THE LINAC COHERENT LIGHT SOURCE PROJECT*

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Abstract

The Linac Coherent Light Source Project will make use of the last kilometer of the SLAC Linac to create the world's first "hard" x-ray laser. A high-brightness photocathode gun and 150 MeV pre-accelerator will be installed in an alcove adjoining the main linac tunnel. It will provide 1 nanocoulomb electron bunches at 120 Hz. The main linac will be modified to incorporate two chicane bunch compressors. Electron bunches with 230 fsec FWHM duration and 3400 ampere peak current will be delivered to the enclosure presently housing the Final Focus Test Beam Facility. These electron bunches will pass through a 122-meter undulator channel, producing a burst of coherent x-rays with peak brightness ten orders of magnitude higher than is presently available from the brightest third-generation storage ring sources. This extraordinary brightness and coherence is the result of the "self-amplified spontaneous emission" (SASE) process. The LCLS Project will include x-ray optics, diagnostics and beamline facilities in two experiment halls, respectively located 40 meters and 322 meters from the source of x-rays. The LCLS will be constructed by a collaboration of US laboratories: Argonne National Labs, Lawrence Livermore National Lab, and SLAC. A conceptual design has been completed and funds for a more complete design are expected in October 2002. The Project completion date is September 2008.

1. X-RAY FREE-ELECTRON LASERS

1.1 Self-Amplified Spontaneous Emission

Synchrotron radiation[1] is emitted by energetic electrons as they are deflected by a magnetic field. The power spectrum of the radiation is proportional to the square of the acceleration of the electrons. If the electrons are made to move on a sinusoidal trajectory by an undulator magnet, the resultant synchrotron radiation spectrum will have power concentrated in a relatively narrow range of wavelengths. Undulator magnets generally have alternating north and south poles separated by 1 - 3 centimeters. Electrons passing through an undulator produce radiation that is Doppler shifted to much shorter wavelength:

$$\lambda = \lambda_u \cdot \frac{\left(1 + K^2/2\right)}{2\gamma^2} \qquad (1)$$

here $K=0.934B_o\lambda_u$ where B_o the peak magnetic field of the undulator (in Tesla) and λ_u is the undulator period (in centimeters). In a free-electron laser (FEL), a relativistic electron beam is subject to an additional deflection from a co-propagating electromagnetic wave. The combined interaction can result in an exchange of energy between the electrons and electromagnetic field and consequently a bunching of the electron current with a period equal to the radiation wavelength. These Angstrom-scale bunches emit synchrotron radiation coherently, as if they were single electrons with the charge of the entire bunch. In this way a high-gain FEL can amplify an electromagnetic signal from an external source. *Self-amplified spontaneous emission* (SASE)[2] is a process in which a bright, high-current electron beam amplifies its own spontaneous synchrotron radiation to megawatt or gigawatt levels in a single pass through an undulator. A SASE FEL will produce pulses of x-rays with unprecedented power and brightness in the 1Å wavelength range. An x-ray free-electron laser will outperform existing light sources by ten orders of magnitude in peak brightness, and many orders of magnitude in average brightness. X-ray FELs will also produce extremely short pulses of radiation, in the 10-100 femtosecond range.

1.2 Research With X-Ray FELs

The extraordinary brightness and short pulse duration of an x-ray laser will make it possible[3] to investigate structural changes in molecules in the process of forming or breaking atomic bonds; such phenomena take place in times of the order 10-200 fsec, and can be initiated in a sample by a short-pulse conventional laser. The x-ray FEL pulse, arriving at the sample with a known time delay, can be used to measure interatomic distances as they change on femtosecond time scales. The high peak power of an x-ray FEL make it possible to create exotic excited states of atoms, or plasmas in a state thought to exist in the centers of jovian planets and brown dwarf stars, but previously impossible to create in the laboratory. The full transverse coherence and enhanced temporal coherence of an x-ray laser pulse will likely create experiment opportunities that are fundamental departures from present-day synchrotron radiation technique.

The first efforts to exploit the unique characteristics of radiation from SASE FELs have begun in the past year[4], using light in the 140 nm – 90 nm wavelength range from the TESLA Test Facility FEL. Two proposals for the construction of SASE FEL user facilities in the 0.1 nm wavelength range have reached an advanced stage of development: the TESLA XFEL Laboratory[5] at DESY

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and the Linac Coherent Light Source at the Stanford Linear Accelerator Center[6].

2. THE LCLS PROJECT

2.1 Time Line

The feasibility of using facilities at the Stanford Linear Accelerator Center (SLAC) to build an x-ray laser first received widespread attention at the 1992 Workshop on Fourth Generation Light Sources, held at SLAC[7]. A study group was formed at SLAC to develop the concept further. This group expanded to become a collaboration of five institutions: University of California – Los Angeles (UCLA), Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and Argonne National Laboratory (ANL). A design study report was published in 1998[8], setting the main features of the LCLS configuration. Research funds were provided by the U.S. Department of Energy (DOE) in 1999, leading to the publication of the LCLS Conceptual Design Report, the basis of a construction project proposal submitted to DOE in April 2002. It is expected that DOE will provide funds to begin the engineering design of the LCLS in October 2002. Project acquisition activities will begin with long-lead procurements in 2005. Civil construction funds are requested for 2006. Based on the requested funding profile, commissioning of electron beam systems would begin in late 2006, and laser commissioning would begin in late 2007. The final phase of the LCLS project, construction and commissioning of experimental facilities infrastructure, will be completed in 2008.

2.2 Project Description

The LCLS will make use of several existing facilities at the Stanford Linear Accelerator Center:

- The last kilometer of the SLAC linac
- The off-axis injector vault at the 2/3 point along the linac
- The Final Focus Test Beam (FFTB) tunnel

The principal LCLS Project construction activities are:

- Addition of a 150 MeV linac with a high-brightness photocathode electron gun in the off-axis injector vault
- Addition of two chicane bunch compressor stages at the 250 MeV and 4.5 GeV points in the LCLS linac
- Replacement of the contents of the Final Focus Test Beam tunnel with a 122 meter long transport line incorporating 33 undulator magnet modules, each 3.4 meters long
- Extension of the FFTB tunnel and installation of x-ray transport and beam handling systems leading to the Near Hall x-ray experimental area, to be constructed 60 meters from the output end of the undulator channel
- Construction of a pass-through tunnel for the x-ray beam, leading to the Far Hall x-ray experimental area, to be constructed 322 meters from the end of the undulator magnet.

X-ray parameters	**Low Energy**	**High Energy**
X-ray energy	0.8 keV	8 keV
FEL fundamental saturation power	17 GW	8 GW
Slice rms bandwidth	0.24%	0.06%
pulse rms bandwidth	0.47%	0.13%
FEL photons/pulse	2.9×10^{13}	1×10^{12}
Peak Brightness†	6×10^{31}	8×10^{32}
Electron parameters	**Low Energy**	**High Energy**
Electron energy	4.5 GeV	14.3 GeV
Normalized slice emittance	1.2 mm.rad	1.2 mm.mrad
Peak current	3,400 A	3,400 A
FWHM bunch length	230 fsec	230 fsec
Slice energy spread	0.025%	0.01%
Gain length	1.3 meters	4.4 meters
FEL fundamental saturation power	17 GW	8 GW
Pulse repetition rate	120 Hz	120 Hz
†photons/(sec mm^2 mrad^2 0.1%BW)		

Table 1. Selected LCLS parameters

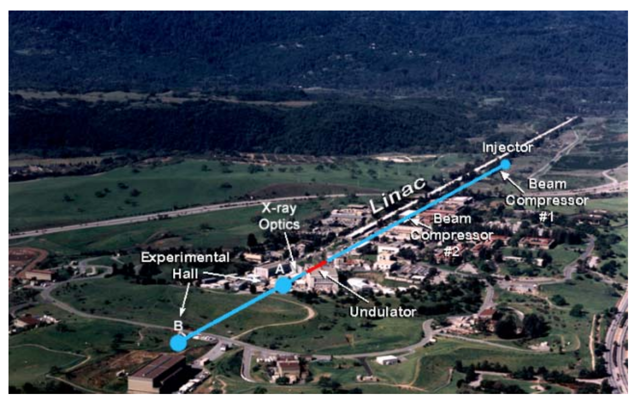

Figure 1. Placement of the LCLS on the SLAC site.

LCLS operation will be compatible with the shared use of the linac for injection to the PEP-II B Factory, or delivery of 30 GeV electrons to an experimental endstation for high energy physics research. The LCLS will be designed to permit restoration of 50 GeV capability to the linac during a 24-hour maintenance period.

The LCLS Project scope also includes six shielded experiment endstations, computer systems and other infrastructure necessary to support the LCLS x-ray research program in the future. Prototype x-ray optics to filter, monochromatize, focus, and attenuate the x-ray beam will be constructed as part of the Project so that, when the laser is operational, the characteristics of the x-ray beam as a research tool can be verified.

3. PHYSICS AND TECHNOLOGY CHALLENGES

3.1 The Notion of "Slice" Properties of the Electron Beam

The SASE process comes about as a result of a prolonged interaction between a high current electron beam and the synchrotron radiation it emits as it travels along an undulator. In order that this process develop rapidly and proceed to the point of *saturation* (full bunching of the electron beam on the nanometer length scale), the electron beam must satisfy rather stringent conditions of emittance, peak current, and energy spread. It is important to note, however, that these conditions need be satisfied by a small longitudinal "slice" of the electron beam as it interacts with a corresponding "slice" of synchrotron radiation which are causally connected as the bunching process evolves. The SASE process evolves as an exponential growth of a random "shot noise" fluctuation in spontaneous synchrotron radiation power. The rate of growth is characterized by a *gain length* L_g, about 5 meters for the LCLS. Since LCLS undulators have a period of 3 centimeters, there are about 167 undulator periods in one gain length. Therefore an electron will emit 167 x-ray wavefronts in one gain length. As an electron travels a distance of one undulator period, its synchrotron radiation travels further by one x-ray wavelength, or 0.15 nanometers for the short-wavelength end of the LCLS operating range. The SASE process is an interaction of electrons at a given point in the bunch with the synchrotron radiation field as it overtakes them. As an electron travels a distance of one gain length, only the radiation originating within a 167 x 0.15 = 250 nanometer segment following the electron can participate in the interaction. For this reason the electron beam parameters averaged over a "slice" (of order 0.5 micron in the case of LCLS), such as the *slice energy spread* and the *slice emittance* determine whether the SASE process can begin. The SASE process begins independently within many longitudinal slices of the electron bunch. *Saturation* or maximum bunching is realized in about 20 gain lengths, a distance over which synchrotron radiation emitted at the start of the undulator can only overtake electrons about 5 microns away within the bunch.

3.2 SASE Requirements for the Electron Beam

The properties of the electron beam prerequisite for lasing may be understood intuitively as conditions that promote a sustained interaction between the electron beam and its own synchrotron radiation[9]. To bring about a strong coherent motion of the electrons, it is desirable that the phase of the electromagnetic radiation be constant across the transverse phase space area of the electron beam. The spontaneous synchrotron radiation that seeds the SASE process has the necessary coherence only within a small area in the transverse phase space of the light beam:

$$\varepsilon_r = \lambda/4\pi \qquad (2)$$

where λ is the radiation wavelength. Therefore the transverse emittances $\varepsilon_{x,y}$ of the electron beam should be of this order. This sets an upper limit on the normalized emittances of the electron beam, $\varepsilon_{x,y}/\gamma$, which must be satisfied at the electron gun and preserved throughout the acceleration and bunch compression process. The LCLS design goal for the normalized *slice* emittances of the electron beam is $(\varepsilon_{x,y}/\gamma)\leq 1.2$ mm-mrad. The diameter of the electron beam can be controlled by quadrupoles, whereas the spontaneous synchrotron radiation forms a diverging cone around the electron beam. In order that the spontaneous radiation be amplified in the SASE process, the amplification must take place before the light has diverged appreciably. Thus the gain length L_g must be of the order of, or less than, the *Rayleigh length* L_r of the radiation:

$$L_g \sim L_r = 2\pi\sigma_r^2/\lambda \qquad (3)$$

where σ_r is the rms radius of the SASE radiation spot. Since the electron beam can be steered away from the photon beam by error fields in the undulator and other magnets, tight tolerances on field quality must be maintained as well.

Finally it is necessary that the energy spread of the electrons must be small enough to promote formation of microbunches in the electron beam at the early stages of SASE. Light emitted by different electrons must add coherently in the course of traveling one gain length, or N= L_g/λ_u undulator periods. Intuition suggests that if light from different electrons stays in phase to within ¼ wave after traveling N periods, the SASE process can proceed. This means that the bandwidth $\Delta\lambda$ of the SASE radiation should be less than $\lambda/4N$. Formula (1) gives the dependence of synchrotron radiation wavelength on electron energy γ. We conclude that the energy spread of the electron beam should be less than

$$\Delta\gamma/\gamma \sim \lambda_u/8L_g \qquad (4)$$

The gain length itself is a function of the energy and charge density of the electron beam, the undulator field strength and the undulator period. In a one-dimensional approximation,

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho} \quad ; \quad \rho \approx \frac{1}{\gamma}\left(\frac{K^2F_1(K)r_c\lambda_u{}^2n_o}{32\pi}\right)^{1/3} \qquad (5)$$

where K and λ_u are respectively the undulator field strength parameter and undulator period used in eq. (1), r_c is the classical electron radius and n_o is the number density of electrons in the beam. $F_1(K)$ is of order 1 for typical values of K. The gain length and FEL or Pierce parameter ρ are quoted here in approximate form, accurate for negligible 3-D effects. The combined requirements on the electron beam define the challenges[10] of making a FEL work at x-ray wavelengths: a "slice" of the electron beam must have an emittance of the order of 0.01 nm, peak currents of 2000A or more, and an energy spread less than 0.01%. If we assume that the FEL undulators are similar to those in common use in storage ring light sources, which typically have periods of 2-3 cm, the electron beam energy must be on the order of 10 GeV. The LCLS operating parameters, listed in table 1, satisfy these requirements for radiation wavelengths down to 0.15 nm. The challenges associated with the undulator and x-ray optics will not be covered in this report, the remainder of which will discuss the electron gun, bunch compression process, and impedance considerations relevant to achieving the necessary properties in the electron beam.

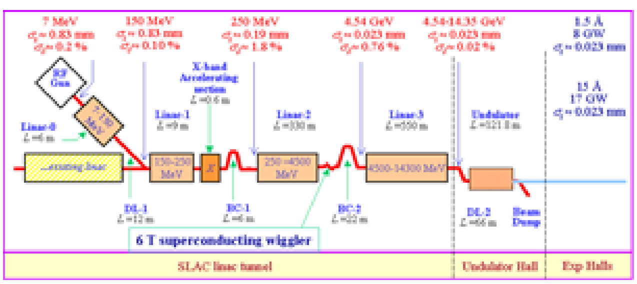

Figure 2. Schematic of LCLS accelerator systems, listing bunch length σ_z and energy spread σ_δ at each stage of compression

3.3 Electron Gun and Injector Linac

The LCLS electron gun is a 1.6-cell s-band RF design, using a laser-driven photocathode. The design was developed by a collaboration of researchers at Brookhaven National Laboratory, Stanford Linear Accelerator Center and University of California – Los Angeles[11]. Nominal LCLS performance goals for this gun are 1 nanocoulomb in a ten picosecond pulse, though it is known that a wide range of operating parameters will provide satisfactory SASE output. Many examples of this gun are in use around the world. The target normalized emittance of the beam at the end of the 150 MeV linac is 1 mm-mrad.

Gun performance tests and verification of computer predictions must be considered one of the most important areas of SASE FEL research at this time. Significant progress has been made at SLAC, BNL[12] and elsewhere in verifying the predictions of gun modeling and design codes against measured gun performance. In particular, recent work[13] has confirmed the importance of proper transverse and longitudinal shaping of the laser pulse. However recent measurements of slice thermal emittance and projected emittance at high current, though supportive the suitability of this gun design for LCLS, also show disagreements with theoretical predictions for ideal cathodes. Continued gun research can be expected to lead to further performance improvements for the LCLS and other SASE FELs.

3.4 Bunch Compression

The LCLS gun will produce a 100A pulse of electrons, which must be compressed to a 3,400 A pulse at the entrance to the undulator channel. As indicated in fig. (2), his will be accomplished in stages as the electron beam progresses though the "dogleg" bend connecting the 150 MeV injector linac to the main linac, through the two chicane bunch compressors located at the 250 MeV point and 4.5 GeV points in the LCLS linac, and finally through the "dogleg" bends connecting the linac to the undulator channel. These bunch compression systems have been designed to minimize degradation of transverse emittances by coherent synchrotron radiation (CSR) in the bending magnets. CSR forces produce a systematic distortion of the transverse phase space of the beam and consequently an increase in its projected emittance.

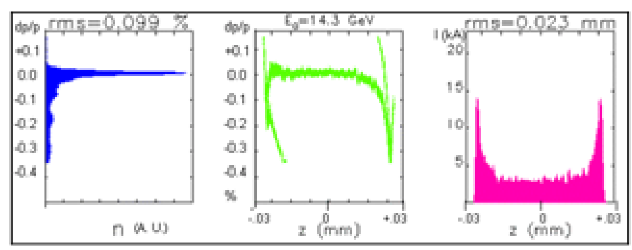

Figure 3. Longitudinal phase space of the electron bunch, compressed to 230 fsec

It is now understood[14,15,16] that CSR can cause a very fast longitudinal instability in the electron beam that is of greater concern because it degrades the slice emittance. Several measures have been taken to reduce damage to the beam properties by CSR. A 4th harmonic RF system based on accelerating structures and RF systems developed for the Next Linear Collider will be installed just upstream of the 250 MeV compression stage to shape the longitudinal phase space of the beam current distribution. It will be operated so as to minimize sharp current spikes in the beam that produce strong CSR forces. The dogleg and chicane magnets are designed and placed to achieve the necessary compression with minimum magnetic field and hence smaller CSR forces. Finally a "wiggler" magnet has been incorporated in the LCLS design just upstream of the 4.5 GeV chicane. Incoherent synchrotron radiation in this magnet will increase the slice energy spread of the electron beam slightly, and Landau- damp the CSR instability.

3.5 Wake Fields

Longitudinal wake fields in the linac are actually used to aid the bunch compression process; the wake fields are exploited to produce a stronger correlation between time and energy in the compressed electron pulse than could conveniently be produced by adjustment of the phase of the accelerating cavities. Strong resistive-wall wake fields and potentially stronger wake fields due to roughness in the walls of the 5 mm undulator beam pipe will cause the energy of the tail of the electron beam to sag as it progresses down the undulator. In the worst case, the rapidly changing energy of the electrons in the tail will halt the SASE process at low peak power. Recent progress in understanding roughness wake fields suggests that they will be less important than resistive wall effects in a properly designed chamber[17]. Resistive wall effects cannot be avoided; however it may be possible to exploit resistive wall wakes so as to have the highly desirable effect of reducing the x-ray pulse from the LCLS to a considerably smaller value than the 230 fsec duration of the electron pulse[18].

4 CONCLUSION

Three principal beam dynamics issues influencing the LCLS design have been highlighted in this paper: performance of the electron gun, coherent synchrotron radiation effects and wake fields. These issues have been addressed in the LCLS conceptual design so as to meet the performance objectives listed in Table 1, and will continue to receive attention as part of ongoing efforts to produce shorter (10-100 fsec) x-ray pulses.

5 ACKNOWLEDGEMENT

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6. REFERNCES

[1] Hofmann, A., "Properties of Synchrotron Radiation", in the proceedings of the CERN Accelerator School – Synchrotron Radiation and Free Electron Lasers, edited by S. Turner, CERN-98-04, 2 August 1998

[2] Bonifacio, R., Pellegrini, C., Narducci, L., *Optics Communications* 50, 373 (1984)

[3] Shenoy, G. K. and Stohr, J., *LCLS- The First Experiments*, October 2000; http://www-ssrl.slac.stanford.edu/LCLS/papers/LCLS_Experiments_2.pdf

[4] T. Laarmann, H. Wabnitz, P. Gürtler, A. R. B. de Castro, R. Döhrmann, W. Laasch, J. Schulz, A. Swiderski, T. Möller, L. Bittner, B. Faatz, A. Fateev, J. Feldhaus, C. Gerth, U. Hahn, E. Saldin, E. Schneidmiller, K. Sytdev, K. Tiedtke, R. Treusch, M.Yurkov, "Coulomb Explosion of Rare Gas Clusters Irradiated by Intense VUV Pulses of a Free Electron Laser", presented at *the 24th International Free Electron Laser Conference*, 9-13 September 2002 (http://www.aps.anl.gov/fel2002/), to be published in Nuclear Instruments and Methods A.

[5] *TESLA Technical Design Report*, DESY 2001-011, March 2001

[6]*Linac Coherent Light Source (LCLS) Conceptual Design Report*, SLAC-R-593, April 2002

[7] Pellegrini, C., "A 4 to 0.1 nm FEL Based on the SLAC Linac", *Workshop on Fourth Generation Light Sources*, M. Cornacchia and Herman Winick, editors, SSRL-92/02, pp 364-372 (1992)

[8] Arthur, J., et al., *LCLS Design Study Report*, SLAC-R-0521, 1998

[9] Krinsky, S., "The Physics and Properties of Free Electron Lasers", to be published in the *Proceedings of the 10th Beam Instrumentation Workshop, Brookhaven National Laboratory, May 6-9, 2002.* Equations (53)-(62) describe beam quality required for SASE.

[10]Emma, Paul, "Accelerator Physics Challenges Of X-ray FEL SASE Sources", SLAC-PUB-9243, May 2002, to be published in the proceedings of *the 8th European Particle Accelerator Conference* (EPAC 2002), Paris, France, 3-7 Jun 2002.

[11] Palmer, D. T., et al.,"Emittance Studies of the BNL/SLAC/UCLA 1.6 Cell Photocathode Gun", in *Proceedings of the 1997 Particle Accelerator Conference, Vancouver B.C., Canada, 12-16 May 1997*, p.2687

[12] Limborg, C. et al., "PARMELA versus Measurements for GTF and DUVFEL", *Proceedings of the 2002 European Particle Accelerator Conference, Paris, 3-7 June 2002*, pp. 1786-1788

[13]J. Yang, T. Nakajyo, Y. Okada, F. Sakai, T. Yanagida, M. Yorozu, A. Endo, K. Takasago, "Experimental Studies of Photocathode RF Gun with Laser Pulse Shaping", presented at the *2002 European Particle Accelerator Conference*, 3-7 June 2002

[14] Borland, M., et al., "Start-to-End Simulation of Self-Amplified Spontaneous Emission Free Electron Lasers from the Gun through the Undulator", Nuc. Inst. & Meth. A483 (2002), 268-272

[15] S. Heifets, et al., "CSR Instability in a Bunch Compressor", SLAC-PUB-9165, March 2002

[16] Huang, Z. and Kim, K.-J., "Formulae for CSR Microbunching in a Bunch Compressor Chicane", Phys. Rev. ST Accel. Beams 5, 074401 (2002)

[17] *Linac Coherent Light Source (LCLS) Conceptual Design Report*, pp. 8-57 – 8-62, op. cit.

[18] Reiche, S., Emma, P., Pellegrini, C., "Pulse Length Control in an X-Ray FEL by Using Wakefields", to be published in the proceedings of *the 24th International Free Electron Laser Conference*, 9-13 September 2002