THE PATH TOWARDS X-RAY FREE-ELECTRON LASERS*

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Abstract
The physics and technology of x-ray sources based on self-amplified-spontaneous-emission (SASE) are 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, the Linac Coherent Light Source (LCLS) is described.

1. PRINCIPLE OF OPERATION OF A SASE FEL

At present, the linac-based 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 ~1500 Å and optical resonators become impractical at short wavelengths. The FEL radiation is also easily tunable by changing the electron beam energy.

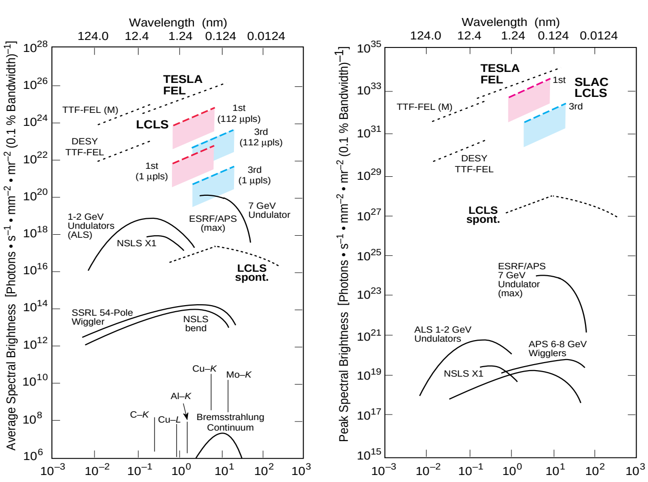

Figure 1. Average and peak brightness of the LCLS and TESLA compared with those of other operating facilities.

Figure 1 shows the average and peak brightness as a function of the photon energy for two proposed x-ray FELs: the Linac Coherent Light Source (LCLS, at SLAC) and TESLA (DESY), together with those of other operating radiation sources.

The chart indicates that the peak brightness of the LCLS and TESLA would be about ten orders of magnitude greater than currently achieved in 3rd generation sources.

The sub-picosecond duration of the FEL pulse will be two orders of magnitude shorter than what can be achieved in a synchrotron. The radiation has full transverse coherence and is delivered in wave-trains[1] that are uncorrelated from each other. The longitudinal coherence is defined by the relative bandwidth of the wave-train, which, at saturation, is approximately 1/number of undulator periods (4.7×10^{-4} in the LCLS).

The physics of SASE [2] demands a high quality of the electron beam [3]. **Table 1** shows the main electron beam parameters of the two most advanced, to the author's knowledge, x-ray free-electron laser designs, the LCLS and TESLA, and of state-of-the-art accelerators like the Stanford Linear Collider (SLC)[4] and the Final Focus Test Beam (FFTB)[5] at SLAC, and the Advanced Photon Source (APS)[6], the 3rd generation light source at Argonne National Laboratory. The table is meant to show higher electron beam brightness that is needed for x-ray free-electron lasers and the similarity between the parameters of the two proposed x-ray FELs. The latter is the result of thorough design and optimization studies.

With reference **Table 1**, the following comments apply:

- Multi-Gev energies for x-ray, linac-based, FELs are a consequence of the need for low emittance and for realistic lengths of the period of the undulator.
- The peak current in x-ray FELs is considerably higher than that at which linacs operate. The LCLS accelerates in a conventional (non-superconducting), S-band linac, whereas the TESLA facility plans to use a L-band superconducting linac. The high peak current is associated with a bunch that, in a x-ray FEL, is 1-2 orders of magnitude shorter than in more conventional sources and is dictated by the

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physics of SASE[2] that requires high current density for the radiation build-up to develop.

- The transverse emittance of the electron beam scales like the wavelength of the emitted radiation[3] and therefore the condition becomes more demanding as the wavelength decreases. In the x-ray region (~ 1 Å) the normalized emittance should not be much greater than 1 mm-mrad in both planes. This is much smaller than anything achievable in storage rings.
- The maximum allowed momentum spread is constrained to be smaller than the bandwidth of the fundamental FEL harmonic.

Table 1.
Electron beam characteristics of the proposed x-ray FELs (LCLS and TESLA), and of other state-of-the-art linear accelerators and of a 3rd generation source, the Advanced Photon Source.

	LCLS	TESLA	SLC	FFTB	APS*
Energy (GeV)	14.3	50	46	46	7
Charge/bunch (nC)	1	1	6	1	38
Peak current (A)	3,400	6,900	1,270	195	300
Normalized emittance (mm-mrad)	1.5 (Hor.& Ver.)	1.6 (Hor.& Ver.)	50/4 (Hor./ Ver)	50/0.7 (Hor./ Ver.)	110 (Hor.)
Bunch length (rms, fsec)	230	80	3700	2000	100,000
Momentum spread (uncorrelated)	0.03%	0.01%	0.16%	0.10%	0.10%

** In single bunch mode.*

The above requirements define the electron beam quality and determine the minimum undulator length (and the cost) required to achieve saturation and maximum FEL power. It is important that the device operates at saturation in order to minimize the fluctuations of the radiation output intensity.

The point of this discussion is to emphasize that x-ray free-electron lasers impose demanding requirements on the quality of the electron beam, in some cases threading over uncharted territories. In the next Section we will examine the status of the R&D and future plans that are needed to meet the requirements of an x-ray FEL.

2 THE EXPERIMENTAL EVIDENCE OF SASE AMPLIFICATION

The first experimental results on SASE were obtained in the microwave region[7], with gains of the order of 10^6-10^7. Early experiments in the infrared and visible region obtained gains of one to two orders of magnitude[8] and, a gain of $3\text{x}10^5$ was obtained at 12 μm[9]. In this experiment the gain length and output power fluctuations were measured, giving results in very good agreement with theory and simulations. More recently, a gain of 10^6 was measured at the TTF-FEL laboratory in DESY at 80-180 nm[10].

The LEUTL facility at the Advanced Photon Source (Argonne National Laboratory)[11] and the VISA experiment (a collaboration that includes BNL, LLNL, SLAC, UCLA)[12] at the Accelerator Test Facility at Brookhaven National Laboratory have both achieved high gain and saturation. The following **Table 2** illustrates some of the measured characteristics of the two experiments.

Table 2
Main parameters of the LEUTL and VISA experiments.

	LEUTL	*VISA*
Peak current (A)	184	250
Bunch length (rms, psec)	0.65	0.30
E^- energy (MeV)	255	71
Photon wavelength (nm)	385	840
Emittance (normalized, mm-mrad, rms, h/v)	7.1/7.1	4/0.8
Undulator length (m)	21.6	4.0
Gain	10^6	2×0^7
Gain length (measured, cm)	76	18.7
Gain length (predicted, cm)	80	19.2

One remarkable feature of these results, apart from the high gain, is the very good agreement of the gain length between theory, simulations and experiments. **Figure 2** illustrates the results of the measurements of the FEL energy along the undulator in the VISA experiments.

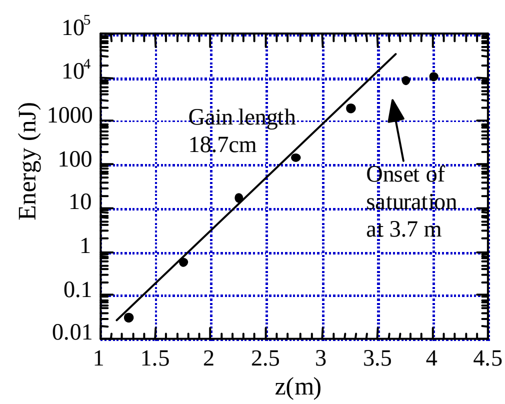

Figure 2. FEL radiation measured along the length of the VISA undulator.

Where then are we now? The theory and the simulations appear to be in good shape down to a wavelength of ~100 nm. Is this sufficient to guarantee the expectations at 0.1 nm? The community is optimistic in this regards, since no "new physics" is expected at these shorter wavelengths. Experiments and facilities at shorter wavelengths are being planned (outlined in Section 5) that will hopefully confirm the predictions.

3 THE ELECTRON SOURCE

The single most important parameter affecting performance and cost of a x-ray FEL is, arguably, the brightness of the electron source. The more the transverse emittance approaches the diffraction limited condition $\varepsilon \approx \lambda / 4\pi$, where λ is the FEL radiation wavelength, the higher the output power and the shorter the undulator length required to achieve saturation[3].
With present photo-injector technology, the design is to achieve a normalized emittance of ~ 1 mm-mrad with 1 nC (see **Table 1**). This goal appears achievable and is the basis of the LCLS and TESLA designs.
The measurements of emittance so far are tantalizingly close to the 1 mm-mrad with 1 nC of charge, without quite yet achieving it. An emittance of 2 mm-mrad at 1 nC was measured at TTF-FEL (DESY) with a 1.3 GHz rf gun[13]. In the S-band region, the most studied rf photo-cathode gun is a design developed by a BNL-SLAC-UCLA collaboration[14]. With this gun, the Accelerator Test Facility at NSLS/BNL reported measurements of emittance of 0.8 mm-mrad at 0.5 nC[15].The Gun Test Facility at SLAC reported the set of measurements shown in **Figure 3**[16].
The agreement between computations and measurements is generally good, with the exceptions of the two points in the short bunch case. The investigation is ongoing.

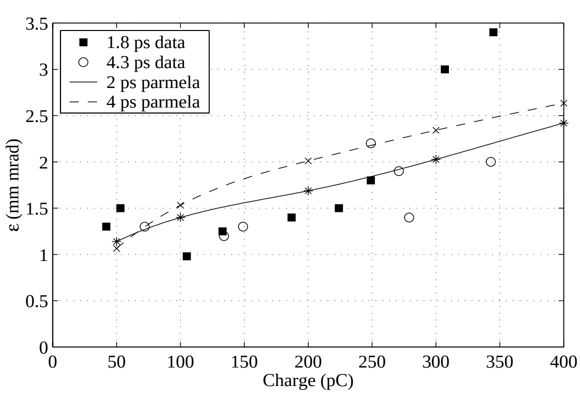

Figure 3. Normalized rms emittance vs. charge for 1.8-ps and 4.3-ps bunch length (fwhm). The lines show the results of simulations with the code PARMELA.

Summary of present status and future directions

At this stage, it is reasonable to expect that 1 mm-mrad with 1 nC will soon be achieved. This view is based on the following considerations:

- The measurements agree reasonably well with the simulations (PARMELA).
- All the measurements so far used an electron beam of approximately Gaussian temporal shape. The simulation code PARMELA predicts that a smaller emittance (the design emittance) can be reached by appropriate longitudinal laser pulse shaping [17].

4 THE PRESERVATION OF BEAM QUALITY DURING ACCELERATION AND COMPRESSION

A free-electron laser is only as good as its electron beam, therefore preserving the quality of the electron beam during acceleration and transport is of fundamental importance. **Table 1** shows that over 1,000 A have already been accelerated in the SLC, albeit with a large horizontal emittance. Only a 30% blow up of the (much smaller) vertical emittance, with a value close to that of LCLS, was observed in the SLC[5]. An even smaller vertical emittance was preserved during acceleration in the FFTB.
Wake-fields are generated by the electron beam interacting with the linac accelerating structure and the vacuum chamber of the undulator[18]: the former is of greater concern in conventional linac (LCLS) than in superconducting linac (TESLA), where different considerations apply. Wake-fields have been the subject of extensive studies over several years in the S-band SLAC linac[19], and its understanding provides a model for a reliable performance prediction with one caveat: the bunch length in the x-ray FEL will be much smaller than anything accelerated so far in s-band linacs, and there are questions as to whether the impedance model is still valid at these short bunches. Experiments planned at SLAC with the “Sub-Picosecond-Photon-Source”[20] will shed light on the impedance of sub-psec long bunches.
Based on the impedance model measured at SLAC, the predictions are that transverse and longitudinal wakefields will not appreciably degrade the transverse and longitudinal emittance of the electron beam in the LCLS[21].
The phenomenon known as “Coherent Syncrotron Radiation” (CSR) has received considerable attention and is considered one of the main threats to the preservation of the transverse emittance in bends. The theory[22] predicts that, as the bunch shortens in the bending field of a magnetic compressor, the radiation of wavelength of the order of the bunch length (thus coherent) emitted by the tail of the bunch can catch up with the head and change the momentum of the particle, causing the propagation of an oscillation for particles occupying a different position in the bunch. Particle tracking studies using *Elegant*[23] and *TraFiC4[24]* predict that, by using cancellation of the forces with a double-chicane compressor[25] the effect leads to only a few percent

emittance blow up in the LCLS. More recent simulations[26], however, predict a potentially destructive micro-bunching phenomenon which is under study. Experimental confirmation of the theory is just beginning. CSR experiments are being performed at CERN[27], Argonne National Laboratory (LEUTL laboratory)[28] and other institutions. It is expected that this effort will grow in several laboratories involved in both free-electron laser and linear collider studies.

5 OVERVIEW OF SASE-FEL PLANNED EXPERIMENTS AND FACILITIES

The two experiments discussed in the previous Section (LEUTL and VISA) were the first to achieve saturation of the radiation. At DESY, commissioning is underway for a 420 Å SASE-FEL that uses the TESLA Test Facility (TTF) superconducting linac (390 MeV) [29]. A gain greater than 10^5 was measured at 108 nm[30].

In phase 2[31], scheduled to be operational around 2003, the wavelength will reach down to 60 Å with an electron beam of 1 GeV. This phase is already approved. Ultimately, in conjunction with the Linear Collider, the 50 GeV beam will be able to emit FEL radiation at 1 Å in a long undulator.

At NSLS/BNL, the Source Development Laboratory is preparing a SASE experiment at 0.3 μm with its 210 MeV linac and photo-injector.

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)[21] is to be based at SLAC and makes use of the last 1/3 of the SLAC Linac. Its layout is shown in **Figure 4**.

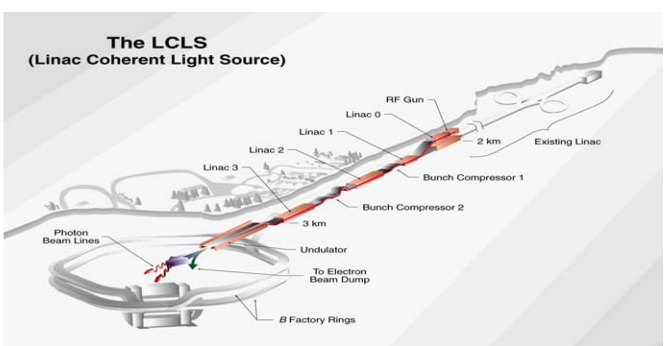

Figure 4. Layout of the Linac Coherent Light Source.

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 1.5 mm-mrad. The 120 m long undulator will be installed in the tunnel that presently houses the (FFTB). After exiting the undulator, the electron beam is deflected onto a beam dump, while the photon beam enters the experimental areas. The main parameters are shown in **Table 3**.

Table 3. Main LCLS parameters at 1.5 Å

Parameters	**Value**	**Units**
Electron energy	14.3	GeV
FEL radiation wavelengths	1.5	Å
Pulse length	230	fsec
Coherent photons/pulse	1.8×10^{12}	
Peak brightness	1.2×10^{33}	Photons/(s,mm^2,mrad^2,0.1%bw)
Average brightness	2.8×10^{21}	Photons/(s,mm^2,mrad^2,0.1%bw)

6 CONCLUSIONS

The technology of accelerators is now able to meet the requirements of a x-ray free-electron laser. While this paper focussed on the accelerator aspects, other components of the FEL technology (undulator, x-ray optics, experimental utilization) are also in an advanced stage of R&D.

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

2 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).

3 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.

4 P. Emma, “The Stanford Linear Collider”,, proceedings of the 1995 Particle Accelerator Conference, May 1-5, 1995, Dallas, TX, IEEE, 0-7803-3053.

5 The Final Focus Test Beam Collaboration, “Results from the Final Focus Test Beam”, presented by D. Burke at the European Particle Accelerator Conference, London (GB), June 27-July 1st, 1994.
6 Y.-C Chae et al.,”Measurement of the Longitudinal Microwave Instability in the APS Storage Ring”, presented at the 2001 Particle Accelerator Conference, Chicago, Ill., June 18-21, 2001.
7 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).
8 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).
9 M. Hogan et al., *Phys. Rev Lett. **80**, 289* (1998)
10 J. Rossbach, “New developments on free-electron lasers based on self-amplified-spontaneous-emission”, presented at the 2001 Particle Accelerator Conference, Chicago Ill. June 18-21, 2001.
11 S.V. Milton, et al., “Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser”, Science, Vol. 292, Issue 5524, 2037-2041, June 15, 2001. Published online 17 May 2001; 10.1126/science.1059955.
12 A. Tremaine et al.,” Characterization of an 800 nm SASE FEL at Saturation”, presented at the 2001 Free-Electron Laser Conference, Darmstadt, Germany, Aug. 20-24, 2001.
13 Ph. Piot, S. Schreiber, D. Sertore, K. Flöttmann, A. Cianchi, “Emittance Measurements at the TTF Photo-Injector”, presented at the Particle Accelerator Conference, Chicago, ILL., June 18-21, 2001.
14 D.T. Palmer et al., SPIE 2522, 514 (1995)
15 X.J. Wang, “Progress and Future Directions in Brightness Electron Beam Sources”, presented at the Particle Accelerator Conference, Chicago, ILL., June 18-21, 2001.
16 P.R. Bolton et al., “Transverse and longitudinal emittance measurements on an S-band photocathode rf electron gun”, presented at the 2001 Free-Electron Laser Conference, Darmstadt, Germany, Aug. 20-24, 2001.
17 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
18 G.V. Stupakov, “Surface Roughtness Impedance”, Proccedings of the 19th Advanced ICFA Beam Dynamics Workshop, “Arcidosso, Italy, 2000, AIP Conference Proceedings 581, pp141-152.
19 K. Bane and P. Wilson, *Proccedings of the 11th Int. Conf. on High Energy Accelerators,* CERN (Birkhuser Verlag, Basel, 1980), p. 592.
20 M. Cornacchia et al, “A Sub-Picosecond Pulse Facility for SLAC”, SLAC-PUB-8950.
21 LCLS Design Study Report, SLAC Publication R-521.
22 E.L. Saldin, E. A. Schneidmiller, M. V. Yurkov,” On the Coherent Radiation of an Electron Bunch Moving in an Arc of a Circle”, TESLA-FEL 96-14, Nov. 1996.
23 M. Borland, “ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulatioin”, LS-287, Argonne National Laboratory, Sept. 2000.
24 A. Kabel, M. Dohlus and T. Limberg, “Using TraFic[4] to Calculate and Minimize Emittance Growth due to CSR”, Nucl. Instrum. & Methods A **445**, 185, (2000).
25 P. Emma, R. Brinkmann, *1997 Part. Acc. Conf.*, Vancouver, BC, Canada, p. 1679.
26 M. Borland et al., “Start-to-End Jitter Simulations in the LCLS”, presented at the 2001 Particle Accelerator Conference, Chicago Ill. June 18-21, 2001.
27 H.H. Braun et al., “Recent Experiments on the Effect of Coherent Synchrotron Radiation on the Electron Beam of CTF II”, presented at the 2001 Particle Accelerator Conference, Chicago Ill. June 18-21, 2001.
28 M. Borland, et. al., “Initial Characterization of Coherent Synchrotron Radiation Effects in the Advanced Photon Source Bunch Compressor”, presented at the 2001 Particle Accelerator Conference, Chicago Ill. June 18-21, 2001.
29 W. Brefeld et al. *Nucl. Inst. And Meth. In Phys. Res.***A 393** 269.
30 J. Rossbach, “New developments on free-electron lasers based on self-amplified-spontaneous-emission”, presented at the 2001 Particle Accelerator Conference, Chicago Ill. June 18-21, 2001.
31 J. Rossbach, *Nucl. Inst. And Meth. In Phys. Res.***A 375** 119-124.