SASE BASED 4TH GENERATION LIGHT SOURCES AND THE LCLS PROJECT

M. Cornacchia#, Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, CA 94309

Abstract

Advances in the physics and technology of photoinjectors, linear accelerators, insertion devices and free-electron lasers make it now possible to generate coherent radiation in the x-ray region by means of the Self-Amplified-Spontaneous-Emission (SASE) process. This radiation has much higher brightness, shorter pulses and coherence than present 3rd generation sources. The status of the physics and technology involved in a radiation source based on SASE is reviewed, together with an overview of the main activities in this field around the world. The design status of a 1.5 Å SASE-FEL at SLAC, called the Linac Coherent Light Source (LCLS), is described.

1 INTRODUCTION

To the author's knowledge, the discourse on the next generation of light sources, what "next generation" might mean in terms of radiation properties, and on what electron source might best achieve them, started in earnest in 1992 at the first Workshop on 4th Generation Light Sources[1]. It was suggested then[2] that progress in electron sources and linear accelerators was making it possible to design and build an x-ray FEL based on Self-Amplified-Spontaneous-Emission. In 1996, a second workshop was held in Grenoble[3]. It was pointed out then[4] that the scientific opportunities in the future would require:

- Shorter light pulses (in the femtosecond regime)
- Transverse and temporal coherence
- Improvements in brighthess by many orders of magnitude

At the same workshop the upper limits of performance of 3rd generation sources were reviewed [5]. It appeared that the types of improvement that would lead to a new generation of light sources were difficult to achieve in a storage ring in the x-ray region. It was shown again [6] that a linear accelerator had the potential to provide the electron source capable of producing coherent light of extremely high brightness, fully transversely coherent and delivered in sub-picosecond pulses. More recently, the Basic Energy Sciences Advisory Committee of the US Department of Energy recognized the importance of x-ray free electron lasers with its report of the "Panel on Future, Coherent Light Sources"[7]. The report states that " Given currently available knowledge and limited funding resources, the hard x-ray region (8-20 keV or higher) is identified as the mos exciting potential area for innovative science. DOE should pursue the development of coherent light source technology in the hard X-ray region as a priority. This technology will most likely take the form of a linac-based free-electron laser device using self-amplified spontaneous emission or some form of seeded stimulated emission…"

2 PRINCIPLE OF OPERATION

At present, the SASE process is the most promising approach to reaching x-ray wavelengths with a free-electron laser. In the Self-Amplified-Spontaneous-Emission process the spontaneous radiation is amplified in the single pass of an electron beam through an undulator, and no mirrors are required. This is an essential requirement for x-ray FELs, since the reflectivity of mirrors decreases at wavelengths lower than ~2000 Å and optical resonators become impractical at short wavelengths. The FEL radiation is also easily tunable by changing the electron beam energy.

The physics of SASE [8] imposes four main conditions on the electron beam quality [9]:

a) For the electron beam transverse emittances, $\varepsilon \approx \lambda / 4\pi$ and λ is the FEL radiation wavelength.

b) For the energy spread, $\sigma_E / E < \rho$, where ρ is the FEL parameter = $\left[K\Omega_p f_b / (4\gamma\omega_u) \right]^{2/3}$, $\omega_u = 2\pi c / \lambda_u$ is the frequency associated to the undulator periodicity and $K = eB_u\lambda_u / (2\pi mc^2)$ (cgs units). $\Omega_p = \left(4\pi r_e c^2 n_e / \gamma \right)^{1/2}$ is the beam plasma frequency, n_e is the electron density, r_e is the classical electron radius and f_B is the Bessel function factor. B_u is the undulator peak magnetic field, mc^2 the electron's rest energy.

c) For the undulator length, $N_u\lambda_u \approx 10L_g$, where L_g is the field gain length, $L_g \approx \lambda_u / (2\pi\sqrt{3}\rho)$.

E-mail: cornacchia@ssrl.slac.stanford.edu

d) The radiation gain length must be shorter than the radiation Raleigh range, $L_g < L_R$, where $L_R = \pi w_0^2 / \lambda$ and w_0 is the radiation beam radius.

The condition indicates that the emittance of the electron beam scales like the wavelength, and therefore the condition becomes more demanding as the wavelength decreases. In the x-ray region (1.5 Å) the emittance must be of the order of 0.01π nm-rad in both planes. This is much smaller than anything achieved, or even achievable, in storage rings. Radio-frequency photoinjectors [10] on the other hands, have reached the stage where such emittances are obtainable. Once a bright electron beam is created, it must be preserved through the beam manipulation and acceleration phases in the linear accelerator. It is essential that transverse and longitudinal wakefields[11] and other effects (like the emission of coherent synchrotron radiation [12] in a bending section) do not appreciably reduce the electron beam brightness

Conditions c) and d) set a limit for the shortest length of the undulator that allows the FEL radiation to reach saturation. It is important that the device operates at saturation in order to minimize the fluctuations of the radiation output intensity.

3 THE EXPERIMENTAL EVIDENCE OF SASE AMPLIFICATION

The results of several experiments in recent years are providing confidence that the theory and the computations give a reliable description of the physics of SASE. The first experimental results on SASE were obtained in the microwave region[13], with gains of the order of 10^6-10^7. Over the last couple of years, experiments in the infrared and visible region obtained gains of one to two orders of magnitude[14] and, more recently, a gain of $3\text{x}10^5$ was obtained at 12 μm[15]. In this experiment the gain length and output power fluctuations were measured, giving results in very good agreement with theory and simulations.

Although these results are encouraging and provide already, together with the theory and the simulations, a solid basis for the SASE-FEL design, no experiment has yet reached the saturation regime, where the LCLS and other future facilities will operate. For this reason, more experiments are planned to further study the SASE-FEL physics at saturation and shorter wavelengths. An overview of these plans is given in the next section.

4 OVERVIEW OF SASE-FEL PLANNED EXPERIMENTS AND FACILITIES

A BNL-LANL-LLNL-SLAC-UCLA group is preparing a 0.6-0.8 μm experiment (VISA, Visible Infrared Sase Amplifier) that will use the high brightness electron beam of the Accelerator Test Facility at NSLS/BNL in 1999. A 4 m long undulator with distributed strong focusing has been built for this purpose. VISA will reach saturation and it will study the radiation time structure and angular distribution. Still at NSLS/BNL, the Source Development Laboratory plans to start late in 1999 a SASE demonstration experiment at 0.3 μm with its 210 MeV linac and photoinjector.

The ANL program makes use of the APS Injector Linac and the Low Energy Undulator Test Line (LEUTL). The initial plan is to start at 0.53 μm with a 218 MeV beam in 1999. This will show some gain, although not yet saturation. More undulators will be added in 1999 allowing the experiment to reach saturation. The time averaged brightness of this facility will be 10^{20} ph/(s mm^2 mr^2 0.1%) and the peak brightness 10^{28}.

At DESY, construction is underway for a 420 Å SASE-FEL that will use the TESLA Test Facility (TTF) superconducting linac (390 MeV), with first operation expected in 1999[16]. In phase 2[17], scheduled around 2003, the wavelength will reach down to 60 Å with an electron beam of 1 GeV. This phase is already approved. Ultimately, when the Linear Collider is built, the 25 GeV beam will be able to emit FEL radiation at 1 Å in a long undulator. Table 1 offers the brightness and flux (in the usual units) at the various stages.

Table 1

Projected performance of DESY FEL.

	Phase I	Phase II	X-ray FEL
Brightness	$4.3\text{x}10^{28}$	$2.2\text{x}10^{30}$	$9.7\text{x}10^{33}$
Flux	$1.0\text{x}10^{26}$	$1.0\text{x}10^{26}$	$3.3\text{x}10^{25}$

A SLAC-ANL-LANL-LLNL-UCLA collaboration is proposing to build a SASE-based free-electron laser operating in the wavelength range of 1.5-15 Å. This facility, LCLS (Linac Coherent Light Source) is to be based at SLAC and makes use of the last 1/3 of the SLAC Linac.

An overview of the design and performances is the subject of the rest of this report.

5 THE LINAC COHERENT LIGHT SOURCE

5.1 General layout

Fig. 2 shows the layout of the proposed facility. The hexagonal shape at the end of the linac is the PEP-II *B* Factory electron-positron collider that uses the first 2 km of the Linear Accelerator as the injector. The last 1 km of the linac will be used by the LCLS.

A new injector consisting of a gun and a short linac will be used to inject an electron beam into the last kilometer of the SLAC linac. With the addition of two stages of magnetic bunch compression, the electron beam exits the linac with an energy of 14.3 GeV, a peak current of 3,400 A, and a normalized emittance of 1.5π mm-mrad. A transfer line takes the beam and matches it to the entrance

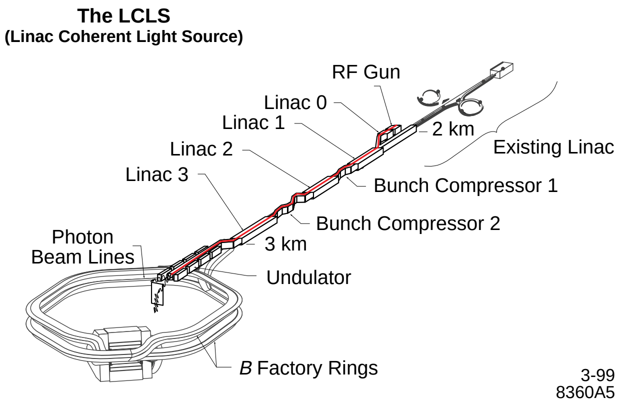

Figure 1. Layout of the Linac Coherent Light Source.

of the undulator. The 100 m long undulator will be installed in the tunnel that presently houses the Final Focus Test Beam (FFTB). After exiting the undulator, the electron beam is deflected onto a beam dump, while the photon beam enters the experimental areas.

5.2 Performance characteristics

The main parameters are shown in Table 2.

Table 2. Main LCLS parameters

Parameters	**Value**	**Units**
Electron Beam Energy	14.35	GeV
Emittance	1.5	π mm-mrad
Peak current	3,400	A
Energy spread (uncorrelated)	0.006	%, rms
Energy spread (correlated)	0.10	%, rms
Bunch length	67	fsec, rms
Undulator period	3	cm
Number of undulator periods	3,328	
Undulator magnetic length	99.8	m
Undulator field	1.32	Tesla
Undulator gap	6	mm
Undulator parameter, K	3.7	
FEL parameter, ρ	4.7×10^{-4}	
Field gain length	11.7	m
Repetition rate	120	Hz
Saturation peak power	9	GW
Peak brightness	1.2×10^{32} – $1.2\text{x}10^{33}$	Photons/(s mm^2 $mrad^2$ 0.1% bandwidth)
Average brightness	4.2×10^{21} – $4.2\text{x}10^{22}$	Photons/(s mm^2 $mrad^2$ 0.1% bandwidth)

Fig. 3 shows the average and peak brightness as a function of the photon energy for the LCLS and other operating facilities. It indicates that the peak brightness of the LCLS would be about ten orders of magnitude greater than currently achieved in 3rd generation sources.

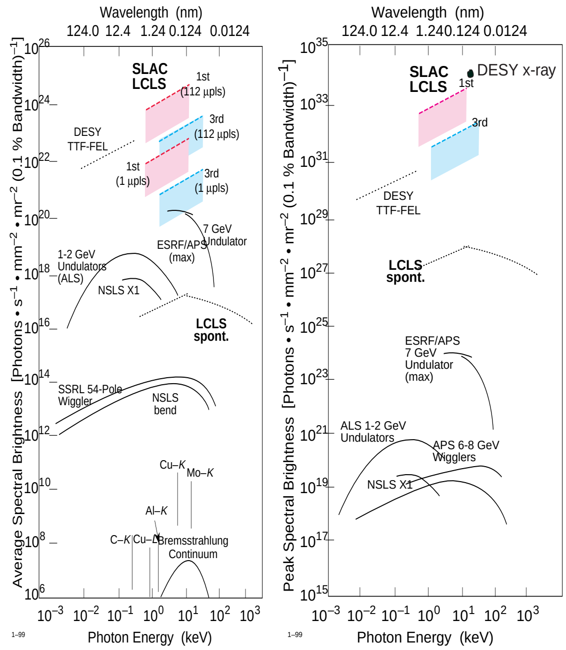

Figure 2. Average and peak brightness calculated for the LCLS and for other facilities, planned or under construction.

The sub-picosecond pulse length is two orders of magnitude shorter than can be achieved in a synchrotron. The FEL radiation has full transverse coherence. Longitudinally, the radiation is delivered in wave-trains[18]. The wave-trains are uncorrelated from each other. The longitudinal coherence is defined by the relative bandwidth of the wave-train, which, at saturation, is approximately $1/N_u \sim \rho = 4.7\text{x}10^{-4}$.

5.3 Components performance and R&D issues

In this section we review the main components of the LCLS and discuss their specifications.

5.3.1 The photoinjector

The rf photoinjector is required to produce bunches of ~ 1 nC charge and 10 ps long with a normalized rms transverse emittance (horizontal and vertical) of ~ 1 π mm-mrad. The design was developed by a BNL-SLAC-UCLA collaboration[19]. A performance (1.2 π mm-mrad with 0.8 nC) close to the design specification was measured at the Accelerator Test Facility[20]. The simulation code PARMELA predicts that the design emittance can be reached by appropriate transverse and longitudinal laser pulse shaping [21]. The research on laser pulse shaping is being conducted at the Gun Test Facility at SLAC.

5.3.2 Acceleration and compression

For operation at 1.5 Å an electron peak current of 3,400 A with a transverse emittance of 1.5 π at 14.3 GeV is required. With these parameters the length of the

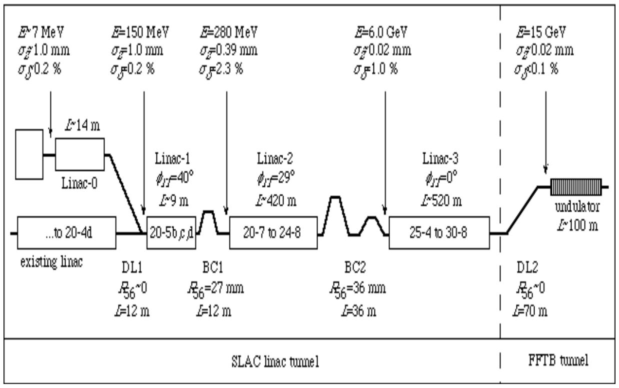

Figure 3. Layout of acceleration and compression systems

undulator that will give lasing with a comfortable margin for field errors and misalignments is ~ 112 m, which fits comfortably in the FFTB SLAC tunnel[22]. Since the photo-injector can produce 1 nC in 3 a ps long bunch, corresponding to a peak current of 100 A, the bunch has to be compressed 30 times to reach the peak current of 3,400 A required for lasing. The layout of the compression and acceleration is shown in Fig. 3.

The energy of the first compressor is 280 MeV, the lower limit being set by the need to minimize space charge effects at low energy, while the upper limit is set by the desire to compress the bunch early in the linac to ease transverse wake-fields. In the first compressor the bunch shrinks from 1 mm to 390 μm rms. After the second compressor the bunch length is only 20 μm. The energy of the second compressor, 6 GeV, is set by the conflicting requirements of longitudinal emittance dilution due to synchrotron radiation effects and longitudinal wake-fields. The second compressor (BC2) is asymmetric, with the last two dipoles having a weaker field to avoid the emittance blow up induced by the coherent synchrotron radiation emitted in the bends where the bunch is shortest [12]. Since the energy spread introduced by the coherent synchrotron radiation is correlated along the bunch, its effect on the transverse emittance is minimized by introducing a double chicane and optical symmetry to cancel the longitudinal-to-transverse coupling. With this scheme the simulations indicate that the emittance blow up due to coherent synchrotron radiation is of the order of 3-5 %.

5.3.3 The undulator

From the end of acceleration a transfer line transports the beam to the undulator.

After reviewing several possible magnet designs, a planar Halbach hybrid type was adopted, with a period of 30 cm and a fixed 6 mm magnetic gap. The poles are made of vanadium permendur, and the magnets that drive them will be made of NdFeB.

The undulator was optimized in terms of its focusing lattice and strength. The eletron optics consists of FODO cells, with a cell length of 4.32 m. Focusing is obtained by placing permanent magnet quadrupoles in the interruptions of the undulator sections. Each interruption is 23.5 cm long, and also includes beam position monitors and vacuum ports. It was found, theoretically [23] and through computer studies, that such interruptions are harmless to the FEL process.

The corrections to the electron orbit are obtained by a small lateral displacement of the quadrupoles; the total movement is 0.5 mm with a resolution of 1 μm. The electron beam trajectory is required to be straight to within 5 μm over a field gain length (11.7 m) to achieve adequate overlap between the electron and photon beams. The excellent resolution of monitors of choice (microwave type detectors), better than 1 μm, is not sufficient to satisfy the requirements for absolute orbit correction, since this requires the knowledge of the absolute position of the monitors with the same order of accuracy as the electron beam straightness. This absolute accuracy is not achievable with present mechanical alignment techniques. Fortunately, a beam based alignment method, already in use at the SLC and FFTB, offers a solution to this problem. The technique uses BPM readings as a function of large, deliberate variations in the electron energy. The measurements are analyzed and then converted to (a) quadrupole magnet transverse position corrections, (b) BPM offset corrections and (3) adjustments of the incoming beam position and angle at the undulator entrance. A detailed description of the method can be found in the LCLS Design Report [24]. The simulations that have been performed to verify the method include all conceivable errors of the BPMs and quadrupoles, and show that the absolute position of the trajectory can be made to be straight to within 5 μm with only two iterations.

5.3.4 The x-ray optics and experimental area

The coherent output of the LCLS features peak output powers in the 10 GW range, average powers of the order of 1 W, spectral bandwidth of the order of 0.1%, full transverse coherence and pulse lengths of approximately 300 fs. The total peak power of the spontaneous radiation is 80 GW, thus largely exceeding the power of the coherent FEL output. The peak on-axis power density of the spontaneous radiation is 10^{13} W/cm^2 (at 1.5 Å), approximately one hundred times smaller than that of the coherent line, which, due to its full transverse coherence can, in principle, be focused to an approximate limit of 10^{25} W/cm^2. In the present concept the Experimental Hall will consist, initially, of one crystal and one mirror beamline.

6 ACKNOWLEDGMENTS

The author wishes to thank all the colleagues with have contributed to the LCLS Design Study [25] and on whose work this paper is based.

This report was prepared for the Department of Energy under contract number DE-AC03-76SF00515 by Stanford Linear Accelerator Center, Stanford University, Stanford, California.

7 REFERENCES

[1] Workshop on Fourth Generation Light Sources, Feb. 24-27, 1992, M. Cornacchia and H. Winick Chairmen, SSRL report 92/02.

[2] Ibid., C. Pellegrini, "A 4 to 0.1 Å FEL Based on the SLAC Linac".

[3] 10th ICFA Beam Dynamics Workshop on 4th Generation Light Sources, Grenoble, Jan. 22-25, 1996.

[4] Ibid., I. Lindau, "Conclusions of Working Group on Scientific Opportunities for 4th Generation Light Sources VUV/Soft X-rays", p. 25.

[5] Ibid., M. Cornacchia, "Conclusions of Working Group on Lattice and Stability Aspects", pp. 41-48

[6] bid., C. Pellegrini, "Conclusions of Working Group on Linac Sources", pp. 57-66.

[7] Report of the Panel on Future, Coherent Light Sources, February 1999.

[8] R. Bonifacio, C. Pellegrini, and L. Narducci, Optics Comm. **50**, 373 (1984); K.-J. Kim, Nucl. Instr. and Meth. **A250**, 396 (1986); J.-M. Wang and L.-H. Yu, Nuclear Instruments and Methods **A250**, 484 (1986); G. T. Moore, Nuclear Instruments and Methods **A239**, 19 (1985); E. T. Scharlemann, A. M. Sessler, and J. S. Wurtele, Phys. Rev. Lett. **54,** 1925 (1985); M. Xie and D.A.G. Deacon, Nuclear Instruments and Methods **A250**, 426 (1986). K.-J. Kim, Phys. Rev. Lett. **57**, 1871 (1986); L.-H. Yu, S. Krinsky and R. Gluckstern, Phys. Rev. Lett. **64**, 3011 (1990).

[9] J.B. Murphy and C. Pellegrini, "Introduction to the Physics of the Free-Electron Laser", in *Laser Handbook*, Vol. 6, pp.9-70, W.B. Colson, C. Pellegrini and R. Renieri eds., North-Holland, 1990.

[10] R.L. Sheffield, "Photocathode rf guns" in *Physics of Particle Accelerators*, *AIP*, Vol. 184, pp.1500-1531, M. Month and M. Dienes, eds. (1992)

[11] See, for instance, K. Bane, "Wakefield effects in a Linear Collider", *AIP Conf. Proc.* Vol. 153, p.971 (1987).

[12] B.E.Carlsen and T.O. Raubenheimer, *Phys. Rev. E 51*: 1453 (1995); Ya. S. Darbenev et al., "Microbunch Radiative Head-Tail Interaction", *DESY Report*, Sep. 1995.

[13] T. Orzechowski et al., *Phys. Rev. Lett.* **54**, 889 (1985); D. Kirkpatrick, *Nucl. Instr. And Meth.* **A285**, 43 (1989); J. Gardelle, J. Labrouch and J.L. Rullier, *Phys. Rev. Lett.* **76**, 4532 (1996).

[14] R. Prazieres et al., *Phys. Rev. Lett.* **54**, 889 (1985); M. Hogan et al. *Phys. Rev. Lett.* **80**, 289 (1998); M. Babzien et al, *Proc. Of the 19th International Free Electron Laser Conference*, pp. V-267-270, North-Holland, 1998. D.C. Nguyen et al., *Phys. Rev. Lett.*, **81**, 4 (1998).

[15] M. Hogan et al., *Phys. Rev Lett.*

[16] W. Brefeld et al. *Nucl. Inst. And Meth. In Phys. Res.***A 393** 269.

[17] J. Rossbach, *Nucl. Inst. And Meth. In Phys. Res.***A 375** 119-124.

[18] R. Bonifacio et al., *Phys. Rev. Lett. 73*, p. 70 (1994).

[19] D.T. Palmer et al., SPIE 2522, 514 (1995)

[20] M. Babzien et al. *Phys. Rev. E*, **57**, 5 (1998).

[21] J.F. Schmerge et al.,"Photocathode rf gun emittance measurements using variable length laser pulses", Presented at SPIE Photonics West, LASE 99 - Free-Electron Laser Challenges II, San Jose, CA January 26-27, 1999, Proceedings of SPIE Vol.3614

[22] The magnetic length of the undulator is 99.8 m. The physical length, that includes the separations between segments, is 111.8 m.

[23] K.-J. Kim, "Undulator Interruption in High-Gain Free-Electron Lasers", LBNL report No. F6, August 1997.

[24] LCLS Design Study Report, SLAC Publication R-521 and UC-414, p. 8-43.

[25] For the complete list of collaborators, see the LCLS Design Report, SLAC-R-521, p.i.