# RESEARCH AND DEVELOPMENT PLAN FOR THE LINAC COHERENT LIGHT SOURCE (LCLS) - FY1999-FY2002

August 1999

## 1. EXECUTIVE SUMMARY

This document outlines the Research and Development plan for the Linac Coherent Light Source. The plan estimates the effort and the material required to conduct the studies that will solidify the design and optimize it in terms of cost and performance. The R&D program extends over four years. The LCLS R&D collaborating institutions are the Stanford Linear Accelerator Center (SLAC), Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL) and the University of California at Los Angeles (UCLA). Up until now the LCLS R&D has been supported by the currently budgeted funds of the collaborating institutions, in some cases LDRD and in other cases operating funds. However, additional funds in the amount of M$ 1.5 per year are requested from the Department of Energy (DOE) to augment the continued support from the collaborating institutions.

Section 2 contains a brief introduction to the project. Section 3 lists those aspects of the LCLS design that require further R&D before construction can start. Section 4 contains the major LCLS R&D milestones and information about the distribution of R&D funds. Section 5 contains the summary.

## 2. INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) is leading the effort to build a Free-Electron-Laser (FEL) operating in the wavelength range 1.5-15 Å. This FEL called "Linac Coherent Light Source" (LCLS) utilizes the SLAC Linac and is characterized by extremely high peak brightness, sub-picosecond long pulses and a fully transversely coherent radiation.

In present operation, the first two thirds of the SLAC linac are used for injection into the SLAC B-factory, leaving the last third of the linac free for acceleration to energies up to 15 GeV. The LCLS takes advantage of this opportunity, opening the way for the next generation of synchrotron light sources in a cost-effective way. The LCLS proposal is consistent with the recommendations of the Birgenau-Shen Panel Report[1] and the Leone Panel Report[2]. The Birgenau-Shen Report recognizes that "fourth generation x-ray sources ... will in all likelihood be based on the free electron laser concepts. If successful, this technology could yield improvements in brightness by many orders of magnitude". The Birgenau-Shen Panel also assigned the highest priority to the R&D of 4th generation x-ray sources. The Leone Panel states that "Given current 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

[1] Report of the Basic Energy Sciences Advisory Committee, Synchrotron Radiation Light Source Working Group, October 1997.

[2] Report of the Leone Subcommittee of the Basic Energy Sciences Advisory Committee on Novel Coherent Light Sources, February 1999.

should pursue the development of coherent light 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 … “. The Leone report also recommends R&D funding be made available to determine the feasibility and design of such a linac-based source.

A Design Study[3] started in June 1996 and was completed and published in April 1998. It was supported by the original LCLS collaborating institutions (SLAC, LANL, LLNL and UCLA) with the additional help of members from other laboratories (Deutches Elektronen-Synchrotron, European Synchrotron Radiation Laboratory, Lawrence Berkeley National Laboratory, University of Milan, University of Rochester). A panel of experts chaired by Dr. Joe Bisognano (Thomas Jefferson National Accelerator Laboratory) reviewed the design in November 1997. The report of the Review Committee finds no “show-stoppers” in meeting the design specifications and states that “the design presented establishes the feasibility of such a project”.

The following is a brief description of the facility. A photoinjector will be used to generate a bright electron beam. Bunches of electrons (one bunch at the repetition rate of 120 Hz) are accelerated and magnetically compressed from an initial length of 10 psec FWHM to a final one of 280 fsec FWHM. After acceleration to 14.3 GeV, the beam is transported to a 100-m long undulator, where the FEL radiation is generated and channeled to an experimental area. The transport system and the undulator area use an existing tunnel that presently houses the Final Focus Test Beam (FFTB).

The projected peak brightness of the FEL radiation is 10 orders of magnitude greater than presently operating synchrotron radiation sources. Accompanying this FEL radiation, and independent of the lasing action, the spontaneous radiation that will be produced has high bandwidth, comes in sub-picosecond long pulses and is 4 orders of magnitude above existing synchrotron radiation sources. This leap in performance is possible because of the FEL amplification of the spontaneous radiation, and of major advances in the physics and technology of high brightness electron beams. These are the development of rf photoinjectors, the acceleration of very high-brightness electron beams in linear colliders, and the progress in undulator design and their error control. In the LCLS all these technologies converge to produce a scientific tool of extraordinary performance.

Although the design of the LCLS is based on a consistent and feasible set of parameters and hardware specifications, it is recognized (as it was pointed out by the Bisognano Technical Review Committee) that some components require research and development in order to guarantee the performance and to optimize parameters and cost. The major focus of the R&D is in the areas of generating the dense electron beam (i.e. RF photoinjectors and bunch compression), understanding the FEL/SASE process (undulator design and SASE saturation and extension to lower wavelengths) and designing experiments to use the light (physics and X-rays optics). In addition a Conceptual Design Report will be written using the LCLS Design Study as a basis to fill in engineering details for the project.

Given the R&D projects summarized in Section 3 and R&D funds tabulated in section 4 for FY1999-FY2002, construction could start in FY2003. The construction cost of the facility, based on a preliminary estimate, is in the range of M$70-100.

[3] LCLS Technical Design Review Report, SLAC, December 1997.

# 3. R&D ISSUES

The main research and development topics of the LCLS can be divided into the following WBS groupings:

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| WBS.1 | FEL Physics |
| WBS.2 | Parameter Control |
| WBS.3 | Injection |
| WBS.4 | Linac |
| WBS.5 | Undulator |
| WBS.6 | X-ray Optics |
| WBS.7 | Scientific Experiments |
| WBS.8 | CDR |

The remainder of this section details the R&D plan of these groups.

## 3.1 FEL Physics

### *3.1.1 Introduction*

The LCLS is a 1.5 Å Self Amplified Spontaneous Emission (SASE) free-electron laser (FEL), generating a diffraction limited X-ray pulse of subpicosecond duration, with very large brightness and peak power - about 10 orders of magnitude larger than 3rd generation light sources. The SASE-FEL theory has been developed starting from the 1980s and continuing in the last decade. However experimental verification of the theory has been obtained only during the last few years, and only at infrared or visible wavelengths[4]. These experiments verified all the critical physics issues of a SASE-FEL, like gain length, slippage, optical guiding in the presence of large diffraction. Another important characteristic, the power saturation level, has not been measured directly until now. New experiments are now being prepared to complete the verification of the theory, and extend it to shorter wavelengths, in the 1000 Å region or shorter. The LCLS collaboration is planning the VISA experiment that will be done using the ATF at BNL. Other experiments will be done using the LEUTL facility, at Argonne-APS, the TTF-FEL at DESY, and the ATF and the DUV-FEL facility at BNL. Even though there is confidence that the present theoretical model on which the LCLS design is based are valid even in the one angstrom region, it is important to continue testing the theory to obtain any information relevant to the LCLS. The VISA experiment is being carried out as part of the LCLS R&D program to test some aspects of the SASE-FEL physics, which have not as yet been explored. These are

- Saturation level;
- Intensity fluctuations at saturation;
- Effects of a strong focusing undulator;
- Mode analysis of the transverse characteristics of the FEL radiation at saturation;
- Evolution of the FEL intensity, line width, and transverse characteristics along the undulator;
- Time structure of the radiation pulse.

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[4] R. Sheffield, J. Goldstein, and D. Nyguen, Proc. SPIE LASE97 Conference, San Jose, California, p.2988 (1997); R. Prazeres et al., Phys. Rev. Lett. 78, 2124 (1997) ; M. Hogan et al., “Measurement of High Gain and Intensity Fluctuations in a SASE FEL”, Phys. Rev. Lett., Vol.80, p. 289 (1998).

The LCLS physics group will give priority to support of the VISA experiment, and to the analysis of the data that VISA and the other experiments will produce. A second point important for the future of the LCLS from the point of view of applications is that an X-ray FEL is very different from a storage ring based light source. The capability of shaping the temporal and spectral structure of the X-ray pulse, and controlling the power level is an important characteristic of an X-ray SASE FEL. The control of the temporal and spectral characteristics can be obtained by inserting optical elements into the FEL, and by using multiple undulators. At the same time, the control of the electron pulse charge and time duration, which can be obtained by changing the photoinjector charge and the compression in the linac, offers the opportunity to change the output power and pulse length over some range. Using these techniques, it is possible to match the LCLS X-ray pulse to the particular experiment being done. This close interaction between the FEL and the users will be a novel feature of the LCLS compared to other light sources. Hence another important task of the LCLS physics group is to explore all these possibilities and prepare the ground for the experiments that will verify these options. Last, but not least, the results of theoretical and exploratory studies will have to be implemented into computer codes that will be used to explore the LCLS parameter space, and compare theory and experimental data.

### *3.1.2. Tasks and Timelines*

The main goals of the FEL physics group in the R&D period of the LCLS follow from the previous discussion. A workshop on LCLS physics and simulation codes will be held in September 1999 at SLAC. This workshop will discuss in more detail what are the important physics issues and what are the corresponding priorities as well as the status and development of numerical simulation codes. Participants to the workshop will include the LCLS physics group members, the FEL theory and simulation communities and the LCLS group leaders. While this workshop is expected to produce many new ideas, the present general outline of the FEL physics R&D is as follows.

- Development of the fundamental understanding of FEL physics;
- Analysis of data from SASE-FEL experiments - VISA, LEUTL, TTF-FEL, ATF and DUV-FEL - to continue the verification of FEL theory and to benchmark the simulation codes;
- Study of the initial LCLS operation and experimental setup to verify the SASE-FEL theory at 1.5 Å;
- Investigation of different modes of FEL operation, including the use of optical instruments and multiple undulators, for the control of the X-ray pulse characteristics - power, linewidth and time duration;
- Studies of electron beam collective dynamics including collective and radiation effects, particularly in the undulator, and their influence on the FEL performance;
- Optimization of the FEL design in order to extend design flexibility and availability of options.

*FY1999*

- Theoretical and simulation support of the VISA SASE-FEL experiments, including data analysis and use of data for benchmarking codes;
- Examination of the available simulation codes, and of the additional features needed, will be used to define a plan to identify and develop one or more codes that will satisfy the needs of

VISA and the LCLS. The code(s) will include error analysis and the transport of radiation to the detectors in the experimental areas;

- Continuation of the studies of electron beam dynamics in the gun-linac-compressors-undulator complex to identify operating conditions that will produce saturated FEL radiation at different power level, emittance, energy spread and energy chirping. This will be done in conjunction with the Injector and Linac groups;
- Studies of the effect of coherent radiation emission in the compressors and undulator; development of strategies to minimize these effects;
- Studies of collective effects in the undulator like resistive wall losses, and diffraction losses due to vacuum pipe roughness.

*FY2000*

- Continuation of the theoretical and simulation support for the VISA, LEUTL, TTF SASE-FEL, ATF and DUV-FEL experiments, including data analysis and use of data for benchmarking codes;
- Continuation of the studies of electron beam dynamics in the gun-linac-compressors undulator complex to identify operating conditions that will produce saturated FEL radiation at different power level, emittance, energy spread and energy chirping;
- Regenerative amplifier, harmonic generation, and two-undulator schemes to reduce the FEL line-width;
- Quantum noise effects in the FEL start-up process;
- X-ray radiation pulse compression schemes.
- Studies of collective effects in the undulator like resistive wall losses, and diffraction losses due to vacuum pipe roughness.

*FY2001,2002*

- Continuation of the theoretical and simulation support for the VISA, LEUTL and TTF SASE-FEL experiments, including data analysis and use of data for benchmarking codes;
- Continuation of the studies of electron beam dynamics in the gun-linac-compressors-undulator complex, to identify operating conditions that will produce saturated FEL radiation at different power level, emittance, energy spread and energy chirping;
- Continuation of the regenerative amplifier, harmonic generation, and two-undulator schemes to reduce the FEL line-width;
- Continuation of the quantum noise effects in the FEL start-up process;
- X-ray radiation pulse compression schemes;
- Studies of collective effects in the undulator like resistive wall losses, and diffraction losses due to vacuum pipe roughness.

## 3.2 Parameter Control

### *3.2.1 Introduction*

The LCLS R&D project, like any other large project, is characterized by a rich set of detailed parameters. Many of the parameters necessary for the LCLS have already been established during the work of the LCLS Design Study group and are published as appendix in the group's report. The LCLS R&D effort will add more parameters and will further optimize the parameters of the initial LCLS design study. The LCLS Parameters Control group will maintain a complete parameter set for the candidate project design as it develops during the course of the R&D effort and will ensure that parameter changes will not negatively affect the integrity of the project design. The parameters will be stored and maintained in an online commercial database with continuous public read access from the WWW. Change access will be controlled by the group and will be restricted to the LCLS management.

### *3.2.2 Tasks & Timelines*

The objectives of the LCLS Parameters group are

- To establish a complete and up-to-date compilation for all parameters relevant to the LCLS project throughout the duration of the project. The data will be stored in a commercial database with WWW interface that will provide controlled access.
- To improve and to use simulation codes to assess the impact of system parameters and parameter changes on FEL performance and to establish parameter tolerances.
- To provide FEL simulation services to other LCLS R&D Groups.

*FY1999*

The main goal in FY1999 will be to start establishing the parameter database, upgrade the capabilities of existing FEL simulation codes and to use FEL simulations to find answers to parameter-related requests.

- Using the ORACLE RDB commercial database product, software will be developed that will allow to store and maintain all parameters of the LCLS project to as much a level of detail as required. The product will include a WWW interface that will allow selected access for various groups: Read-Access to the general public, Update-Request-Access to the LCLS management group and Modify Access to the Parameter Controls group.
- The simulation codes FRED3D and NUTMEG will be migrated to the J90 platforms at NERSC to make them again available as simulation tools. They had been installed on the C90 platforms at NERSC and have become unavailable when the C90 computer system was put out of service last Fall. The GINGER code will be upgraded with the goal of making it one of the two main LCLS Project Codes (the other Project Code will be GENESIS 1.3).
- Simulations and parameter optimizations will be carried out to test the feasibility of various project parameters that are being considered as part of the general R&D effort.

*FY2000*

The main goal in FY2000 will be to establish a working set of project parameters that are backed by simulations. The setup of the parameter database will be completed, the upgrade of FEL simulation codes and the support of R&D efforts with FEL simulations will continue.

- The parameter database setup will be completed early in this fiscal year. The database will be available as general project resource and will contribute to the communication between the groups. The Parameters Control group will be providing maintenance support for the parameter database.

- The upgrade of the GINGER FEL simulation code will be continued. Other FEL simulation codes, especially GENESIS 1.3, will be added to the list of supported codes. It is felt that it will be important to be able to have several codes available for cross-checking.
- Simulations and parameter optimizations, especially for the undulator selection, will continue. A program of simulations to establish a complete list of tolerances for the undulator will begin in this fiscal year.

*FY2001, FY2002*

In FY2001 the generation of a complete list of tolerances and the maintenance of the parameter database as well as of the FEL simulation codes will continue. FEL simulations to support parameter control will also continue.

## 3.3 Injector

### *3.3.1 Introduction*

The LCLS injector is required to produce nominal bunches of 1 nC charge in a 10-ps FWHM length with a transverse emittance of $<1\ \pi$ mm-mrad at a repetition rate of 120 Hz and energy of 150 MeV. Although simulations show that this should be possible, an experimental verification does not yet exist. Additionally, the timing and intensity stability requirements for the injector beam represent a state-of-the-art performance. The R&D outlined here will demonstrate that it is possible to meet the requirements for the LCLS injector.

### *3.3.2 Tasks and Timelines*

The Injector R&D program is organized according to the following project structure.

WBS.3.1 Photoinjector Design

Although the photoinjector design presented in the LCLS Design Study Report predicted an injector beam meeting the LCLS requirements, there was no headroom to allow for practical shortcomings in the constructed system, and in addition the thermal emittance and other possible effects were ignored. It is known that the design can be improved, and in fact in the intervening two-year period there have been significant advances in our understanding of the emittance compensation process, which is fundamental to the design. The principal simulation code used for photoinjector design is PARMELA. The PARMELA code will be enhanced to include thermal emittance and other effects. The LCLS photoinjector design will be re-examined and a new improved design created with the goal of an integrated emittance of $=0.8\ \pi$ mm-mrad at 150 MeV for the nominal LCLS injector bunch assuming a thermal emittance of $0.3\ \pi$ mm-mrad.

WBS 3.2 Experimental Demonstration of Low Emittance

A transverse integrated emittance of $=1\ \pi$ mm-mrad for a nominal LCLS injector beam will be demonstrated experimentally. This measurement will be accompanied by a full characterization of the 6-dimensional emittance.

WBS 3.3 Comparison of Experiment with Simulations

The validity of PARMELA in the regime represented by the nominal LCLS injector bunch has not been demonstrated. A comparison of PARMELA and experimental results for a nominal LCLS injector beam in the regime of 1 $\pi$ mm-mrad will be made paying careful attention to using the same physical parameters.

WBS.3.4 Scaling of Emittance

The occasional operation of the LCLS in modes requiring variations in the injector beam parameters is being discussed. Scaling rules for photoinjectors exist, but are experimentally unverified in the regime of interest for the LCLS. The scaling of transverse emittance with bunch charge, radius, and bunch length in the regime of the nominal LCLS injection bunch will be experimentally determined.

WBS.3.5 Emittance Growth during Acceleration

Due to non-linear or presently unknown effects, the beam emittance may grow as it is accelerated from the level of 20-30 MeV to the final injector energy of 150 MeV. The emittance growth or lack thereof will be measured for acceleration to 150 MeV.

WBS.3.6 Development of New Instrumentation

The LCLS photoinjector will require the development of new state-of-the-art instrumentation capable of characterizing the unique properties of the beam. Instrumentation to be developed includes: a) devices for measuring, controlling, and monitoring UV laser pulse shapes in the picosecond regime; b) devices for measuring and monitoring electron beam pulse shapes in the picosecond regime; c) devices for real time measurements of the beam emittance on a shot-to-shot basis; d) devices for non-destructive monitoring of the beam emittance; e) devices for measuring, controlling, and monitoring the electron beam timing stability in the sub-picosecond rms regime; and f) devices for non-destructive monitoring of the beam transverse profile.

WBS.3.7 Photocathode R&D

The photocathode material most likely will play an important if not crucial role in the ability to consistently generate nominal LCLS injector beams with integrated emittance of 1 ? mm-mrad. Cu cathodes are the initial choice for the LCLS because they allow an S-band gun to operate with the desired cathode gradient of ~130 MV/m. However, the quantum efficiency (QE) of metal cathodes is low, requiring very high laser energy, and in addition the uniformity of the QE across the cathode surface tends not to be uniform and to change with time. A better understanding of the factors controlling the performance of metal photocathodes will be developed, and in addition new methods of cleaning will be investigated. $Cs_2Te$ photocathodes have been chosen for the AFEL (LANL), A0 (FNAL), CTF (CERN) and TTF (DESY) photoinjectors. The properties of $Cs_2Te$ cathodes and their application to the LCLS photoinjector will be examined.

*FY1999*

- A re-examination of the LCLS photoinjector design will be made.
- The Gun Test Facility (GTF) at SLAC, which uses an S-band split photoinjector, will be used to experimentally demonstrate an emittance of $<2\ \pi$ mm-mrad for a nominal LCLS injector beam at 20-30 MeV.
- The Advanced Free Electron Laser (AFEL) at LANL, which uses an integrated L-band photoinjector, will be used to make a backup low-emittance measurement.
- The PARMELA code will be upgraded at LANL.

*FY2000*

- An emittance of $=1\ \pi$ mm-mrad for a nominal LCLS injector beam at 20-30 MeV will be demonstrated using the GTF at SLAC.
- The emittance measurements at SLAC will be compared with PARMELA simulations in which the same physical parameters are used.
- The 150-MeV injector for the LCLS will be constructed and commissioned at SLAC.
- Instrumentation development will begin at SLAC and BNL. (Some of this work will be shared with the Linac Group.)
- Photocathode R&D will begin at SLAC, BNL, LANL, and UCLA.

*FY2001, 2002*

- Emittance measurements at SLAC including scaling will continue.
- PARMELA simulations will continue at SLAC.
- Instrumentation development will continue at SLAC and BNL. Where appropriate, completed instrumentation will be transferred to the LCLS beamline and commissioned.
- Photocathode R&D will continue at SLAC, BNL, and UCLA.

## 3.4 Linac

### *3.4.1 Introduction*

The LCLS Injector produces nominal 150 MeV electron bunches. These are injected into the linac using a dogleg and are accelerated to 5 - 15 GeV and compressed to 20 *m*m in length. The LCLS Linac group is responsible for all of the systems from the entrance to the dogleg to the entrance of the undulator. In addition the group is also responsible for the systems used to dump the spent electron beam after the undulator. The main challenge in the linac systems is to preserve the transverse emittance during the acceleration and compression and to produce the required peak bunch current at the input to the undulator. The accelerator performance needed for LCLS has to be as good or better than the present best performance of the SLAC accelerator complex. The nature of the SASE process is such that even small degradations in the operational performance of the accelerator will significantly degrade the light output, reducing it to zero in an exponential manner. The existing SLAC linac hardware has to be significantly modified to provide the needed LCLS electron beam parameters and these changes have to be shown to be feasible. In addition work is needed to allow for the range of bunch parameters that may be required for the SASE-FEL physics and scientific experiments.

### *3.4.2 Tasks and Timelines*

The Linac R&D program is organized according to the following project structure.

WBS.4.1 Parameter Optimization

The very short bunch length (i.e., high peak current) of the electron beam presents several of the most significant challenges presented by the LCLS design. These challenges arise in such processes as coherent synchrotron radiation (CSR) within the bending systems, the longitudinal wake-field induced by a rough vacuum chamber surface, and the resistive wall wake-field of the accelerator and undulator vacuum chambers. Unless controlled, these processes will degrade the electron beam parameters such as the transverse emittance and peak current. In order to meet these challenges it is desirable to operate the LCLS at the longest bunch length possible and/or reducing the peak current. Since the peak current required to achieve saturation in the FEL depends strongly on the final transverse emittance, the choice of optimum bunch length and charge should be explored further. This study involves many factors, including a thorough simulation of the incoherent component of the transverse emittance dilution through the entire machine, as suggested by the Technical Review Committee.

WBS.4.2 Bunch compression & CSR

- Study bunch coherent synchrotron radiation theoretically and experimentally. The work will consist of further refining the theoretical model and doing experiments to validate the theory.
- Study the performance of bunch compressors to see if the performance agrees with theory
- Demonstrate the wakefield cancellation of the energy spread coming out a bunch compressor

There is a number of groups at various institutions looking at the theory of CSR and some efforts to measure the effects are underway. The Linac group will keep track of developments and apply them to the LCLS. There are a number of bunch compressors that are capable of looking at bunch compression and CSR effects (e.g. at BNL, LANL, TJNAF). The Linac R&D group will provide any needed expertise in the design of bunch compressors and CSR experiments. LEUTL (at ANL) plans to install a bunch compressor at an energy of approximately 200 MeV and has about 400 MeV linac after the compressor. This setup can be used to validate the LCLS BC1 compressor design and to make careful measurements of CSR.

WBS.4.3 Other accelerator effects

- Further refine surface roughness theory and determine if experiments are possible to validate the theory
- Study significance of $1/z^{1/2}$-wakefield for first few structures
- Look at the possibility of running more than one electron bunch per macropulse in the linac.

SLAC has expertise in both these effects. Designing an experiment to measure surface roughness effects will be a challenge.

WBS.4.4 Instrumentation and Feedback Systems

- Design non-invasive bunch length monitors after BC1, BC2 and DL2. These monitors should measure bunch length pulse-by-pulse or at least over a few seconds. These devices can make relative measurements as long as scaling is constant to a few percent over the scale of at least a week. Ideally the devices would also provide information concerning the pulse shape.
- Study and propose details of feedback algorithms for bunch length control. They must distinguish RF amplitude jitter from phase jitter in order to maintain bunch length and the mean energy at each chicane. A separate system should be proposed for each of BC1 and BC2. It may require knowledge of the details of the diagnostic used for bunch length measurement.
- Specify details of slice emittance measurements for the LCLS beam in the SLAC linac.
- Examine LCLS commissioning, tuning and operating modes to determine that the existing feedbacks will work and that additional feedbacks can be designed. If additional diagnostics are needed they will be designed.
- Design an emittance diagnostic section in between the undulator and the electron beam dump. This will enable the measurement of the degradation of the electron beam parameters in the undulator.
- Survey the existing SLAC linac instrumentation and determine if any new instrumentation is needed or if existing instrumentation needs improvement.

Beam tomography systems, i.e. bunch length and slice emittance measurements, need to be designed for the LCLS. This will be done as group collaboration with perhaps BNL taking a leading role. It is proposed that a bunch length monitor prototype be constructed and tested, perhaps at the LEUTL facility at Argonne. The rest of the items in this WBS are SLAC specific and will be led by SLAC personnel with help from members of the rest of the group.

WBS.4.5 SLAC Linac R&D and Compatibility Issues

- Study and quantify phase and amplitude stability of linac RF systems. Stability over full spectrum of time scales (from 120 Hz to 24 hr scale) needs to be quantified. Recommendations for improvements to meet 120-Hz 0.15° (S-band) rms LCLS specifications will need to be made. In addition the question of whether multiple tube stability is better or worse than single tube stability and at what time scales will have to be answered.
- Study RF phase stability with respect to gun laser timing using GTF.
- Investigate choice of RF master oscillator configuration for running the LCLS linac. When running PEP-II, the linac phase is adjusted on a pulse-by-pulse basis to allow for injecting into the correct ring location. A determination of whether this will cause problems for running the LCLS is needed and if changes in the oscillator configuration will need to be designed to eliminate these problems.
- Determine if there are other compatibility issues when running with the rest of the SLAC accelerator complex. A need for test beams into the SLAC End Stations exists and the parameters of such test beams will have to be accommodated in the LCLS design.
- Examine quality of RF structures in sectors 21-25 to verify 300-μm rms misalignment simulation validity. Beam energy in LCLS Linac-2 can be up to 100 times lower than SLC beam at these locations. Structure swapping for SLC in the 1980's may have concentrated worst structures where LCLS beam is most sensitive.

These items concern details on how the SLAC linac runs and will be done by SLAC personnel with help from who ever is interested from the rest of the group.

WBS.4.6 Start-to-End Simulation

- Set-up a simulation system that all aspects of the LCLS accelerator can be realistically simulated and data from one program can be transferred to another.
- Make a list of the programs that can be used and tabulate what is missing from them. If possible try to add the missing physics. There should be at least two independent programs (or sets of programs) to simulate the entire LCLS.
- Simulate electron bunch through full LCLS accelerator. Include space charge effects at least up to Linac-1. Space charge effects in Linac-3 where bunch is shortest will need to be checked. Particle tracking through imperfect accelerator structures will be made. These computations will include wakefields, chromatic effects, steering algorithms, and bunch compression.

These items will be done group and collaboration wide. A new post-doc will be heavily involved in the start-to-end simulation.

WBS.4.7 Alignment

The linac alignment tolerance is nominally 300 *m*m for the structures and 150 *m*m for the quadrupoles. These tolerances assume that “emittance bumps” – as used successfully in SLC running – will be used to reduce the emittance growth due to misalignments to acceptable levels. In addition the alignment of the last kilometer of the SLAC linac that is used for the LCLS has been less critical for SLAC accelerator operation up till now. For this reason and in order to reduce the dependence on “emittance bumps” it is desirable to re-align the linac structures and quadrupoles as well as possible. An improved alignment could be reached with conventional methods, but this would require more linac down time than is expected to be available. It is therefore suggested to develop a laser-based system built on the Hamar Lasersystems’ components. An early start is desirable, as this study requires access to the linac tunnel.

WBS.4.8 Help write CDR

The work in WBS.4.1, WBS.4.3, WBS.4.4, WBS.4.5 and WBS.4.8 will be ongoing during the whole LCLS R&D period. Some projects can be completed in FY1999, FY2000 and these are described below.

*FY1999, FY2000*

The nominal LCLS bunch length at 15 GeV is 20 *m*m rms. CSR and surface roughness effects on the emittance are worse the smaller the bunch length. An optimization of this and other linac parameters will be carried out, aiming to increase the final bunch length to 35 *m*m rms. Work will also be done for other bunch length, emittance and charge parameters to see if there are better operational parameters sets and to extend the capabilities of the LCLS. Of course these parameters have to be consistent with the SASE process in the undulator. This work will be done at SLAC (WBS.4.1).

SLAC will help with the design of the new bunch compressor to be installed at LEUTL. This compressor can be made to look similar to the LCLS BC1 and experiments done using this compressor will help validate its design. In addition, CSR theory can be compared to the experimental results. SLAC will also help evaluate the SDL bunch compressor and analyze the results. Additional CSR experiments will be conducted using the SPA at LANL. The results from all these experiments will be compared with theoretical estimates of CSR effects used to design compressors and dog-legs in the LCLS (WBS.4.2).

Work on the main elements of the start-to-end simulation will be completed (WBS.4.6)

The alignment of the LCLS linac will have to be checked as part of the commissioning process. In order to do this in a time scale consistent with the SLAC B-factory running schedule, a new more automated alignment system will be designed (WBS.4.7).

## 3.5 Undulator

### *3.5.1 Introduction*

The LCLS undulator generates and amplifies X-ray radiation when the low emittance, short-pulse electron beam from the SLAC Linac passes through it. The undulator has a dual function: first, it serves as a electron beam buncher and second, as a radiation amplifier. In order to carry out both functions effectively the undulator consists of the periodic magnetic structure, a focusing system, beam position monitors, radiation diagnostics, a vacuum system, mechanical supports and an alignment system. Independently of the LCLS project, several components of these systems, although used for different purposes, have been already built within LCLS specifications. But never before have all of them been combined together in one 100-meter long structure where most of the components have to perform at state-of-the-art levels. Therefore, significant scientific effort and, more importantly, engineering effort is required to accomplish the R&D in support of the undulator part of the LCLS project.

### *3.5.2 Tasks and Timelines*

The main goal of the undulator R&D part of the LCLS is to establish and prove the technology of the construction of the x-ray FEL undulator, build and test undulator prototypes. These prototypes would include several meters long periodic magnetic structure sections, electron beam focusing system, electron beam diagnostics, vacuum system, mechanical supports and alignment system, radiation diagnostics. The plan is to examine two types of periodic magnetic structure: a planar, hybrid type (LCLS Design Study choice) and a helical, superconducting one. Each structure has its own advantages and drawbacks and the R&D goal would be to choose, based on the experience with prototypes, most efficient and reliable structure for the LCLS FEL. The R&D plan also calls for the design, fabrication and test of diagnostics, vacuum, mechanical and alignment systems.

All undulator related R&D activities would be directed toward achieving the main goal and would comprise from following major tasks:

- Conduct simulations of the SASE FEL process for the x-ray FEL and based on the results of these calculations:
  - Produce complete physics specifications for the undulator.
  - Complete engineering specifications along with the construction feasibility study for the system that includes:
    - Periodic magnetic structures with ends terminations;
    - Vacuum system;
    - Beam and radiation diagnostics;
    - Mechanical supports and alignment.
- Design of periodic magnetic structures: planar hybrid and helical superconducting.
- Establish the potential fabrication site and produce, in coordination with future potential vendors, a full set of engineering drawings of prototypes.
- Develop a magnetic measurement system that includes:
  - Magnetic sensors
  - Control system
  - Alignment system
- Build, assemble and test prototypes.
- Conduct comprehensive computational analysis of radiation properties.
- Design and build prototypes of the electron beam and radiation diagnostics equipment.
- Conduct tests of prototypes with a low-energy beam.

The R&D tasks described above can be grouped in the following "WBS" tasks.

WBS 5.1 Simulations and Calculations

The first part of the development of the LCLS undulator system will consist of a numerical analysis of the SASE FEL process for the specific LCLS case. This work will be done in coordination with the FEL Physics and Parameters Control groups and will absorb results presented in the LCLS Design Study Report. The completion of this analysis will result in a comprehensive list of physical and engineering specifications for both types of the periodic magnetic structures as well as a full list of tolerances needed for the engineering design. This list will include tolerances not only for periodic magnetic structures but also for the focusing elements, beam and radiation diagnostics and vacuum and mechanical systems.

WBS 5.2 Engineering Design Process

After the completion of the specifications the detailed engineering design of prototypes for most of the components of the undulator system will take place. Both the planar hybrid magnetic and helical superconducting structures will be designed. The focusing system, beam position monitors and mechanical supports with the required alignment systems will also be designed. The design process will be conducted in close communications with prospective vendors in order to assure the design feasibility. A Design Review Committee will be formed to assess the quality of the design.

WBS 5.3 Magnetic Measurements

Magnetic measurement techniques play a crucial role in the characterization of the magnetic quality of undulators as well as in their improvement using different "shimming" methods. In order to conduct magnetic measurements of the LCLS prototype undulators, the APS magnet measurement facility (MMF) will be upgraded with new magnetic sensors. These sensors will be capable of taking measurements of both vertical and horizontal field integrals in very small magnetic gaps. Also, a new special sensor to conduct magnetic measurements of the helical superconducting undulator will be designed and built. Equipped with these new sensors and improved measurement techniques, the MMF will perform comprehensive magnetic characterizations and final tuning of undulator prototypes. In addition the beam focusing system will be measured and certified at the MMF.

WBS 5.4 Prototype Construction

Although many components of undulator prototypes will be manufactured by outside vendors, some of the components will have to be made at the APS or at SLAC. The BPM and the vacuum chamber prototypes could be fabricated and tested at these institutions. The final assembly of the whole system will take place at the APS. The experience accumulated by the APS in vacuum chamber design and fabrication and the experience acquired by SLAC in the construction of the FFTB will be used in the process of the construction of undulator prototypes.

WBS 5.5 Prototype Testing

The final test of components and the integrated undulator system will take place at the APS and SLAC. Based on the results of these tests the final design approach will be established.

The WBS tasks described above are broken down in years as follows.

*FY1999, 2000*

The work in FY1999 and FY 2000 will consist of doing simulations and calculations, working out the details of the engineering design process and setting up the magnetic measurements system (WBS 5.1, 5.2, 5.3).

*FY2001*

In FY2001 the simulation and calculation work will be completed and the engineering design process will be completed (WBS 5.1, 5.2). Work on the magnetic measurement system will continue (WBS 5.3). Work on prototype construction and testing will begin (WBS 5.4, 5.5).

*FY2002*

In FY2002 the undulator work will consist of prototype construction, magnetic measurement and prototype testing (WBS 5.3, 5.4, 5.5).

## 3.6 X-ray Optics

### *3.6.1 Introduction*

A single ~300fs LCLS 1.5Å pulse, at the baseline power density, will deposit 10-100 eV/atom in any solid material placed in the beam at normal incidence. The challenge for x-ray optics is to develop reliable methods to manipulate and control the optical parameters of this beam and to provide the experimenter an accurately diagnosed x-ray source with the appropriate intensity, energy spread, time structure, angular extent and coherence as required by the experiment.

A preliminary design of the LCLS X-ray Optics system has been completed and is described in the LCLS Design Study Report. Its basic features include:

- windowless radiation transport through a series of Ultra High Vacuum regions isolated by differential pumping sections,
- an attenuation cell to reduce the peak power density of the LCLS pulses to levels required by the experiments, and
- a nominal set of spectral and angular filtering capabilities to provide a flexible range of beam parameters for exploratory experiments.

The basic x-ray optics components to provide these capabilities are: grazing incidence mirrors, diffraction crystals, pinholes and a gas attenuation cell. In the preliminary design study simplifying assumptions were made concerning the phase-space properties of the coherent and spontaneous radiation, and the optical constants of the beam line elements. In addition, the radiation/matter interaction was assumed to be in the linear regime (e.g. the energy absorbed was assumed to be proportional to the intensity multiplied by an interaction time). The proposed X-ray Optics R&D program will:

- improve the understanding of the LCLS source properties,
- extend the modeling to include non-linear phenomena,
- refine and improve the designs for the vacuum and transport systems and optical components,
- develop specific x-ray optics and diagnostics for several initial experiments.

### *3.6.2 Tasks and Timelines*

The proposed work divides into two categories, the first being tasks that are absolutely critical to a successful CDR, and the second being more far-reaching, innovative R&D that promises to greatly expand the LCLS capability.

*R&D Critical to LCLS approval:*

WBS.6.1 X-ray diagnostics

Having reliable, absolutely calibrated diagnostics to measure the photon spectrum, intensity, and spatial and temporal distributions as a function of the electron beam charge during the commissioning of LCLS and its subsequent operation is of utmost importance. It is necessary to understand whether conventional diagnostics and optics or extrapolations thereof will be able to withstand the LCLS baseline power density (1.2 x $10^{33}$ photons/(sec-mm$^2$-mrad$^2$-0.1% BW), 1.5 x $10^{12}$ W/mm$^2$ in the coherent radiation). LASNEX, Particle-in-Cell (PIC) codes and ray-tracing codes will be used to study the response of metals and diffraction crystals to x rays.

WBS.6.2 Attenuation cell

To deliver light with minimum shot-to-shot fluctuations, the LCLS must operate at saturation, i.e. 10 orders of magnitude brighter spectral brilliance than 3$^{rd}$-generation light sources. However, many of the experiments will need to be conducted at a much lower intensity thereby requiring a reliable means to reduce the x-ray intensity by many orders of magnitude without increasing the shot-to-shot variation. An absorption cell capable of meeting this requirement will be designed and modeled. Of critical importance is the variation of column depth of bound electrons during the x-ray pulse and the material response to the total fluence of coherent lines, spontaneous emission, bremsstrahlung and secondary particle spectra. Hydrodynamic codes with specialized atomic physics databases, PIC codes and Rayleigh scattering codes will be used to investigate the threshold for non-linear phenomena such as multi-photon absorption and to evaluate the effect of the absorption cell on the temporal and spatial structure of the x-ray beam.

WBS.6.3 Transport system vacuum

Design and performance studies of differentially pumped sections and cryo-pumping to achieve the ultra-high vacuum and ultra-clean environments needed in the optical transport system will be conducted. Ultra-high vacuum systems are required for protection of the optical elements themselves and to preserve the optical parameters of the FEL after it exits the undulator. In addition, techniques for in-situ cleaning of metal, multi-layer optics and crystal surfaces by electron or ion beam bombardment to remove carbon build-up plated on the surfaces by radiation-induced cracking of hydrocarbons found in all imperfect vacuum systems will be investigated.

WBS.6.4 Radiation shielding

Bremsstrahlung and muon production from the beam halo interaction with the collimators protecting the undulator will be evaluated along with possible radiation damage to the magnets, mirrors and collimators from spontaneous syncrotron radiation. Shielding to protect hardware and personnel against photoneutrons, thermal neutrons,and hadrons from the electron dump or due to bremsstrahlung will be designed and modeled.

WBS.6.5 CDR

The optics group will prepare the X-ray Optics content for a CDR, identifying and addressing areas of technical risk in transferring the FEL beam from the undulator to the experiments. In addition to x-ray transport, radiation shielding issues to protect personnel and hardware will be identified and addressed. Documentation will include cost and schedule estimates for design, fabrication, installation and testing of x-ray optics and diagnostics.

*R&D to Expand LCLS Capability:*

WBS.6.6 Micro-focussing optics

Concepts to make a compound x-ray lens utilizing low-Z materials will be investigated and evaluated. One possible realization of this idea would be a linear array of microvacuoles surrounded by liquid helium. Such a compound lens of $F/10^4$ could in principle focus the beam to a spot of order ~ 1 micron, thus increasing the FEL brilliance by 3-4 orders of magnitude. Other micro-focussing concepts to be studied include ellipsoidal mirrors, transmissive multilayer optics and zone plates. Fabrication technologies will be investigated and the performance of micro-focussing optics will be designed and numerically modeled with the goal of focussing the LCLS beam to ~1 micron spot size.

*FY1999*

The principal milestones are:

- use analytic theory and perform numerical simulations of the interaction of the intense x-ray beam (from the FEL) with matter (i.e. metals, dielectrics and gases) and identify the limits where standard diagnostics can be used,
- design an attenuation cell to provide a means to reduce the intensity to below those limits. Theoretical and numerical studies of the source properties of the LCLS will be continued in support of these goals.

LASNEX will be used to model the radiation interaction in metals. X-ray intensity thresholds corresponding to:

- no damage (continuous use),
- localized damage in one pulse (raster undamaged material into the beam after each pulse),
- severe damage (replace optic each pulse) will be identified. Comparisons will be made with nuclear experiments and laser-damage data.

Analytic estimates will be made for the change in the index of refraction due to ionization.

LASNEX will be used to model absorption in gases to provide basis for the design of an attenuation cell. In addition Compton and Rayleigh scattering codes will be used to assess the effect of the attenuation cell on the optical parameters of the beam.

An attenuation cell will be designed based on the results from the interaction with matter studies to provide protection to the diagnostic components. Hydrodynamic and PIC code simulations will be used to evaluate the effect of the intense x-ray beam on the cell and the effect of the cell on the temporal and spatial structure of the beam. Effects of both spontaneous and coherent radiation will be calculated and the requirements for up-stream collimating slits will be determined. The attenuation cell may make it possible to use conventional X-ray diagnostics to continuously diagnose the FEL parameters from low intensity levels through gain saturation.

*FY2000*

The modeling foundation established in FY99 will be extended and benchmark experiments to validate the predictions of grazing incidence mirror performance under high energy loading will be performed. Prototypical x-ray optics components will be designed, fabricated and tested. Mechanical and vacuum design and performance studies of the absorption cell will be continued. In addition, the x-ray optics and diagnostic requirements for specific applications and experiments will be investigated. The group will begin writing the Conceptual Design Report to be ready by early-2001.

Pulse-probe experiments to measure the response of various x-ray optics to 1.5 Å radiation while being irradiated with an intense, short pulse laser will be designed. The experiments will be designed to produce energy-loading profiles similar to those calculated for LCLS.

Grazing incidence collimating slits located at ~10 meters from the undulator exit will potentially have the largest energy loading of any of the optical components. The performance of metal mirrors at 1.5Å under these conditions is not well known. The USP laser facility will be used to create a beam of 8-keV photons and measure the reflectivity of metal surfaces while another short pulse laser will provide the appropriate energy loading profile.

Modeling the LCLS source properties (coherent, spontaneous and bremsstrahlung) will continue and radiation shielding requirements to protect personnel and hardware will be established.

All x-ray optics components for one specific experiment (mirrors, crystals, x-ray slits, etc.) will be designed and prototypical optics will be fabricated. In addition those components whose performance has not been demonstrated will be tested at suitable facilities. Anticipated signal levels for typical diagnostics will be calculated to determine the need for further R&D.

Differential pumping designs to isolate the attenuation cell gas load from the rest of the beamline/transport system will be evaluated. If the performance appears marginal, a test prototype will be built and R&D conducted to establish an adequate differential pumping capability.

Concepts for reflective and transmissive refractive optics to focus the LCLS beam will be investigated. Analytic and numerical studies of the optimal surface shape will be conducted and possible fabrication technologies will be evaluated.

*FY2001& FY2002*

Investigations of specific experimental requirements will continue with extension and refinement of the optical components and diagnostics systems definition and design. Studies of LCLS source properties, as well as the development of the absorption cell design, will be continued. Development of microfocusing optics and other special-purpose optics that may be identified will continue. Integral simulations of the signal strengths recorded by the diagnostics for individual experiments will be made.

Thresholds for damage in dielectrics will be identified. LASNEX will be used to calculate the heat loading which will be used as input to other specialized codes to address time dependent Debye-Waller effects, spall, the possibility of Coulomb explosion and internal structural damage produced by ionization of the dielectric. Analytic estimates will be made for the change in the index of refraction due to ionization.

The USP laser facility will be used to study x-ray diffraction optics under extreme energy loading. One beam will create a point source of 8-keV photons which will be diffracted by the crystal. The diffracted signal will be monitored while a second beam of optical radiation will deposit an energy loading profile similar to that calculated for LCLS. Thresholds for the onset of non-linear diffraction phenomena and for permanent lattice damage will be determined.

## 3.7 Scientific Experiments

### *3.7.1 Introduction*

The LCLS will provide a uniquely powerful source of radiation in the hard x-ray spectral region. Its peak intensity and peak brightness will be many orders of magnitude higher than can be produced by any other source. The sub-picosecond pulse length will be orders of magnitude shorter than can be achieved with any other bright source such as a synchrotron. And the radiation will be highly coherent, with a degeneracy parameter (photons/coherence volume) equal to $10^9$ or more. No other hard x-ray source has a degeneracy parameter significantly greater than one.

These properties offer the chance to study chemical, biological, and condensed matter dynamical processes with sub-picosecond time resolution and angstrom spatial resolution. Using the LCLS, one could determine the atomic structures of very short-lived chemical states, or study changes associated with transient extreme environments such as ultra-high pulsed magnetic fields. Dynamics in materials such as gels and glass-forming liquids could be studied, on a time scale complementary to that probed by neutron spin echo and dynamic light scattering techniques, but with better spatial resolution. Furthermore, the high peak power of the LCLS radiation could be used to create precisely-controlled chemical and structural modifications inside samples. There is also the possibility that nonlinear x-ray interactions could be used to give increased resolution for spectroscopic studies, to greatly expand the parameter space for atomic physics studies, and to permit new fundamental tests of quantum mechanics.

The great leap in capability provided by the LCLS will take some time to be utilized fully, requiring advances in x-ray optics, sample handling, detection, and data analysis, as well as some advances in understanding the basic physics of the interaction of very fast, intense x-ray pulses with matter. The challenge for the Scientific Experiments R&D is to define the first few experiments that can be done that will clearly demonstrate the possible capabilities of the LCLS.

### *3.7.2 Tasks & Timelines*

The main goal of this R&D task is to define four to five experiments with exciting science taking advantage of the unique properties of the LCLS source and compatible with the developments of x-ray optics and end-station instrumentation.

*FY1999*

- initiate the selection of a number of scientific experiments according to the ”overall goals”;
- initiate discussion of a visitors program for which SSRL hosts a series of medium – term visits (3-12 months) by respected senior scientists who are willing to take on responsibilities for the test experiments on the LCLS;
- define a program for the scientific interaction with the relevant laser physics community;
- initiate discussions with the x-ray optics group on possible developments of the required optics and instrumentation;

*FY2000*

- conduct a workshop in conjunction with the SRI ’99 with the purpose of defining and selecting the most exciting and feasible experiments for the LCLS;
- define the selection of a number of scientific experiments according to the ”overall goals” and with the inputs from the SRI ’99 workshop and the scientific case report prepared by G. Shenoy;
- implement a visitors’ program for which SLAC hosts a series of medium-term visits as described under ”tasks FY99”;
- assist the visiting scientists (above) in organizing workshops addressing specific problems related to proposed research programs;
- carry out a program for the interaction with the relevant laser physics technology community and establish close ties with the laser expertise available at Stanford University;
- work in close collaboration with the x-ray optics group with the required optics for specific experiments and for the diagnostic instrumentation required for the experiments;
- on a continual basis their will be close interaction with the LCLS management and the machine physics groups on the overall aspects of the project;

*FY2001&2002*

In the third and fourth years the efforts described for FY 2000 will continue. The tasks will be refined as required by the continued progress.

## 3.8 CDR

### *3.8.1 Introduction*

Working backwards from an LCLS construction start in FY2003, a CDR has to be finished before April, 2001. It is proposed that all the major design decisions needed to write the CDR will be made by the end of FY2000 and that writing, editing and publishing the CDR will happen in the first half of FY2001.

### *3.8.2 Tasks & Timelines*

The LCLS CDR will be based on the LCLS Design Study Report dated April 1998. It will be updated based on subsequent decisions and the results of the R&D Program. New sections will be added on a Work Breakdown Structure (WBS), Cost and Schedule, and Management. Also, a separate section will be provided for the Experimental Hall.

The WBS.8 group will take responsibility for the Preface, Executive Summary, Experimental Hall and project management sections and the overall editing and production. The other sections will be the responsibility of the individual subsystem managers. The costs for preparing those sections should be included in the subsystem R&D budgets.

*FY1999, FY2000*

This time will be used to prepare to write the CDR. By the end of FY2000 all of the substantial questions concerning the configuration of the LCLS will have been answered.

*FY2001*

The final draft of the CDR will be completed by the end of December, 2000. In January through February of 2001 the document will be edited and put into its final form. The CDR will go to press in March of 2001.

# 4. MILESTONES AND DISBURSEMENTS

## 4.1 Milestones

The milestones for the LCLS R&D program are as follows:

| | |
|---|---|
| Begin the formal research and development program | July, 1999 |
| Complete R&D program MOUs with collaborating institutions | September, 1999 |
| Key parameters and technologies determined<br>(Beam lattice, injector structure, undulator type, etc.) | October, 2000 |
| Conceptual Design Report complete | March 2001 |
| DOE Review of the design | May 2001 |
| Construction begins | October 2002 |

## 4.2 Disbursements

The LCLS R&D funds will be distributed to the collaborating institutions by the SSRL Business Office at the direction of the LCLS Program Manager. The statements of work for these funds are described in the MOUs (and their addenda) between SLAC and the collaborating institutions. The collaborating institutions will submit monthly cost reports to the SSRL business office for review by the LCLS program management.

The statements of work and the associated distribution of funds will be reviewed every six months as provided in the MOUs. The initial distribution of LCLS R&D funds for FY2000 will be approximately as follows:

| | |
|---|---|
| Stanford Linear Accelerator Center | $425K |
| Argonne National Laboratory | $375K |
| Lawrence Livermore National Laboratory | $350K |
| University of California at Los Angeles | $150K |
| Los Alamos National Laboratory | $100K |
| Brookhaven National Laboratory | $100K |
| Total | $1,500K |

## 5. SUMMARY

The LCLS is a multi-institutional collaboration bringing together excellence in accelerator technology, free electron lasers, and x-ray optics. The LCLS will have capabilities that are unique and the opportunity to use the SLAC linac puts these capabilities within reach in a reasonable time with modest funding.

The R&D plan described in this document spans four years of research and development effort from FY1999 through FY2002. This effort will lead to a design of the LCLS such that it can be built with a high confidence of success starting in FY2003.

The cost of this R&D effort has been estimated at approximately $12 million. The DOE/BES is expected to fund $6 million of this directly through the LCLS Program Office at SLAC/SSRL. The remaining $6 million will come from other funds at the collaborating institutions.

## APPENDIX: GLOSSARY OF ACRONYMS

This appendix list the acronyms used in this documents.

| | |
|---|---|
| AFEL | Advanced Free Electron Laser (at LANL) |
| ANL | Argonne National Laboratory |
| APS | Advanced Photon Source (at ANL) |
| ATF | Accelerator Test Facility (at BNL) |
| BES | Basic Energy Sciences |
| BC | Bunch Compressor |
| BNL | Brookhaven National Laboratory |
| BPM | Beam Position Monitor |
| CDR | Conceptual Design Report |
| CERN | European Center for Nuclear Research |
| CSR | Coherent Synchrotron Radiation |
| DESY | Deutsches Elektronen-Synchrotron |
| DL | Dog Leg |
| DOE | Department of Energy |
| DUV-FEL | Deep Ultra Violet FEL (at BNL) |
| FEL | Free Electron Laser |
| FFTB | Final Focus Test Beam (at SLAC) |
| FNAL | Fermi National Accelerator Laboratory |
| GTF | Gun Test Facility (at SLAC) |
| LANL | Los Alamos National Laboratory |
| LCLS | Linac Coherent Light Source |
| LDRD | Laboratory Directed Research and Development |
| LEUTL | Low Energy Undulator Test Line (at APS) |
| LLNL | Livermore National Laboratory |
| MMF | Magnet Measurement Facility (at APS) |
| NERSC | National Energy Research Scientific Computing Center |
| QE | Quantum Efficiency |
| R&D | Research and Development |
| RF | Radio Frequency |
| SASE | Self Amplified Spontaneous Emission |
| SDL | Source Development Laboratory (at BNL) |
| SLAC | Stanford Linear Accelerator Center |
| SPA | Sub-Picosecond Accelerator (at LANL) |
| TJNAF | Thomas Jefferson National Accelerator Facility |
| TTF-FEL | Tesla Test Facility FEL (at DESY) |
| UCLA | University of California at Los Angeles |
| VISA | Visible Infrared SASE experiment (at ATF) |
| WBS | Work Breakdown Structure |