. B. Neal, W. K. B. Panofsky, and others, is still young and vigorous. It will last another ten to fifteen years, and more if there are good ideas [1]. There is a good idea from the traditional high energy front: The SLAC linac is an important test bed for the Next Linear Collider [2]. This paper describes another good idea from a different perspective, namely its use for the Linear Coherent Light Source (LCLS) at the frontier of photon science [3]. The LCLS is an intense, coherent source of x-ray beams, which is a kind of free-electron laser (FEL) but operating in a special mode called the self-amplified spontaneous emission (SASE).

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]. See Fig. (1). Undulators placed in straight section 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 from the brightness of the x-ray tubes. The recognition of the power of the undulator radiation in studying the structure of atoms and molecules, and their arrangements in organic and inorganic materials, with 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.

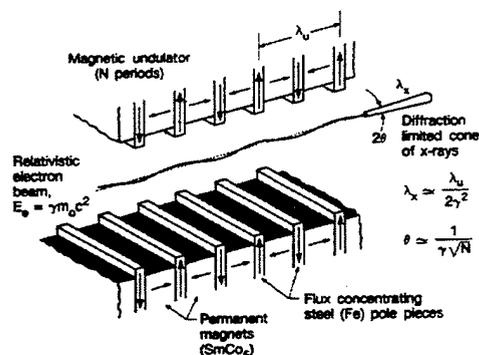


Figure 1. Schematic of a periodic magnetic structure (an undulator) of period λ_u and with a number of periods, N . The structure is based on permanent magnets.

The 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 $\epsilon_x \leq \lambda/4\pi$ [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 $\epsilon_x(\epsilon_y)$ is about $10^{-9}(10^{-11})$ m-rad. Therefore, the coherence condition is satisfied for UV radiation with the wavelength $\geq 100\text{\AA}$. Even for wavelengths down to tens of \AA 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 reason why the brightness of the third generation synchrotron radiation source is so high.

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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 the 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 the free-electron laser (FEL), produces highly coherent radiation beams of spectral brightness many orders of magnitude higher than that of the undulator radiation [6].

The advantage of the FELs over the conventional lasers is that the wavelength can be chosen arbitrarily if electron beams of suitable energy and beam brightness, and high reflectivity mirrors, were 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

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 been attracting much attention recently as the basis for the "fourth generation" light source is the fact that 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.

A. Exponential Growth and Saturation

Various performance characteristics of SASE can be expressed by a single dimensionless parameter ρ : the power

e-folding length (gain length) is about $1/4\pi\rho$ 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 the x-ray wavelengths in the range 10 to 1 Å, this requires the peak current of several kiloamps, the invariant emittance $\gamma\epsilon_x \leq 10^{-6}$ m-rad, where γ is the Lorentz factor, $\gamma \approx 2-3 \times 10^4$, and the energy spread $\Delta\gamma/\gamma \leq 10^{-3}$.

B. Temporal Coherence

The temporal coherence of SASE radiation at saturation is very similar to that of an undulator radiation of periods $N = 1/\rho$; 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 $\Delta\omega/\omega \sim \rho$, which 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 frequency domain or in time domain. In the case of the usual undulator radiation, the reduction factor is large, due to the long electron bunch and short radiation wavetrains. Therefore, the fluctuation is hardly observable. In case of SASE, the electron bunches are shorter and the radiation wavetrains longer, so that the intensity fluctuation could be 10-20%.

C. Transverse Coherence

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, the capabilities of which we already have emphasized, are all based on storage rings. However, we will see that linacs are better suited than storage rings for driving an 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 the 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 the high brightness storage rings for the 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. With the impedance control and the size of storage rings that appear reasonable and feasible at present, 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 became a very promising option for driving for SASE at x-ray wavelengths: the state-of-the-art RF gun technology could produce 1 nC electron bunches of invariance emittance $\epsilon_x \approx 10^{-6}$ 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, emittance $\epsilon_x \approx 0.3 \cdot 10^{-10}$ m-rad can be prepared, which are adequate for producing SASE radiation at $\geq 1 \text{ \AA}$ 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.

A. RF Photocathode Gun

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], causing 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.

B. Bunch Compression and Acceleration

The beam from the RF photocathode gun is normally about ten picoseconds long. It needs to be compressed by a factor of 100 to increase the peak current to the level of a few kA, and accelerated to 10-20 GeV to achieve the required gain in a reasonable length (about 100 m) of an SASE undulator for x-ray wavelength. Avoiding the emittance dilution due to the single particle effects (focusing mismatch, dispersive and chromatic effect, etc.), and due to the beam instabilities, is a non-trivial problem due to the small emittance, high current beam under consideration. The R&D on this topic was studied extensively both numerically as well as 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.

C. Long Undulator

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 need of the third generation synchrotron radiation facilities. The interruptions between the segments can be used for focusing the electron beam and for installing diagnostic equipment. All segments must be aligned to within a few microns of accuracy.

VII. SASE PROJECTS

A. Overview

Several experimental projects are either in progress or being planned in several laboratories around the world, some of which are listed in Fig. 2. As indicated in the figure, the proof-of-principle experiments for wavelengths longer than 1μ have already achieved a significant level of single pass gain. The experiments at APS [16] and DESY [17], at wavelength around 1000 Å, will be carried out within one to two years. Eventually the goal is to achieve SASE at x-ray wavelength, for which the only linac available to date is the SLAC linac.

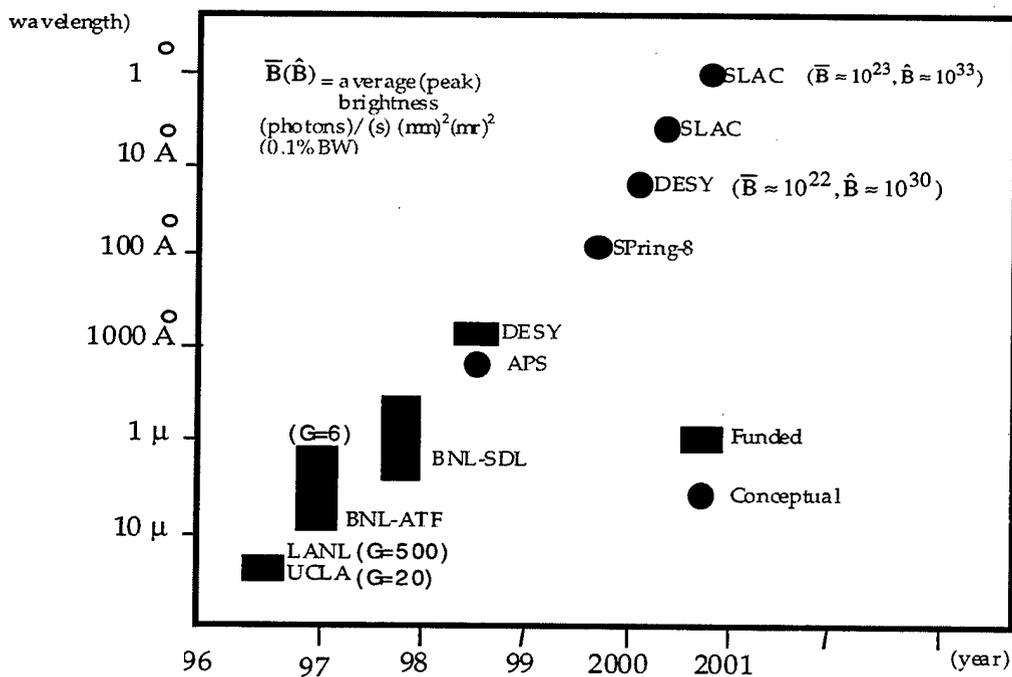


Figure 2. SASE projects around the world. The numbers within round brackets (G=) indicate the experimental gain observed recently.

B. LCLS

Fig. 3 shows the layout of the x-ray SASE project using the SLAC linac, called the Linear Coherent Light Source (Fig. 3) [3]. 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 Fig. 4, and that of the time averaged brightness of Fig. 5. 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 a hundred times shorter, thereby improving the time resolution by the same factor. The enhancement of the average brightness is less, due to the smaller repetition rate of the linac. However, the average spectral brightness of LCLS is still 3-4 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 planned at DESY [18].

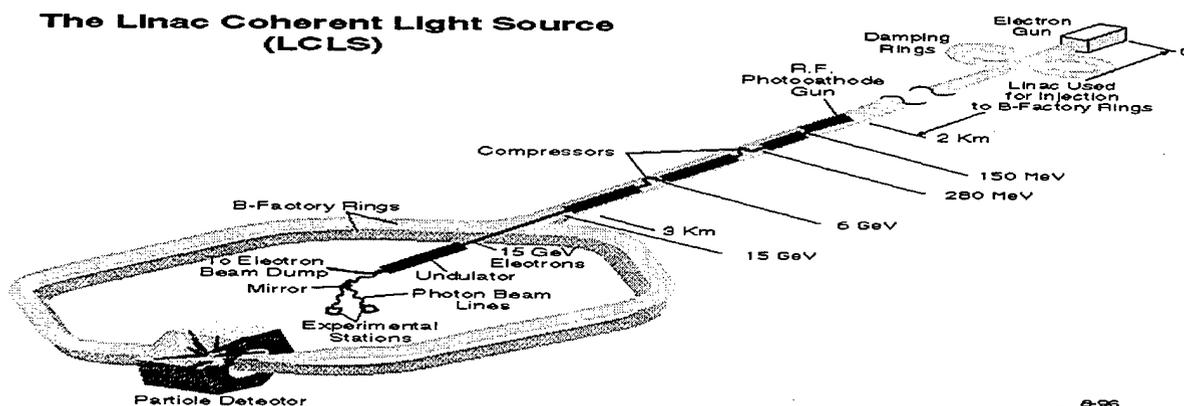


Figure 3. Layout of the LCLS.

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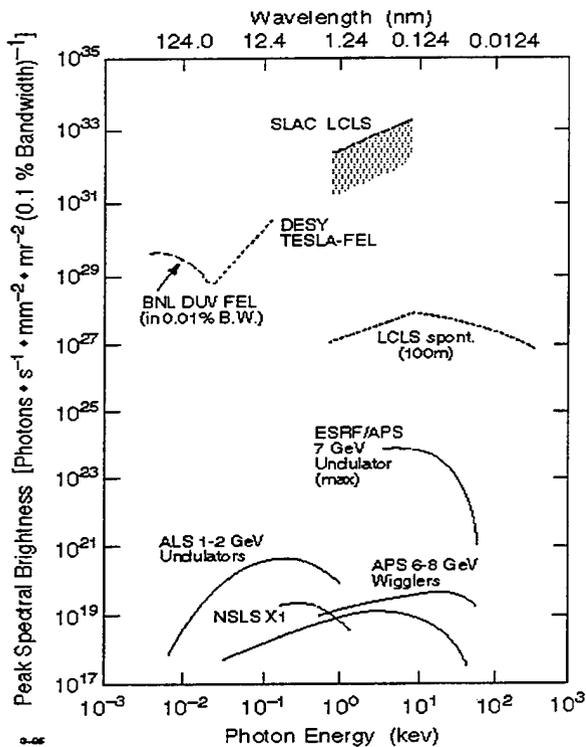


Figure 4. Peak spectral brightness

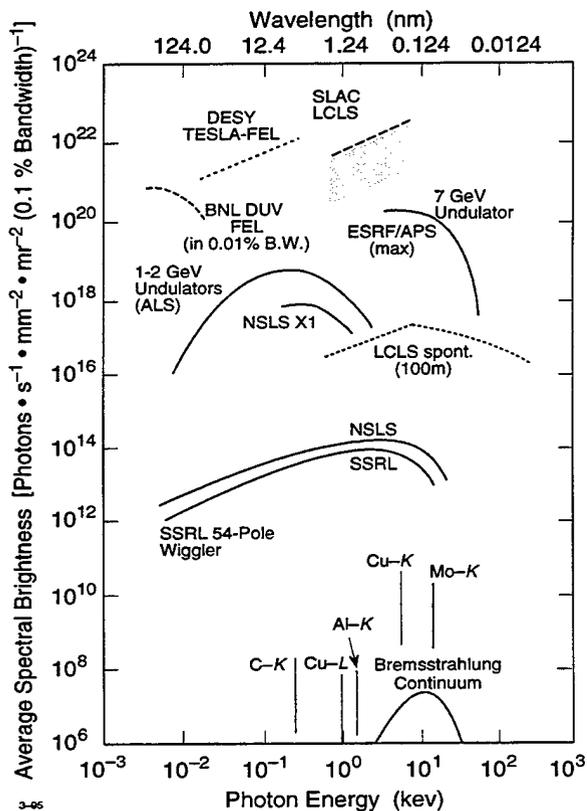


Figure 5. Average spectral brightness

VIII. SUMMARY AND CONCLUSION

In this article, we have discussed the principles of SASE, how the SASE could be the basis of next generation light sources exceeding the current performance—by many orders of magnitude in spectral brightness, and by a factor of a hundred in time resolution. We have also discussed how the SLAC linac, due to its high energy and its precision control, is ideally suited for the x-ray SASE. Therefore, using the SLAC linac for generation of x-ray SASE for the frontier of the photon sciences will ensure that the SLAC linac remain scientifically vigorous for a long time.

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