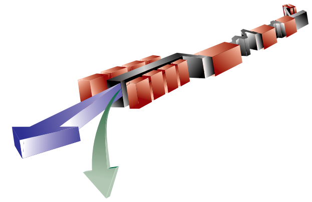
2 Overview



2.1 Introduction

The x-ray research community has become accustomed to exponential increases in performance parameters of synchrotron light sources since the construction of the first dedicated facilities. Each stepwise increase in performance was initially perceived as revolutionary. Indeed, after their initial impact, the successive generations of x-ray sources have become indispensable tools for research in chemistry, materials science, biology and environmental sciences. The immediate and sustained nature of this impact was assessed in the 1984 Seitz-Eastman Report [1] to the National Research Council and, thirteen years later, in the Birgeneau/Shen Report [2] to the DOE Basic Energy Sciences Advisory Committee. The latter report states that:

"…the advent of synchrotron radiation sources over the last three decades…has led to a genuine scientific revolution."

In three decades, the average brightness of synchrotron sources has improved by about a factor 10^{10}. This Conceptual Design Report proposes the construction of the Linac Coherent Light Source, the next major step in light source capability: an x-ray free-electron laser. In peak brightness, it will surpass existing sources by a factor of 10^{10}. The Birgeneau/Shen Report [2] cited the scientific promise of an x-ray free electron laser, and recommended that DOE-BES allocate funds to 4^{th}-generation source R&D. In response to this recommendation, BESAC charged a subpanel chaired by Steven R. Leone to assess the scientific opportunities offered by new coherent light sources and to propose a research and development plan for novel coherent sources. The Leone Committee Report [3] stated that

"Given currently available knowledge and limited funding resources, the hard X-ray region (8-20 keV or higher) is identified as the most exciting potential area for innovative science. DOE should pursue the development of coherent 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 stimulated emission or some form of seeded stimulated emission."

At the time of the Leone Committee report, the Linac Coherent Light Source concept had been under development for nearly seven years by SLAC scientists, in collaboration with experts at UCLA, the Brookhaven National Laboratory, the Los Alamos National Laboratory, and the Lawrence Livermore National Laboratory. Argonne National Laboratory scientists joined the collaboration in 1999. The Leone Committee endorsed the multi-institutional nature and the mission of this collaboration. In response to the Leone Committee recommendations, DOE-BES has provided $1.5M per year since 1999 for research and development of the LCLS concept.

The Leone Committee also stated that:

"… the scientific case for coherent hard x-ray sources is in the formative stages and appears extremely promising, but must be improved to attain a more compelling and rigorous set of experiments that can be achieved only if such a new coherent light source becomes available."

This recommendation was acted upon by the LCLS Scientific Advisory Committee, which took on the task of identifying and developing specific concepts for experiments at the LCLS. This committee, chaired by Gopal Shenoy and Jo Stöhr, created a report entitled "LCLS – The First Experiments" [4]. The report described six experiment plans, in diverse areas of science that exploited the extraordinary properties of the LCLS beam. Based on the BESAC review of this report, as well as on input gathered from the scientific community through workshops such as the May 2001 *Basic Energy Sciences Workshop on Scientific Applications of Ultrashort, Intense, Coherent X-Rays*, the DOE Office of Science approved Critical Decision 0, Approval of Mission Need, for the Linac Coherent Light Source, on 13 June 2001. Critical Decision 0 was the authorization for the creation of this Conceptual Design Report.

The First Experiments document provides three key insights into the scientific potentials of the LCLS. First, it is clear that, like existing synchrotron light sources, the LCLS will be a powerful tool for research spanning the physical and life sciences. The six examples were chosen to illustrate the breadth of opportunity:

- Atomic physics
- Plasma physics
- Structural studies on single particles and biomolecules
- Femtosecond chemistry
- Studies of nanoscale dynamics in condensed matter physics
- X-ray laser physics

Second, it is clear that the short duration of the LCLS pulse (230 fs and shorter) is of crucial importance to certain areas of science. The LCLS will provide the opportunity to observe atomic states and molecular structure on time scales characteristic of the processes of atomic transition, chemical bond formation and breaking, and transitions in condensed matter structures. With a sufficiently short pulse the LCLS can, in effect, function as a stroboscopic flash for freeze-frame photography of atomic, molecular and nanoscale structures as they evolve.

Third, it is clear that, as diverse as the scientific opportunities may be, it is possible to discern much commonality in the instrumentation requirements for LCLS experiments. It will be necessary to provide:

- Controlled attenuation

- Filtering
- Monochromatization
- Focused beams
- Synchronization of the LCLS beam to a pump laser
- X-ray beam splitters with adjustable time delay
- 120 Hz x-ray detectors with large area and high angular resolution

For this reason, the scope of the LCLS Project also includes the development of the above listed prototypical capabilities and techniques, spanning the 0.8 – 8 keV operating range of the facility. After characterizing the first pulses of SASE radiation from the LCLS, the "0th experiments" will be the performance characterization of optics and instrumentation developed as part of the Project. **Chapter 3** of this report gives an overview of the proposals included in the First Experiments document and provides motivation for the selection of instrumentation to be included in the Project. **Chapter 9** of this report describes the suite of x-ray diagnostics and prototypical instrumentation that will be included in the scope of the Project.

This Conceptual Design Report proposes to modify the SLAC Linac and associated facilities to create a Free-Electron Laser (FEL), the Linac Coherent Light Source (LCLS), capable of delivering coherent radiation of unprecedented characteristics at wavelengths as short as 1.5 Å. At its inception, the Stanford Synchrotron Radiation Laboratory shared the SPEAR Storage Ring as it was operated for high-energy physics experiments. Likewise, the LCLS will be integrated with the SLAC Two-Mile Accelerator, which will continue to support ongoing programs in particle physics and accelerator R&D. The upstream 2/3 of the SLAC linac will be used concurrently for injection to the PEP-II B-Factory. The last one-third of the linac will be converted to a shared but independently operable 4-15 GeV electron linac. Construction of a dedicated linac for the LCLS would add about $300M to the Total Estimated Cost, more than doubling its price. SLAC management has pledged that 75% of the operating time of the last third of the linac will be available for operation of the LCLS.

The LCLS is based on the Self-Amplified Spontaneous Emission (SASE) principle, described in **Chapter 4** of this report. Its design makes use of up-to-date technologies developed for the SLAC Linear Collider Project and the next generation of linear colliders, as well as the progress in the production of intense electron beams with radio-frequency photocathode guns. These advances in the creation, compression, transport and monitoring of bright electron beams make it possible to base the next (fourth) generation of synchrotron radiation sources on linear accelerators rather than on storage rings.

2.2 Technical Objectives and Mission

2.2.1 Design Goals

The synchrotron radiation output of the LCLS is crucially dependent on the properties of the electron beam, which must be controlled throughout the acceleration process to ensure that the SASE process can be initiated and brought to saturation. However, it is possible to vary the electron beam characteristics in a linac-based light source over a much wider range than is the case for a storage ring. Thus, the properties of SASE radiation can be varied over a much wider range than in any given storage ring light source. In a linac-based source, there is much greater freedom to control bunch length, emittance, energy spread and peak current than in a storage ring.

In operation, the LCLS will explore the full range of its operating capabilities to produce x-ray beams best suited to the needs of its community of users. However, to enable the coordinated planning of experiments for the LCLS, it is necessary to set well-defined parameters for its x-ray beams. A comprehensive list of design goals may be found in chapters 3 and 5 of this report. The prime performance characteristics of the SASE radiation are listed below in **Table 2.1**:

Table 2.1 Prime performance characteristics of SASE radiation.

X-ray beam energy	0.8 keV		8 keV
FWHM x-ray pulse duration		230 fs	
X-ray peak power	10 GW		8 GW
Max. pulse repetition rate		120 Hz	

The LCLS is not limited to the range of pulse lengths and peak powers listed above. Chapter 4 describes the range of operating modes and performance characteristics that have been explored to date. It must be remembered that the power levels listed above are for the radiation produced in the SASE process. The LCLS beam will also produce copious spontaneous synchrotron radiation. Within the opening angle and bandwidth of the FEL radiation, the spontaneous radiation power is negligible. However, integrated over its full opening angle and spectral range, the peak spontaneous radiation power is 92 GW.

2.2.2 Shared Use of the Linac

- The LCLS will operate without interfering with injection to PEP-II. This requirement has no impact on the LCLS design.
- The LCLS will not prevent 50 GeV operation of the linac. It must be possible to switch the linac from LCLS operations to 50 GeV operations in 24 hours.

- The LCLS operation will be compatible with transport of a 30 GeV beam through the last 1/3 of the linac, by rapid resetting of alternate operating parameters from the main control room.
- Up to 25% of the annual linac operating schedule may be dedicated to uses that preclude LCLS operation.

2.3 Alternatives Analysis

The purpose of an alternatives analysis is to choose the most efficient, cost effective path to the desired goal, a coherent 8 keV x-ray beam. Evaluation of alternatives may be made in terms of the three components of a project baseline: technical performance, cost and schedule. The most compelling argument for construction of an 8 keV x-ray laser based on the SLAC linac is the existence and availability of the SLAC linac itself, and the staff and infrastructure of the Stanford Linear Accelerator Center.

2.3.1 Cost

The SLAC site is the best choice among alternative sites for the LCLS because it makes use of a portion of the two mile linac as the source of a high-quality electron beam for the LCLS free-electron laser. There is no other linac or synchrotron in the world capable of providing a 14 GeV electron beam with properties suitable for the LCLS. Duplication of the SLAC linac facilities to be used for the LCLS would cost more than $300M. Duplication of the core competencies and support staff necessary to operate the linac (required for other programs at SLAC) would incur significant additional annual expenditures beyond the operating cost of the LCLS.

2.3.2 Schedule

Early access to the extraordinary capabilities of the LCLS is extremely important in terms of the scientific opportunities that the facility will offer. Early access is equally important to planning the future of synchrotron radiation research over the next 20-30 years. The LCLS can produce first laser beams at the end of FY2007, at least five years before any other planned hard x-ray lasers can be brought on line.

2.3.3 Technical

The SLAC linac technical performance is very well characterized. Risks associated with the operation of the linac itself are very low. Technical risks associated with undulators and beam lines are neither reduced nor increased by use of the SLAC linac for LCLS.

2.4 Project Schedule

The cost estimate is based on a three-year construction schedule, FY2005-2007. Major procurements for the undulator modules, injector and experiment halls can be placed as soon as construction funds are allocated if the Project Engineering Design funds are allocated as requested in FY2003-2004.

Major milestones for this project schedule are:

Table 2.2 Major project schedule milestones

Milestone	Date
Project start	October 2004
Near Hall construction award	February 2005
Undulator first article received	January 2006
First beam from the injector to the main linac	June 2006
Near Hall beneficial occupancy, start installation	October 2006
Undulator delivery 50% complete	October 2006
Far Hall beneficial occupancy, start installation	November 2006
First beam through bunch compressor 2	April 2007
Start commissioning laser	May 2007
Undulator deliveries complete	June 2007
Project completion	September 2007

The milestones quoted above are placed to provide approximately 3 months "float" in the schedule. The schedule "float" throughout is strongly dependent upon contract award dates in the first year of the project. The critical path for project completion is determined by the rate of delivery of undulators, assumed to be two per month. It is assumed that construction of both experiment halls can be awarded in the first year. However it should be kept in mind that, since the project begins with a two-year PED effort, complete bid packages can be released at the start of construction. Because of these PED funds and the fact that the LCLS project is a multi-laboratory collaboration, funds can be committed rapidly from the very start of the project. With proper planning, commissioning of the FEL may begin before the last undulator is installed.

A four-year construction schedule has also been considered. The most attractive alternative is to build injector, linac, undulator systems and FFTB extension on a three-year schedule as outlined above. Commitment of funds to construction of the experiment halls would be delayed one year. FEL commissioning would continue through the fourth year of the project. After one year of FEL commissioning, reliability and stability of the laser will be well-understood, and commissioning of the x-ray beam lines may go more smoothly.

2.5 Cost Estimate

The R&D costs for the LCLS have been $6M, prior to authorization of PED funds. The estimated TEC range is $165M-$225M, and the TPC range is $185M-$245M.

2.6 Funding Requirements

2.6.1 R&D

In the years F1999-2002, the abovementioned R&D funds enabled the following activities:

- Experimental investigations of the SASE process
- Experimental investigation of rf gun performance
- RF photocathode gun design
- High quantum efficiency cathode fabrication
- Construction of a prototype LCLS undulator
- Theoretical investigations of the SASE process
- Theoretical and numerical calculations of the effects of coherent synchrotron radiation
- Computation of tolerances for magnet alignment, rf fields, magnet fields, etc.
- Numerical computation of damage thresholds for x-ray optics
- Experimental verification of computed damage thresholds of x-ray optics materials
- Tests of fabrication techniques for reflective and transmissive optics for the x-ray beam

2.6.2 Project Engineering Design and Construction

Completion of the LCLS construction project in three years requires a nearly flat funding profile in the first two years. In the first year of the project, funds must be committed to both experiment halls, the undulator and the injector. This in turn requires $3M PED for the injector and a similar amount for the conventional construction in FY2004. A total of $33.5M for PED was forecast in the supporting documentation for Critical Decision 0.

2.6.3 Startup

For either a three- or a four-year construction schedule, injector and linac commissioning begin in FY2006. Since FEL commissioning occurs late in FY2007, startup funding requirements are set to support linac commissioning activities for most of the year.

On a four-year schedule, additional startup funds to support commissioning of the FEL and x-ray beam lines are required throughout FY2008. Though this increases the TPC, the increase is, for practical purposes, cancelled by the delay in the start of operating funds until FY2009.

2.7 Risk Assessments and Strategies

In the years since the start of R&D funding for the LCLS, technical risks associated with the feasibility and success of an x-ray laser have been reduced considerably as a result of improved theoretical understanding of free-electron lasers along with several very successful and thorough experimental investigations of the SASE process. Several SASE FELs have demonstrated high gain and saturation at wavelengths ranging from 10.6 μm to 90 nm and below. Recent results are presented in **Chapter 4**. A list of the major physics risk elements follows.

2.7.1 Technical Risks

2.7.1.1 Performance of Photocathode Guns

PARMELA results predict that slice emittances less than 1 mm-rad will be produced by the LCLS gun. This prediction has been confirmed in computer simulations, performed by several groups using a wide variety of computational tools; the TESLA FEL design is based on achievement of slice emittance 0.8 mm-mrad, as predicted in simulations with HOMDYN, ASTRA and MAFIA. Achievement of LCLS design goals is based on achievement of a slice emittance of 1.2 mm-mrad, 50% larger than predictions. Measurements of gun performance have been made at the Gun Test Facility (GTF) at SLAC, under conditions approaching those to be used in the LCLS. Agreement between emittances measured at the GTF and predictions of computer codes such as PARMELA has been very good. PARMELA results predict that, if matched to the LCLS today, the GTF gun would provide an electron beam at the entrance of the undulator that would reach saturation power near 1 GW with a 140-fs pulse duration.

2.7.1.2 Acceleration and Compression

It is necessary to accelerate electrons in the LCLS to 14.35 GeV and, by means of dogleg and chicane bunch compressors, increase the peak current in the bunch to 3,400 A. This must be done while avoiding dilution of the beam emittance by Coherent Synchrotron Radiation (CSR) effects in the bend magnets of the compressors. Great progress has been made in theoretical, numerical and experimental investigation of CSR during the past year [5]. Based on this progress, the LCLS bunch compressor designs have been optimized to avoid microwave instability effects. A superconducting wiggler has been added to the LCLS design, upstream of the second bunch compressor. Computer codes, used to predict CSR effects on LCLS performance, have been benchmarked against codes written at three other laboratories. The agreement is good, with the LCLS codes providing slightly more pessimistic results than TraFiC4, the “particle-in-cell” code used to design the TESLA FEL. Start-to-end simulations of the LCLS predict that the LCLS will reach its design power output with a 1 nC current pulse.

2.7.1.3 Undulator

A prototype of the LCLS undulator module has been constructed and measured at Argonne National Laboratory. The field quality meets LCLS requirements and the measured peak field is 8% better than LCLS requirements. Prototype magnet movers have been built and are in testing. The prototype work carried out to date has significantly reduced the uncertainty and risk associated with undulator magnet field quality and stability.

2.7.1.4 Wake Field Effects of the Undulator Vacuum Pipe

Simulations indicate that performance goals for LCLS will be met if a smooth, 6-mm copper beam pipe is used in the undulator channel. Wake fields due to surface roughness and resistive wall impedance in the undulator beam pipe can have significant effects on the SASE process since it can cause a correlated energy spread to develop in the electron beam as it travels along the undulator. Direct measurements of candidate beam pipe material indicate that roughness effects are at acceptably small levels in commercially available tubes. Investigations of prototype chamber designs and fabrication techniques will be carried out in the coming year. Resistive wall effects in the 6-mm beam tube are expected to be important, and have been taken into account in start-to-end simulations and predictions of output power. Assuming best performance of the proven planar hybrid undulator design, the net effect of increasing the undulator gap and beam pipe diameter is not very significant; at increased gap, the improvement in longitudinal impedance is largely cancelled by the reduction in undulator peak field which results in increased gain length.

2.7.1.5 SASE FEL Physics

As described in **Chapter 4,** the theory of self-amplified spontaneous emission has been independently verified in experiments carried out at ANL and BNL by members of the LCLS Collaboration, as well as at the TESLA Test Facility. Theoretical predictions of gain, saturation, nonlinear harmonic generation, and temporal structure have been experimentally verified at wavelengths down to 98 nm. Based on these results and on theoretical predictions, the LCLS can attain saturation over its full spectrum, for a range of achievable peak currents and electron pulse lengths. The LCLS undulator tunnel will be constructed about 30 m longer than the undulator line to make possible the addition of undulator segments and other hardware required for producing shorter or longer light pulses using seeding techniques.

2.7.1.6 X-Ray Optics and Beam Handling

Numerical simulations and experimental tests have shown that LCLS optical elements can be designed to handle the extraordinary peak power of the FEL. The choice of materials and of placement of optical elements is important, and low-Z materials will withstand the highest power densities encountered in the front hutch of the near Hall, as indicated in **Table 9.4** (**Chapter 9**). Peak power densities are challenging but tractable in the Near Hall. In the Far Hall, power densities on the optics are more easily managed.

2.7.1.7 Conventional Facilities

The ground stability of the Research Yard, where the undulator system and the Near Hall will be sited, has been carefully monitored and characterized since the Final Focus Test Beam program began in 1993. Experience with operation of the SLAC Linear Collider has demonstrated that the effects of ground vibrations and settling can be compensated by feedback control of the electron beam. The LCLS buildings are conventional in design and pose no special risks or challenges.

2.7.2 Schedule Risks

A three-year construction schedule is aggressive but achievable if sufficient PED funding is secured to have the critical and long-lead procurement packages ready for release as soon as construction begins. Schedule risk is also minimized by progressive commissioning of the injector and linac in advance of FEL commissioning. Procurement strategy for undulators will be carefully planned to minimize technical and schedule risk.

2.7.3 Cost Risks

The LCLS cost estimate has over 25% contingency, reasonable for this stage of planning. In the coming year, the cost estimate will be further refined.

2.8 Stakeholder Input

Throughout the planning process for the LCLS, every effort has been made to maintain and promote communication with the agencies responsible for science policy in the US, the prospective LCLS user community, and the management of SLAC itself. Since it was first conceived in 1992, the evolution of the LCLS design has been guided by input from the synchrotron science community. The Basic Energy Sciences Advisory Committee has carried out two formal assessments of the future of synchrotron radiation science in the US, the role of free electron lasers in general and the LCLS in particular. As already mentioned, the Birgeneau subpanel report and the Leone subpanel both supported the Critical Decision 0 finding that the LCLS fills a key mission need in Basic Energy Sciences research.

The LCLS R&D effort has also been guided by two key advisory groups, the LCLS Science Advisory Committee and the LCLS Technical Advisory Committee. These committees were founded in 1999 to advise the SSRL and SLAC Technical Division Associate Directors on the LCLS scientific program and accelerator science/technology issues.

Since 1992, there have been 34 workshops, attended by members of the light source research community worldwide, which have addressed scientific opportunities and challenges of importance to the LCLS.

The SLAC Directorate and Faculty have been actively involved in planning the integration of LCLS operations and science with the rest of the SLAC Scientific Program. The main advisory body to the President of Stanford University, the SLAC Science Policy Committee, has received regular updates on LCLS activities and planning.

2.9 Acquisition Strategy

The lead contractor for acquisition of the Linac Coherent Light Source is Stanford University, which operates the Stanford Linear Accelerator Center. SLAC will collaborate with two national laboratories (Argonne National Laboratory and Lawrence Livermore National Laboratory) to construct the LCLS.

The SLAC site is the best choice among alternative sites for the LCLS, because it makes use of a portion of the Two Mile Linac as the source of a high-quality electron beam for the LCLS free-electron laser. There is no other linac or synchrotron in the world capable of providing a 14 GeV electron beam with properties suitable for the LCLS. Duplication of the SLAC linac facilities to be used for LCLS would cost more than $300M. Duplication of the core competencies and support staff necessary to operate the linac (required for other programs at SLAC) would incur significant additional annual expenditures beyond the operating cost of the LCLS that would certainly exceed $30M. The linac facilities will be shared between LCLS and other programs; however, 75% of the operations schedule of the linac will be available for LCLS.

A significant component of the LCLS budget as well as technical risk are associated with the undulator magnets that induce oscillatory motion of the electron beam as it passes through the magnets. Undulator magnets have been constructed for light sources and lasers at several laboratories around the world. The US DOE laboratory with the most recent and comprehensive experience in undulator design and construction is Argonne National Laboratory (APS). The APS is operated by the University of Chicago under contract with the Department of Energy. Since 1993, the APS has designed, procured and tested over 35 undulators and wiggler magnets, totaling over 75 m in length. This is to be compared with the required 33 undulators, totaling 112 m, required for the LCLS.

The LCLS is a source of unprecedented peak x-ray power. The development of optical elements to collimate, focus and filter the beam poses unique challenges. Though it is impossible to create LCLS-like x-ray beams without actually building the LCLS, Lawrence Livermore National Laboratory (LLNL) has extensive related experience in development of precision high-power optics within its laser programs. LLNL has high-power laser facilities, which can be used for testing materials under conditions approximating the LCLS laser beam. Finally, LLNL has already developed computer simulation codes that can predict the effect of the LCLS beam on materials. For this reason, LLNL will manage the acquisition of x-ray beam handling systems to be put in the path of the x-ray beam. An alternative would be to re-develop this expertise at SLAC, incurring considerable delay and additional expense.

Brookhaven National Laboratory (BNL), the University of California-Los Angeles (UCLA), and Los Alamos National Laboratory (LANL) have contributed to the LCLS conceptual design.

Milestone FEL experiments have been carried out at BNL by the LCLS Collaboration, and BNL has led the way in exploration of the capabilities of the 1.6-cell rf photocathode gun to be used in the LCLS. UCLA has provided theoretical support and innovation in design of the LCLS. LANL has provided research on photocathodes for RF guns. It is expected that these organizations will continue to play a key role in support of LCLS, and will participate in LCLS construction as necessary.

2.10 Design Alternatives

Although the fundamentals of the LCLS design have not changed since 1992, a wide range of alternatives has been evaluated in the course of preparing the design in this report. Placement of the injector linac within the main linac tunnel, and a newly excavated injector enclosure were considered at earlier stages of the design. The bunch compressor designs have been modified as understanding of CSR effects has improved. In the past year, the decision to increase the length of the FFTB tunnel was taken, to provide space for self-seeding systems that could be implemented as an upgrade to the LCLS to produce very short x-ray pulses from the laser. The most significant change in terms of cost has been the addition of the Far Hall, or Hall B, to the scope of the project. This was based on unanimous advice from the LCLS Science Advisory committee. The addition of the Far Hall significantly reduces technical risks associated with the design of high-power optics for the LCLS. As an ALARA measure, it was decided to move the front-end systems (gas attenuation cells, beam stoppers, etc) out of the Near Hall and into the more heavily shielded undulator tunnel. Significant effort has gone into the selection of x-ray beam handling systems, x-ray optics and x-ray diagnostics that can span the full spectrum of the LCLS. The technical challenges in optics design change character radically over the 0.15-1.5 nm range of the LCLS. Details of these and other design alternatives are mentioned in the body of the Conceptual Design Report, though of course emphasis is placed on description of the optimized design.

2.11 Principle of Operation

As described in **Chapter 4**, lasing action is achieved in an FEL when a high brightness electron beam interacts with an intense light beam while traveling through a periodic magnetic field. Under the right conditions, the longitudinal density of the electron beam becomes modulated at the wavelength of the light. When this occurs, electrons contained in a region shorter than an optical wavelength emit synchrotron radiation coherently; i.e., the intensity of the light emitted is proportional to the square of the number of electrons cooperating, rather than increasing only linearly with the number of electrons, as is the case with normal synchrotron radiation. The increasing light intensity interacting with the electron beam passing through the magnetic field enhances the bunch density modulation, further increasing the intensity of the light. The net result is an exponential increase of radiated power ultimately reaching about ten orders of magnitude above conventional undulator radiation.

The main ingredients of an FEL are a high-energy electron beam with very high brightness (i.e., low emittance, high peak current, small energy spread) and a periodic transverse magnetic field, such as produced by an undulator magnet. Electrons bent in a magnetic field emit synchrotron radiation in a sharp forward cone along the instantaneous direction of motion of the electron, and hence the electric field of this light is predominantly transverse to the average electron beam direction. In most present FELs the light from many passes of the electron beam through the undulator is stored in an optical cavity formed by mirrors. Many of these FELs work in the IR range and some have been extended to the UV range. Extending these devices to shorter wavelengths poses increasing difficulties due primarily to the lack of good reflecting surfaces to form the optical cavity mirrors at these shorter wavelengths. It has recently become possible to consider another path to shorter wavelength, down to the Angstrom range. This new class of FEL achieves lasing in a single pass of a high brightness electron bunch through a long undulator by a process called Self-Amplified Spontaneous Emission (SASE). No mirrors are used. This is the process proposed for the LCLS.

The LCLS reaches the Angstrom range with this approach with a high energy (14.3 GeV), high peak current (3.4 kA), low normalized emittance (1.2 mm mrad), small energy spread (0.02%) electron beam passing through a long (121 m) undulator magnet. The spontaneous radiation emitted in the first part of this long undulator, traveling along with the electrons, builds up as the bunch-density modulation begins to take place during a single pass, resulting in an exponential increase in the emitted light intensity until saturation is reached. Usually this occurs after about 10 exponential field gain lengths.

2.12 Overall Layout

Figure 2.1 shows the layout of the proposed facility. The PEP-II electron-positron collider uses the first 2 km of the Linear Accelerator as its injector. The last 1 km of the linac is used by the LCLS.

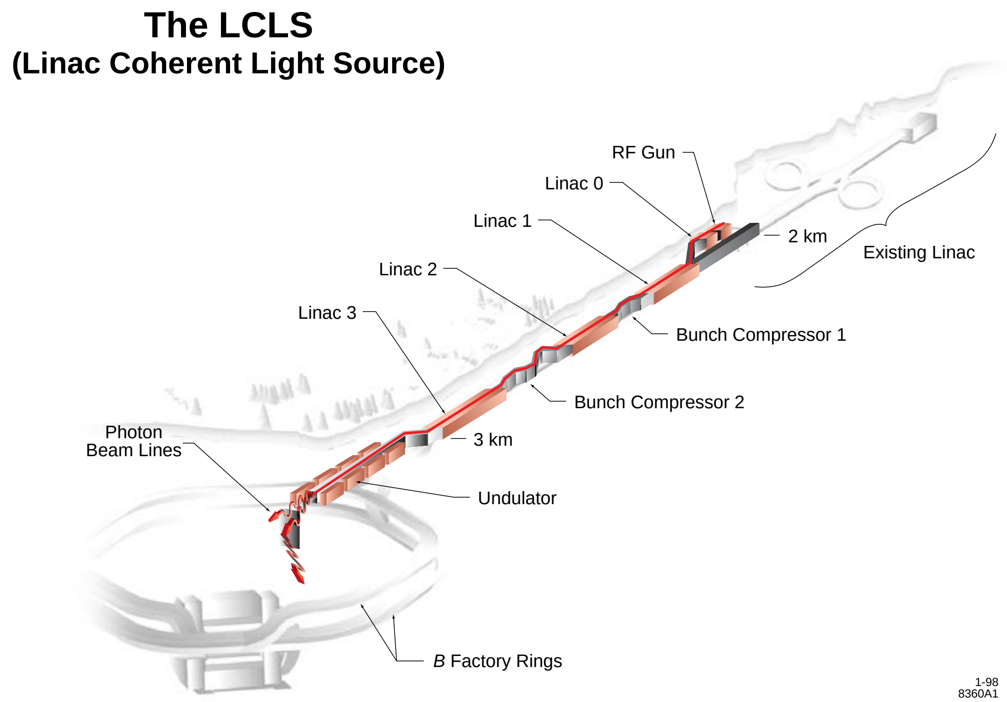


Figure 2.1 Layout of the Linac Coherent Light Source.

A new injector consisting of a gun and a short linac is 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 beam at the entrance to the undulator has an energy of 14.3 GeV, a peak current of 3,400 A, and a normalized emittance of 1.2 mm-mrad. A transfer line takes the beam and matches it to the entrance of the undulator. The 121-m long undulator will be installed in the tunnel that presently houses the Final Focus Test Beam Facility. After exiting the undulator, the electron beam is deflected onto a beam dump, while the photon beam enters the experimental areas.

The experimental areas are housed in two halls. The first hall, located just after the beam dump in the SLAC Research Yard, is a 30m × 55 m structure, which will contain two x-ray hutches for characterization of the beam and subsequently for experiments. The x-ray beam will pass through the Near Hall into a 227 m tunnel to the Far Hall, a 57 m × 33 m structure with experiment facilities below grade and office/lab space on grade. This building will also include two x-ray hutches at the completion of the project.

2.13 Performance Characteristics

Figure 2.2 shows the peak and average brightness as a function of photon energy. The LCLS is designed to be tunable in the photon wavelength range 1.5 – 15 Å, corresponding to 4.5 –14.3 GeV electron energy.

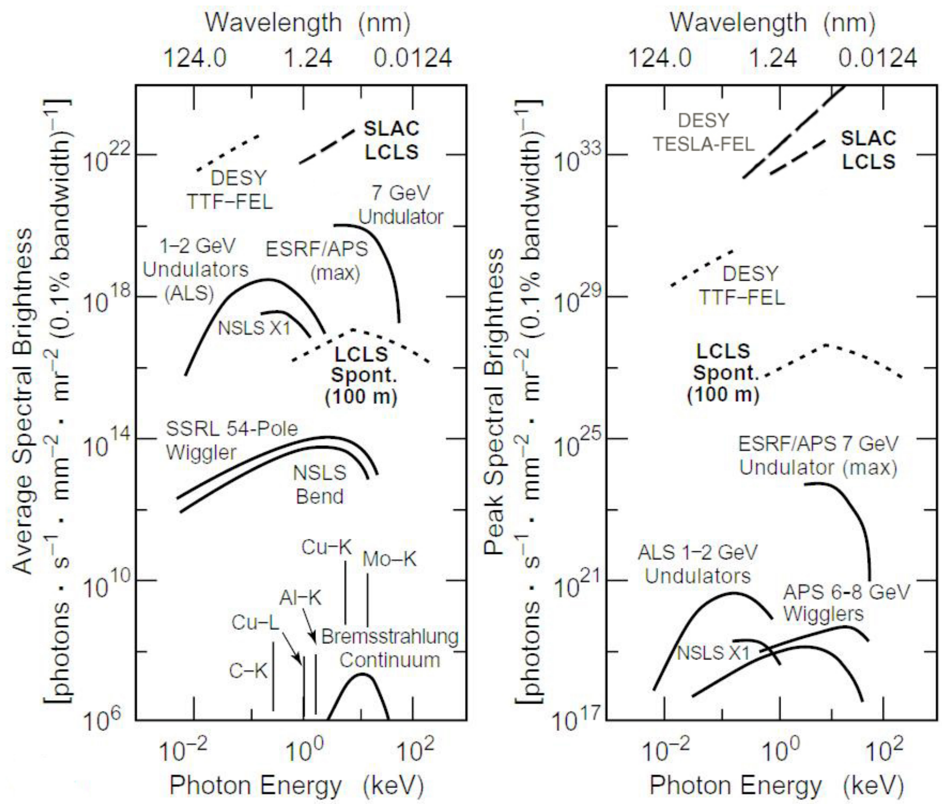


Figure 2.2 Average and peak brightness calculated for the LCLS and for other facilities operating or under construction. The data for the Average Spectral Brightness of the planned TESLA FEL facility is above the limit of the figure.

Table 2.3 lists some of the basic parameters of the LCLS electron beam, of the undulator, and of the FEL performance at the shortest operating photon wavelength.

Table 2.3 LCLS electron beam parameters.

Parameters	Values		Units
Electron beam energy	4.54	14.35	GeV
Normalized rms slice emittance	1.2	1.2	mm mrad
Peak current	3,400	3,400	A
Slice energy spread	0.025	0.008	%, rms
Projected energy spread	0.20	0.06	%, rms
RMS bunch length	77	77	fs
Undulator period	3		cm
Number of undulator periods	3,729		
Undulator magnetic length	112.86		m

Undulator field	1.325		Tesla
Undulator gap	6		mm
Undulator parameter, K	3.7		
FEL parameter, ρ	14.5×10^{-4}	5.0×10^{-4}	
Power gain length	1.3	4.7	m
Repetition rate	120		Hz
Saturation peak power	19	8	GW
Peak brightness	5×10^{31}–5×10^{32}	10^{32}–10^{33}	Photons/(s mm^2 mrad^2
Average brightness	2×10^{20}–2×10^{21}	2.7×10^{21}–2.7×0^{22}	Photons/(s mm^2 mrad^2

The curves for the presently operating third-generation facilities indicate that the projected peak brightness of the LCLS FEL radiation would be about ten orders of magnitude greater than currently achieved. Also note that the peak spontaneous emission alone (independent of the laser radiation) is four orders of magnitude greater than in present sources. This, coupled with sub-picosecond pulse length, makes the LCLS a unique source not only of laser, but also of spontaneous radiation. This spontaneous radiation is also transversely coherent at wavelengths of 6 Å and longer.

2.14 The Photoinjector

The design goal of radio-frequency photocathode guns currently under development at various laboratories is a 3 ps (rms) long beam of 1 nC charge with a normalized rms emittance of 1 mm-mrad.

In a radio-frequency photocathode gun, electrons are emitted when a laser beam strikes the surface of a cathode [6]. The extracted electrons are accelerated rapidly to 7 MeV by the field of a radio-frequency cavity. The rapid acceleration reduces the increase in beam emittance that would be caused by the space charge field. The variation of phase space distribution along the bunch, caused by the varying transverse space charge field along the bunch, is compensated with an appropriate solenoidal focusing field [7].

The laser will have a YAG-pumped Ti:sapphire amplifier operating at 780 nm that will be frequency tripled (3rd harmonic). Very restrictive conditions are required for the reproducibility of the laser energy and timing. Stable FEL operation requires a pulse-to-pulse energy jitter of better than 1% and a pulse-to-pulse phase stability of better than 0.5 ps (rms). These tight tolerances are needed to ensure optimum compression conditions.

2.15 Compression and Acceleration

The purpose of the compressors is to reduce the bunch length, thereby increasing the peak current to the 3,400 A required to saturate the LCLS. Accelerating the beam off the crest of the rf waveform in the linac creates an energy-phase correlation that can be used by a chicane to shorten the bunch by appropriate energy-path length dependence. It is preferable to utilize two, rather than one, chicane. This reduces the sensitivity of the final bunch length to the phase jitter in the photocathode laser timing [8]. The rms length of the bunch emitted from the cathode is 1 mm (3 ps). After compression, the bunch shortens to 0.02 mm.

The choice of energies of the various compression stages is the result of an optimization that takes into account beam dynamics effects, the most relevant ones being the space charge forces in the early acceleration stage, the wakefields induced by the electromagnetic interaction of the beam with the linac structure [9], and the coherent synchrotron radiation emitted by a short bunch [10]. With all dynamic effects included, the simulations [11] indicate that the emittance dilution up to the entrance of the undulator will be less than 50%.

From the linac exit a transport system carries the beam to the entrance of the undulator. This transport system includes a suite of diagnostics to characterize the electron beam.

2.16 The Undulator

Several candidate undulator types were evaluated, including pure permanent magnet helical devices, superconducting bifilar solenoids, and hybrid planar devices. Superconducting devices were ruled out because of their complexity and higher risk. A hybrid device has a stronger field, and, therefore, a shorter length, than a pure permanent magnet device. It also offers superior error control. The advantage of a pure permanent magnet system is that it allows superposition of focusing fields. Since the focusing quadrupoles can be placed in the interruptions and need not envelop the undulator, this property of pure permanent magnet undulators is not critical.

The other choice is between a planar and a helical undulator. Helical devices offer a shorter gain length to reach saturation, but are less understood than planar devices, particularly in terms of magnetic errors, a crucial factor in the SASE x-ray situation. Measurements of the magnetic field are also difficult. A planar hybrid undulator was chosen for this design for its superior control of magnetic errors and simplicity of construction and operation. The magnetic length of the undulator is 113.7 m, its period is 3 cm, and the pole-to-pole gap is 6 mm.

2.17 The X-Ray Optics and Experimental Areas

After leaving the undulator, the electron beam, carrying an average power of 1.6 kW, will be dumped into a shielding block by a sequence of downward-deflecting permanent magnets, while the FEL radiation will be transported downstream to the experimental areas. Anticipating the broad range of applications and associated beam requirements described in the "First Experiments" report, a corresponding range of transmissive, specular and crystal optics will be employed. A system of attenuators will allow the intensity of the tradition to be varied from the level of current third-generation facilities up to the maximum FEL output.

2.18 Summary

In summary, this Conceptual Design Report describes the design of an x-ray Free-Electron Laser operating on the single pass SASE principle. The FEL uses the unique capability of the SLAC linear accelerator to create an intense electron beam of low emittance, and a long undulator, to produce high brightness coherent radiation down to 1.5 Å. Theory and computations indicate that the peak brightness from such a device would be about ten orders of magnitude greater than currently achievable in third-generation synchrotron radiation sources. Such performance, coupled with the very short bunch length (230 fs FWHM) and full transverse coherence, would allow the exploration of new horizons in material science, structural biology, and other disciplines.

2.19 References

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