IS THE X-RAY FEL THE 4TH GENERATION LIGHT SOURCE?

C. Pellegrini

UCLA Physics Department

Los Angeles, California 90095

Abstract

Recent theoretical and experimental work has led to important advances in the physics of Self-Amplified Spontaneous Emission free-electron-lasers (SASE-FELs), and in the production of high brightness, high energy electron beams. This work has made possible the design and construction of X-ray FELs at a few to 0.1 nm. The X-ray FEL has the characteristics required for a "4th Generation Light Source": diffraction limited radiation, subpicosecond pulse length, peak and average brightness largely exceeding that of 3rd generation sources. We review the status of SASE-FELs, and of the X-ray FEL projects.

1. INTRODUCTION

Presenting the conclusions of the working group on X-rays at the "4th Generation Light Sources Workshop", held at Grenoble in 1996, the chairman, J. Als-Nielsen, made a "Wish List for 4th Generation Sources"[1]. He listed: lower emittance, shorter pulses, higher average brightness, much higher peak brightness, circular polarization, tunability from 0.15 to 0.05nm, multiple beams, fundable construction and operational cost. His final conclusion was: " [The] Hard X-ray group [is] unanimously excited about the FEL project as a 4th generation light source".

	3rd Gen.	FEL	3rd Gen.	FEL
Wavelength, nm	100-10		1-0.1	
Emittance, nm rad	4	0.2	2	0.05
Pulse length, ps	30-100	1	15-30	0.06
Average brightness	10^{18}	10^{22}-10^{24}	10^{20}	10^{22}-10^{25}
Peak brightness	10^{20}	10^{30}	10^{23}	10^{33}
Peak power	1	10^9	10^3	10^{10}

Table 1. Typical characteristics of undulator radiation from 3rd generation light sources, and FELs. The emittance is in nm rad; the pulse length in ps; the brightness in photons/s/mm^2/mrad^2/0.1%bandwidth; the power in W. The range in brightness corresponds to room temperature or superconducting linacs.

The reason for this interest can be seen in Table 1, where we compare the typical performance of a 3rd generation source and a FEL, showing that the FEL satisfies most of the "wish list" requests. Much progress has been made from that workshop to make the X-ray FEL a reality. New electron guns have produced higher brightness beams. The SASE-FEL theory has been verified in recent experiments at infrared and visible

wavelength. More experiments, extending the verification to the visible and UV regions, are scheduled for the next one to two years. A SLAC-LLNL-LANL-UCLA collaboration has proposed the construction in the period 2002-5 of the Linear Coherent Light Source (LCLS), a SASE-FEL, based on the SLAC linac.

Electron beam	
Electron energy, GeV	14.3
Emittance, nm rad	0.05
Peak current, kA	3.4
Energy spread, %	0.02
Bunch length, fs	67
Undulator	
Period, cm	3
Field, T	1.32
K	3.7
Gap, mm	6
Total length, m	100
Radiation	
Wavelength, nm	0.15
FEL parameter, ρ	5×10^{-4}
Field gain length, m	11.7
Bunches/sec	120
Average brightness	4×10^{22}
Peak brightness	10^{33}
Peak power, GW	10^9
Intensity fluctuations, %	8

Table 2. LCLS characteristics, at a beam energy of 14.3 GeV. Energy spread, pulse length, emittance are rms values. Brightness is in the same units of Table 1. The energy spread is the local energy spread within 2π cooperation lengths. A correlated energy chirp of 0.1% is also present along the bunch.

The main characteristics of LCLS are given in Table 2, for beam energy of 14.3 GeV, and a first harmonic of 0.15nm. The first harmonic is tunable from 0.15 to 1.5nm, changing the energy from 14.3 to 5 GeV. LCLS generates also a third harmonic, about two order of magnitude smaller than the first, extending its wavelength to 0.05nm.

2. SASE-FELs

A FEL can amplify the coherent spontaneous radiation emitted in the initial part of an undulator (SASE-FEL). For a long undulator the intensity grows exponentially along the undulator, until it attains a saturation value. Since it does not use an optical cavity,

which has large losses at short wavelength, a SASE-FEL can be operated at any wavelength, and is tunable.

The first papers proposing a SASE-FEL to generate coherent X-rays were written in the 1980s [3,4]. It was soon realized that the beam properties needed to achieve this goal were, at that time, beyond the state of the art. The best beams available from storage rings would limit the wavelength to about 50nm [5].

The development of photoinjector electron guns changed the situation, and made possible to consider a linac based SASE-FEL for soft X-rays [6]. The work on linear colliders demonstrated the possibility of accelerating electron beams to tens of GeV, with an emittance as low as 10^{-11}m rad and peak currents of several kA. These advances in beam physics and technology, and the theoretical developments on SASE-FELs [7], opened new possibilities. A proposal to use the SLAC linac to build a SASE-FEL at a wavelength of 4 to 0.1nm was presented at the first workshop on 4th Generation Light Sources held at SLAC in 1992 [8]. A study group with physicists from SLAC, LBNL, UCLA, and other institutions, developed this idea in the following years.

Starting in 1995 a program to develop SASE-FELs using superconducting accelerator was initiated at DESY [9]. The work at SLAC and DESY was discussed in workshops at Grenoble and KEK in 1996, and Argonne in 1997, confirming the interest in X-ray FELs.

The initial study group at SLAC was followed by the LCLS design group, a SLAC, UCLA, LLNL, LANL, LBNL, ESRF, Rochester, Milan, DESY collaboration. The LCLS design report has been recently reviewed, and the review committee has endorsed the feasibility of LCLS, if the FEL physics, demonstrated in the infrared and visible, is valid also at shorter wavelengths.

2.1 SASE-FEL physics

An electron beam, passing through an undulator of period λ_u and parameter K, produces spontaneous radiation with wavelength $\lambda = \lambda_u (1+K^2/2)/2\gamma^2$, where γ is the energy in rest mass units. The interaction of the beam with its own spontaneous radiation leads to a collective instability, and an exponential growth of the intensity along the undulator axis, z. For an undulator long compared to the gain length, L_G, the radiation intensity is given by [7]

$$I=(I_0/9)\exp(2z/L_G), \qquad (1)$$

I_0 being the coherent spontaneous radiation intensity for an undulator of length L_G. The gain length is approximately

$$L_G=\lambda_u/2\sqrt{3}\pi\rho, \qquad (2)$$

where ρ, the FEL parameter, is proportional to the beam plasma frequency to the power 2/3, or $(Q/\sigma^2L)^{1/3}$, Q

being the electron bunch charge, σ its radius, and L its length. Saturation occurs after about $10L_G$, and the intensity at saturation is about ρ times the beam energy.

The spontaneous radiation intensity from many electrons, I_0, is proportional to the square of the bunching factor

$$B_0=\Sigma_k\exp(2\pi iz_{0k}/\lambda), \qquad (3)$$

where z_{0k} is the electron position within the bunch when the bunch enters the undulator. If the electrons have a uniform longitudinal distribution the bunching factor is zero. If the bunch length is much smaller than λ, the bunching factor is approximately equal to the number of electrons, and the intensity is proportional to the square of the electron number. This regime is called coherent spontaneous emission. For the case of interest to us, a beam produced from a photocathode and a bunch length much larger than λ, the bunching factor is a random number with zero average, and the average of the square, $<|B_0|^2>$, equal to the number of electrons in the bunch. In this case the spontaneous radiation intensity fluctuates from pulse to pulse, and its average value is proportional to the charge in the bunch.

The fluctuation level is associated to the time structure of the radiation pulse. In the simple case of spontaneous radiation the intensity changes in each pulse slice one wavelength long, and is proportional to the local random bunching factor. However, as the beam and the radiation propagate through the undulator, the radiation moves ahead of the electrons by one wavelength per undulator period, an effect called slippage. In a long undulator the radiation generated by a slice interacts with the electrons in front and drives them to produce more radiation, thus establishing a correlation between the fields emitted by the electrons within one cooperation length,

$$L_c=(L_G/\lambda_u)\lambda, \qquad (4)$$

a distance equal to the slippage in one gain length [10]. The result is to generate a series of spikes about $2\pi L_c$ long, with an amplitude changing randomly between zero and a maximum value. The number of spikes is M= bunch length/$2\pi L_c$. Since the intensity in each spike is independent from that of other spikes the standard deviation of the intensity distribution is $1/\sqrt{M}$ [10]. The length of the spikes determines also the line width of the radiation, which at the undulator exit is about $1/N_u$.

The time structure and intensity fluctuations are important for X-ray FEL applications. The time structure can be changed filtering it with a monochromator. It has also been proposed [11] to modify the time structure and intensity fluctuations by splitting the undulator in two parts and inserting optical elements between them, to filter the radiation and increase the spike length.

Diffraction, energy spread, σ_E, and slippage can increase the gain length over the value (2) if the conditions $\epsilon<\lambda/4\pi$, $\sigma_E<\rho$, $\lambda N_u <L$, $Z_R>L_G$ are not

satisfied, where ε is the beam emittance, N_u the total number of undulator periods, and Z_R the radiation Rayleigh range.

2.2 Experimental results on SASE-FELs

Experimental results on SASE-FELs have been obtained in the microwave region [12], with gain of the order of 10^6-10^7. Recent experiments in the infrared, and visible obtained gains of one to two orders of magnitude [13]. The largest gain to date in the infrared, 3×10^5 at 12μm, was obtained in an experiment with a 2m long, hundred period, undulator [14].

The results of this last experiment are shown in figures 1, 2, and 3. Figure 1 shows an increase in output intensity by more than 10^4, when changing the charge in the electron bunch by a factor of seven, for fixed undulator length. The bunch radius, energy spread, and length also change with the charge, making impossible to have a simple analytical model to evaluate the intensity. To compare the results with theory we use the simulation code Ginger [15], where we can input the measured values of all bunch parameters. The results from Ginger, together with the measured intensities, are plotted in figure 2. Within experimental errors there is agreement between the theory and the data.

The gain length can be evaluated directly from the ratio of the measured intensity to the spontaneous radiation intensity, and also from the Ginger simulation. The two results agree, giving a gain length of about
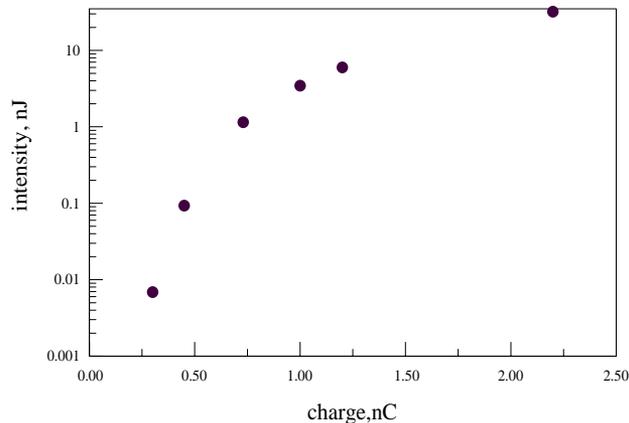
25cm.

Fig. 1 Experimental results from the UCLA-LANL-RRIK experiment at 12μm, showing the increase in intensity versus charge, for a constant undulator length.

Direct observation of the time structure is difficult because the typical length of the spikes in the infrared region is below one picosecond. It is instead possible to observe the intensity fluctuations. The fluctuations have been observed before for a short undulator, with no FEL gain [16] and for SASE radiation in the infrared [13]. In figure 3 we show the distribution of intensity in the UCLA-LANL-RRIK experiment. The theory predicts a

standard deviation of about 33%, in agreement with the experimental results. Figure 3 shows also a fit to the distribution with the theoretical prediction of a Gamma function with M=9.

2.3 Next generation experiments

More experiments are being prepared to further test the SASE-FEL physics, extending it to shorter wavelength. A BNL-LANL-LLNL-SLAC-UCLA group is preparing a 0.8-0.6μm experiment, using a 4m long undulator with distributed strong focusing quadrupoles, to reach saturation and study the radiation time structure, and angular distribution. Another BNL group is studying SASE and harmonic generation in the infrared to visible region.

A DESY group is preparing a SASE-FEL experiment using the TESLA Test Facility superconducting linac. The Phase 1 experiment will be done in 1999 at 390 MeV, and a wavelength of 42nm. Phase 2, scheduled for 2002, will have a linac energy of 1000 MeV, wavelength of 6nm, undulator length of 30m. The ultimate goal is a X-ray FEL in conjunction with the TESLA linear collider.

An Argonne group is preparing an experiment using the APS injector, energy of 220-444 MeV, wavelength 500-20nm, an 18m long undulator. Similar experimental programs on SASE-FELs are being prepared also in Japan, at Spring8 and other laboratories, and in China.

A SLAC-LANL-LLNL-UCLA group has proposed to build the LCLS, with construction starting in 2002.

3. A X-ray SASE-FEL

We discuss in this section some of the main technical and physical issues of an X-ray SASE-FEL, following closely the LCLS design report [2].

3.1 Electron Beam Acceleration and Compression

The LCLS electron beam parameters at the undulator entrance are given in Table 2. The electron beam is produced in a photoinjector gun, and accelerated and compressed in the S-band SLAC linac. The LCLS electron gun is a photoinjector developed by a BNL-SLAC-UCLA collaboration [17] and tested at the Brookhaven ATF linac [18]. The gun design characteristics are: charge, 1nC/ bunch; normalized emittance, rms, 1mm mrad; pulse length, rms, 3.3 ps. The results of measurements at the ATF at 1nC are: normalized emittance, rms, 2 mm mrad; peak current, 200A. These values have been measured using a laser pulse on the photocathode with a uniform radial distribution, and a Gaussian longitudinal distribution. Theoretical calculations show a reduction in emittance by a factor of two using a laser pulse with a longitudinal flat top.

It is also important to notice that the FEL gain depends on the local value of the emittance over a length of the order of the cooperation length, which for the X-

ray case is less than 1/100 of the bunch length. The measurements at the ATF [18] have shown that a 1ps long bunch slice has an emittance of about 1mm mrad, compared with a total projected emittance twice as large.

The bunch from the gun is accelerated to 14.3 GeV, and compressed to produce a final peak current of 3400A. During acceleration and compression the transverse and longitudinal phase-space densities are increased by space charge, longitudinal and transverse wakefields, RF-curvature, coherent synchrotron radiation effects. These effects must be kept under control to obtain the beam needed at the undulator entrance. The requirements to minimize one or the other of these effects are often in contrast. The acceleration and compression system has been designed to minimize all these effects simultaneously.
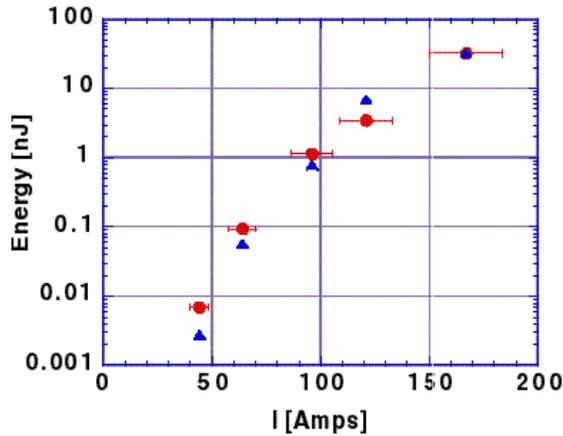

Fig. 2 Plot of measured FEL average intensity, circles, and Ginger simulations, triangles.

The compression is done in two steps. The first compression, reducing the bunch length by a factor 2.5 at 280 MeV, is done at the lowest energy possible to limit transverse wakefield effects, while minimizing space charge effects. The second compression, reducing the bunch length by 20, is done at 6 GeV to minimize synchrotron radiation effects and longitudinal wakefields. Since the energy spread generated by coherent synchrotron radiation is correlated along the bunch, its effect on the transverse emittance is compensated by using a double compressor and symmetrical beam optics to cancel longitudinal to transverse coupling. The emittance growth in the double compressor is limited to 3-5%.

The effects of misalignments of the LCLS linac structures have been simulated, using realistic values for the misalignments, correction techniques, and wakefields. The results show an emittance dilution of about 10%.

The emittance and energy spread are also sensitive to phase and charge jitters of the bunch. To avoid phase-space dilution the pulse to pulse RF-phase jitter is about 0.8 ps,

and the charge fluctuations jitter tolerance is 1%. These values are tight but within the present state of the art.

3.2 Undulator

A planar hybrid undulator has been chosen for LCLS because of the experience in building this type of undulators. The undulator must satisfy many criteria. To minimize the gain length the undulator parameter is large, K=3.7, requiring a strong magnetic field on axis, and a small gap. The undulator is built in sections 1.92m long, separated by 23.5cm straight sections. The poles are vanadium permendur, and the magnets NdFeB.

The natural undulator focusing is weak at the LCLS energy. Additional focusing is provided by permanent magnet quadrupoles located in the straight sections. Optimum gain is obtained for a horizontal and vertical beta function of 18m, giving a betatron wavelength of the same order of the undulator length. With this beta function the transverse beam radius in the undulator is 30 μm, and the radiation Rayleigh range 20m, twice the field gain length. With these parameters diffraction is small, and the straight sections in the undulator give only a small gain reduction.

The beam position monitors and vacuum ports are also located in the same straight sections.
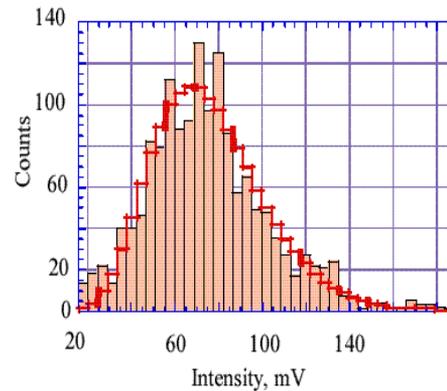

Fig. 3. Measured FEL intensity distribution, together with a plot of a Gamma function distribution with M=9.

The FEL gain is sensitive to errors in the undulator magnetic field, and to deviation in the beam trajectory. Simulations of these effects, including beam position monitors and steering magnets at many stations along the undulator to correct the trajectory, show that the field error tolerance is 0.1%, and the beam trajectory error tolerance is about 5 μm. Both values can be obtained in the LCLS undulator.

3.3. Radiation Properties and optical elements

The 100m long LCLS undulator generates coherent radiation at a wavelength between 1.5 and 0.15 nm and its harmonics. It also generates incoherent radiation, which, at 14.3 GeV, has a spectrum extending to about

500 keV, and a peak power density on axis of 10^{13}W/cm^2. For the same beam energy the power density of the coherent first harmonic at the undulator exit is about 2×10^{14}W/cm^2, and the peak electric field is about 4×10^{10}V/m. Filtering and focusing the radiation and transporting it to the experimental areas is a challenge. A normal incidence mirror at 100m would see an energy flux of about 1J/cm^2, corresponding to a deposited energy of 1eV/atom, large enough to damage exposed materials. To avoid this problem LCLS will use mirrors at extreme grazing incidence. To keep the absorbed energy density below the damage threshold the mirror surface must be polished to a roughness of a few Angstrom, and kept free of contamination. For crystal optics it seems convenient to use low Z materials like diamond and beryllium.

The LCLS large power density will push the optical elements and instrumentation into a new strong field regime, but offers also new opportunities for physics. As an example consider focusing the diffraction limited X-ray beam to a focus with a radius of 0.3nm. The electric field at the focus is 3×10^{15}V/m, or 0.3% of the Schwinger critical field. A field this large can "boil the vacuum", i.e. produce a large number of electron-positron pairs from vacuum fluctuations [19]. This is only one example of the strongly non-linear physics that will be made accessible by the LCLS.

4. Conclusions

The possibility of large amplification of the spontaneous undulator radiation has been demonstrated in the recent SASE-FELs experiments in the infrared and visible. These results, and the progress in the production, acceleration, measurements, and control of high brightness electron beams, and in the construction of high quality undulators, have opened the way to build a X-ray SASE-FEL in the 0.1nm region, a Fourth Generation Light Source, at the beginning of the next century.

Acknowledgments

References

[1] J. Als-Nielsen, "Scientific Opportunities for 4th generation Light Sources, Hard X-rays", in Proc. of the Workshop on 4th Generation Light Sources, ESRF Report, Grenoble, 1996.

[2] LCLS Design Study Report, Report SLAC-R-521, (1998).

[3] A.M. Kondratenko, and E.L. Saldin, Particle Accelerators **10**, 207 (1980); Ya. S. Derbenev, A.M. Kondratenko, and E.L. Saldin, Nuclear Instruments and Methods **A193**, 415 (1982).

[4]. J.B. Murphy and C. Pellegrini, Nuclear Instruments and Methods **A237**, 159 (1985); J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am., **B2**, 259 (1985).

[5] M. Cornacchia et al., Nuclear Instruments and Methods **A250**, 57 (1986);

[6] C. Pellegrini, Nucl. Instr. and Meth. **A272**, 364 (1988)

[7] 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).

[8] C. Pellegrini, "A 4 to 0.1 nm SASE-FEL Based on the SLAC Linac", in Proc. of the Workshop on Fourth Generation Light Sources, SSRL Report 92/02, M. Cornacchia and H. Winick, eds., p. 364 (1992); K.-J. Kim, ibid. p. 315; W. Barletta, A. Sessler and L. Yu, ibid, p.376.

[9] J. Rossbach et al., Nucl. Instr. and Meth. **A375**, 269 (1997); "Conceptual Design of a 500GeV Linear Collider with Integrated X-ray Laser Facility", DESY 1997-048.

[10] R. Bonifacio, et al, Phys. Rev. Lett. **73**, 70 (1994); E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, "Statistical properties of Radiation from VUV and X-ray Free Electron Laser", DESY rep. TESLA-FEL 97-02, (1997).

[11] J. Feldhaus et., Optics Comm. **140**, 341 (1997).

[12] 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).

[13] R. Prazeres et al., Phys. Rev. Lett. **78**, 2124 (1997); M. Hogan et al. Phys. Rev. Lett. 80, 289 (1998); M. Babzien, et al., "Observation of Self-Amplified Spontaneous Emission in the Near-Infrared and Visible", To be published in Phys. Rev. E; D. C. Nguyen et al., "Self Amplified Spontaneous Emission Driven by a High-brightness Electron Beam", in course of publication in Phys. Rev. Lett.

[14] M. Hogan et al., "Measurements of Gain Larger than 10^5 in a SASE-FEL", submitted to Phys. Rev. Lett.

[15] W. M. Fawley, Private Communication.

[16] M.C. Teich, T. Tanabe, T.C. Marshall and J. Galayda, Phys. Rev. Lett. **65**, 3393 (1990).

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

[18] V. Yakimenko et al. "Emittance control of the photoelectron beam using transverse laser shape modulation and tomographic techniques", presented at this conference.

[19] P. Chen and C. Pellegrini, private communication