The Stanford XFEL Project-LCLS

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Abstract

In this paper we describe the plans at Stanford University for an x-ray free-electron laser based on the last kilometer, 15 GeV, of the SLAC linear accelerator. The technical requirements are summarized as well as the novel scientific opportunities with this fourth generation source. It is concluded that with the present research and development efforts under way it should be possible to start the construction of such a facility in 2002 with a completion date in 2005.

1. Introduction

In 1992 a workshop was held at Stanford on the 4th Generation Light Sources [1]. At this workshop C. Pellegrini suggested [2] that with progress in electron sources and linear accelerators it should be possible to design and build an x-ray FEL based self-amplified-spontaneous-emission (SASE). In 1996 a second workshop was held in Grenoble [3] where the upper limits of performance of 3 rd generation sources were reviewed and prospects for future sources were discussed. It was concluded that a linear accelerator had the potential to go beyond what is possible with storage ring technology, namely: 1. provide x-ray pulses in the femtosecond time-regime; 2. give fully transversely coherent radiation; 3. Improve the brightness with several orders of magnitude. A technical design study for such a source was undertaken at Stanford and a report was published in April 1998 [4]. The report concluded that it is technically feasible to build such a source, named the Linac Coherent Light Source (LCLS). In February 1999 a Department of Energy panel [5] changed with setting priorities in the area of novel coherent light sources endorsed the LCLS concept and recommended research and development funding. This was provided by the Department of Energy in April 1999. This paper gives a short review of the status of the LCLS project and some potential scientific applications.

2. Principle of operation

A free-electron laser relies on the interaction between a high-energy electron beam and an electromagnetic field to produce coherent amplification of the field. This interaction is achieved by a periodic magnetic field (an undulator) which causes the electron beam to undulate and produce synchrotron radiation. Proper phase matching between the electromagnetic field and the electron beam and the oscillatory motion of the electrons will lead to longitudinal bunching of the electron beam. The bunching produces a stronger field which leads to further bunching until saturation is reached. This is the Self-Amplified-Spontaneous-Emission (SASE) process.

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 [6] imposes four main conditions on the electron beam quality [7].

a) the electron beam transverse emittance must not be much larger than the wavelength of the FEL radiation;

b) the electron beam energy must be small to give a sufficiently narrow line width to the spontaneous undulator radiation peaks;

c) the FEL power gain length must be short enough so that the increase in radiation intensity along the undulator is not lost due to diffraction spreading;

d) the electron pulse length must be longer than the FEL radiation wavetrain that is produced from it.

A strict description of these conditions can be found in ref. [4]. These conditions are demanding but recent technical advances in photocahode guns, emittance control in linaes and undulator technology provide confidence that an x-ray FEL can be built.

3. Status of SASE

The heart of the LCLS approach is the SASE concept.

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 [8], 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 [9] and, more recently, a gain of $3x10^5$ was obtained at 12 μm[10]. 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.

Presently there are three major efforts under way to demonstrate SASE at shorter wavelengths. An LCLS collaborative effort (VISA) is taking place at Brookhaven for experiments at 0.6-0.8 μm. 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 angula distribution. Still at NSLS/BNL, the Source Development Laboratory plans to start late in 1999 SASE demonstration experiment at 0.3 μm with its 210 MeV linac and photoinjector at Argonne. A 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. This will show some gain, although not yet saturation. More undulators will be added allowing the experiment to reach saturation.

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 late 1999 or early 2000[11]. In phase 2[12], scheduled around 2003, the wavelength will reach down to 60 Å with an electron beam of 1 GeV. This phase is already approved.

4. The Linac Coherent Light Source

4.1 The layout of LCLS

Fig. 1 shows the layout of the proposed LCLS at Stanford. 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 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 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.

4.2 The radiation characteristics

The radiation from the SASE x-ray FEL will have unprecedented peak brightness, about 10 orders of magnitude greater than today's brightest synchrotron radiation sources, see fig. 2. The coherence properties will also be spectacular, about 10^9 photons (degeneracy parameter) in the coherence volume. The length of the x-ray pulse is 230 fs, about two orders of magnitude shorter than in a state-of-the-art storage ring. Table I summarizes the calculated characteristics of the LCLS radiation. It is noteworthy that there are 10^{12} photons7pulse (and 10^{14} photons/second). In addition to the FEL radiation, an intense, broadband pulse of spontaneous radiation will be produced (see fig. 3). Though it does not have the coherence it will be very useful because of the broad wavelength region and femtosecond time-structure. Above 100 keV its average brightness will exceed any other radiation source.

4.3 The main components and their performance characteristics

We summarize briefly the performance characteristics of the key components of LCLS. Further details can be found in ref. [4]. 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 [13]. A performance (1.2 Π mm-mrad with 0.8 nC) close to the design specification was measured at the Accelerator Test Facility [14]. The simulation code PARMELA predicts that the design emittance can be reached by appropriate transverse and longitudinal laser pulse shaping [15]. The research on laser pulse shaping is presently ongoing.

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 undulator that will give lasing with a comfortable margin for field errors and misalignments is ~ 112 m. 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. 1. 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. 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.

From the end of acceleration a transfer line transports the beam to the undulator. A planar magnet of the Halbach hybrid type has been adopted, with a period of 30 mm 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 electron 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 of the undulator sections. Each interruption is 23.5 cm long, and also includes beam position monitors and vacuum ports. It was found, theoretically [16] 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.

This absolute accuracy is not achievable with present mechanical alignment techniques. A beam based alignment method, offers a solution to this problem. The technique uses BPM readings as a function of large, deliberate variation in the electron energy. The measurements are analyzed and then converted to (a) quadrupole magnet transverse position corrections, 8b) 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.

The peak coherent power is 9 GW, the peak coherent power density 10^{14} W/cm^2, and the peak power of spontaneous emission 80 GW. These kinds of power levels will put very stringent conditions on the x-ray optics in the experimental area. Development of novel x-ray optical elements is also an important part of the R & D plans. After the x-ray beam exits the undulator it will pass through an absorption cell so that the power levels can be adjusted to the appropriate levels for the optics and the sample.

5. Scientific Applications

The third generation synchrotron radiation sources based on storage rings have been exceedingly successful and are now serving a large user community. Their rôles will not be replaced by the x-ray FEL but the two types of sources will be complementary. Some applications are quite forward to predict for the x-ray FEL. Classes of experiments now ongoing would benefit from the higher average and/or peak brightness offered by the x-ray FEL. But the x-ray FEL will open up new areas of research because of its unprecedented properties of coherence and time-structure. And there will certainly be many experiments that have not been conceived at the present – the increase in performance characteristics of the x-ray FEL is just mind-boggling.

The possible scientific applications cover a broad range of fields from fundamental quantum mechanics, atomic and molecular physics, plasma physics, chemical physics, condensed matter physics and structural biology. Here we just provide a few selected examples and refer to three recent workshops for more details [17-19].

The time-structure, subpicoseconds, opens up new areas in pump-probe experiments, e.g. dynamical structure determinations on the femtosecond timescale or the time-evaluation of the electronic/structural properties of an excited state. Even though most dynamical time scales of interest in biological systems are typically microseconds or longer there are a number of phenomena (e.g. photosynthetic reactions, light sensors) that require femtosecond time-resolution in combination with structure determination. The opportunity to extract information from a single x-ray pulse gives the tantalizing approach to follow the formation or breaking of chemical bonds with atomic resolution on the relevant time-scale, namely femtoseconds. Recently, there has been much interest about the possibility to image noncrystalline biomolecular fragments, nanostructures or even single biomolecules (see the contribution by J. Hajdu in ref. 19). If this works out it would revolutionize the possibilities for structure determinations. One large class of experiments that can take advantage of the x-ray FEL are these involving x-ray photon correlation spectroscopy (a spectroscopy used in the long wavelength regime for a long time based on conventional lasers). The length scale can be reduced to atomic dimensions and a variety of problems in statistical physics (e.g. phase transitions and their dynamics) can be addressed. By its very nature the x-ray FEL would be ideally suited to study nonlinear phenomena, in particular in the field of core atomic electrons that is completed unexplored at the present but of great importance for, for instance, plasma physics. Finally, it is interesting to note that very fundamental questions in quantum electrodynamics can be addressed. The focussed x-ray beam would have enough intensity to ”boil” the vacuum, i.e. to create electron-position pairs.

6. Concluding Remarks

In this paper we have reviewed the technical feasibility to construct an x-ray free-electron laser at Stanford and the potential scientific applications, based on a 15 GeV section of the SLAC Linear accelerator and a 100 m long undulator. Research and development efforts are presently under way and it is anticipated that a proposal to construct this facility, the Linace Coherent Light Source, can be submitted in 2002. If funded the facility would be completed in 2005 and opened to the scientific community.

Acknowledgments

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TABLE 1. Calculated characteristics of the LCLS radiation.

Parameter	Value	Unit
FEL wavelength	1.5	Å
FEL bandwidth ($\delta E/E$)	0.002	
Pulse duration (FWHM)	233	fs
Pulse length (FWHM)	67	μm
Peak coherent power	9	GW
Peak coherent power density	1.5×10^{14}	W/cm^2
FEL energy/pulse	2.6	mJ
Peak brightness	1.2×10^{33}	flux/(mm^2 mrad^2 0.1% BW)
FEL photons/pulse	$2. \times 10^{12}$	
FEL photons/second	2.4×10^{14}	
Degeneracy parameter	3.3×10^{9}	
Peak EM field (unfocused)	3.4×10^{10}	V/m
Average FEL power	0.31	W
Average FEL brightness	4.2×10^{22}	flux/(mm^2 mrad^2 0.1% BW)
Transverse size of FEL beam	78	μm (FWHM)
Divergence of FEL beam	1	μrad (FWHM)
Peak power of spontaneous radiation	81	GW

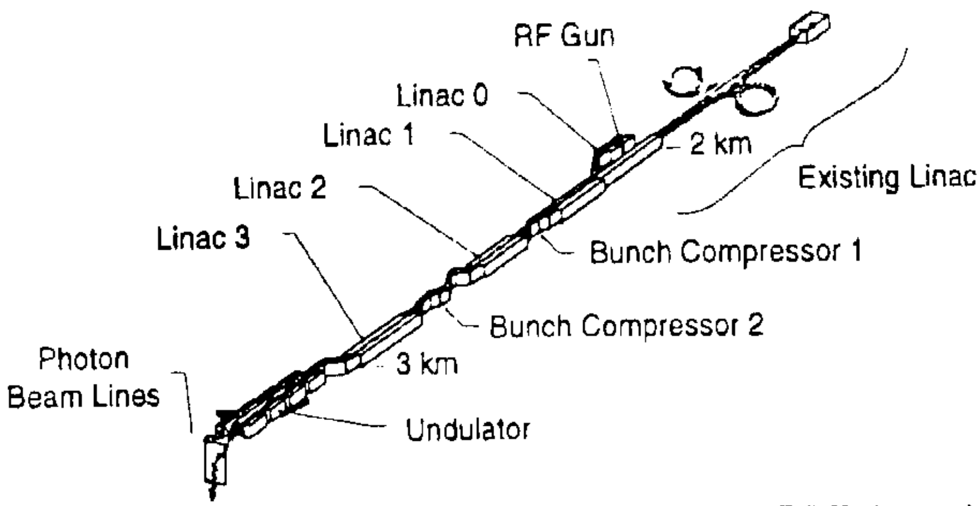

FIGURE 1. The Linac Coherent Light Source (LCLS), a proposed SASE FEL that would utilize one third of the 3-km linac at the Stanford Linear Accelerator Center. An RF photocathode electron gun would be added, along with electron bunch compressors and a 100 m undulator. The design FEL radiation wavelength is 1.5 Å.

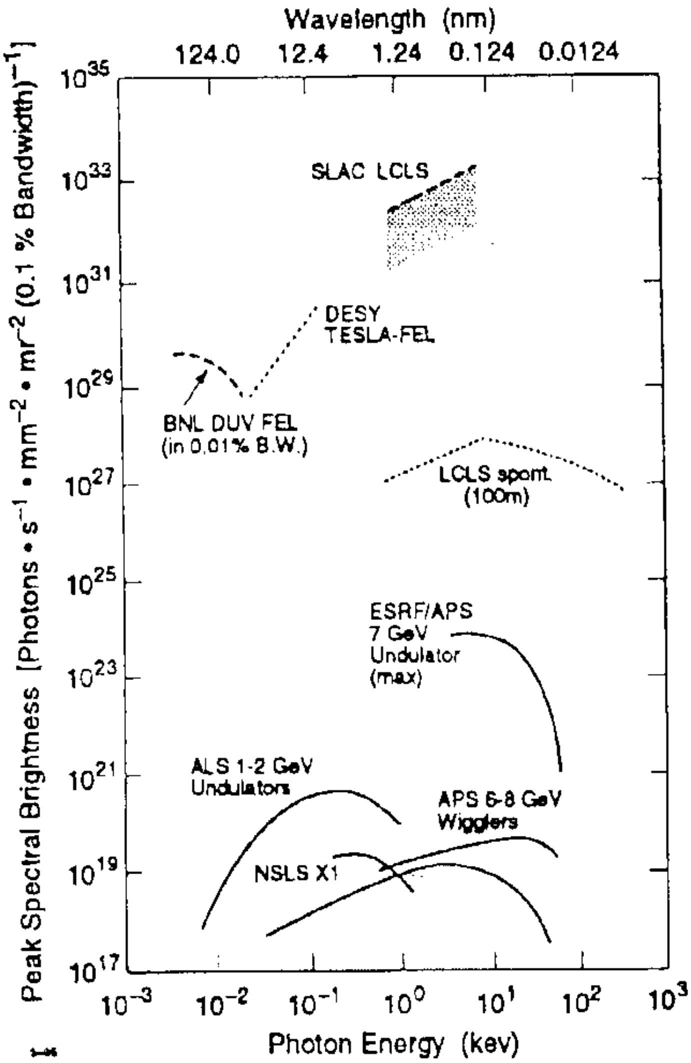

FIGURE 2. A comparison of the peak spectral brightness (photon density in phase space) of several hard and soft x-ray sources. The top curves all apply to FEL sources that are either proposed or under construction. These curves represent calculated values (the shading around the LCLS curve indicates an estimated range of uncertainty, allowing for possible errors in the electron optics). The curves at the bottom apply to existing synchrotron sources, but they are also calculated values incorporating expected future improvements in brightness. One curve in the middle shows the expected peak brightness of the spontaneous (non-FEL) radiation from an x-ray FEL source.

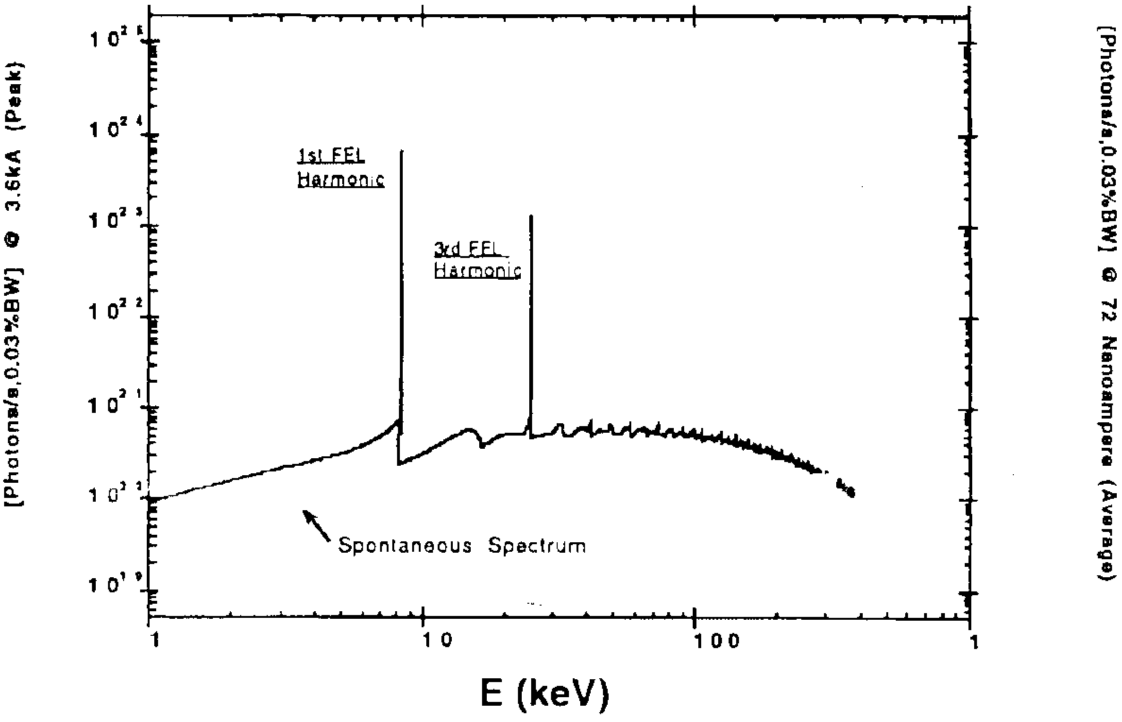

FIGURE 3. Calculated spectrum for the LCLS, a SASE FEL source. The FEL fundamental wavelength is 1.5 Å. FEL amplification is also possible at the third harmonic wavelength, though the gain is much less than for the fundamental, and may be suppressed by errors in the electron beam alignment.