A 2-4 nm Linac Coherent Light Source (LCLS) Using the SLAC Linac*

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Abstract

We describe the use of the SLAC linac to drive a unique, powerful, short wavelength Linac Coherent Light Source (LCLS). Operating as an FEL, lasing would be achieved in a single pass of a high peak current electron beam through a long undulator by self-amplified spontaneous emission (SASE). The main components are a high-brightness rf photocathode electron gun; pulse compressors; about 1/5 of the SLAC linac; and a long undulator with a FODO quadrupole focussing system. Using electrons below 8 GeV, the system would operate at wavelengths down to about 3 nm, producing ≥10 GW peak power in sub-ps pulses. At a 120 Hz rate the average power is ≈1 W.

I. INTRODUCTION

Two recent developments have opened the possibility to construct linac-based x-ray lasers operating at short wavelengths, down to 2 nm and eventually as low as 0.1 nm. The first is the development, at Los Alamos and elsewhere, of rf photocathode electron guns which can now deliver low emittance (3-4 mm-mrad normalized emittance), high charge (>1 nC) electron beams. The second is the development at SLAC, as part of the SLC project, of the tools and understanding associated with the transport, acceleration and compression of electron bunches without dilution of phase space density. These developments make it possible to deliver electron beams with the required phase space density to drive short wavelength lasers.

The main components of the short wavelength LCLS we have studied are (1) a high brightness, rf photocathode electron gun, (2) 7 sectors of linac, (3) beam transport and compressor systems, (4) beam diagnostics and controls, (5) a long undulator (50-75 m), (6) an enclosure to house the undulator, (7) electron beam dump, (8) mirror station, (9) a photon beam line and two diagnostic/experimental stations and (10) a building to house these stations.

In addition to the existing linac, an enclosure to house the undulator exists at the end of the SLAC linac. This is the Final Focus Test Beam (FFTB) housing completed in early 1993 for r&d associated with final focus systems for future linear colliders. There is ample room in this enclosure for the LCLS undulator. After a slight upgrade, the FFTB enclosure would provide adequate shielding for alternating operation of both facilities.

We propose an r&d facility aimed at the development of linac-driven, short wavelength x-ray lasers, and their scientific and technological utilization. The first laser would start operation at a wavelength around 10 nm or longer and then reach the 3 nm region. With more extensive r&d, along with the use of higher energy electrons and additional undulators, and with improvement in the performance of certain components such as the rf photocathode gun, it is expected that the facility could achieve (with additional funding) a laser functioning at even shorter wavelengths, possibly in the 0.1 nm region.

The LCLS photon beams emerge into the SLAC research yard, about 125 m from SSRL beam lines on SPEAR. Thus, once the LCLS facility is operational, it is possible to bring a beam from it and SPEAR to the same sample chamber, for pump/probe experiments for example.

The proposed LCLS operates on the principle of the FEL, but does not require an optical cavity which is difficult or impossible to make at such short wavelengths. Instead, x-ray laser operation is achieved by Self-Amplified-Spontaneous-Emission (SASE) in a single pass of an electron beam through a 50-60 m long undulator.

Although SASE theory is well developed, there is, to date, little experimental data with which to compare it since most FELs have used oscillator cavities. It is therefore important to make detailed comparisons between experiment and theory, for example to verify the accuracy and wavelength dependence of simulation codes and assumptions about startup from noise. We plan to do this initially at wavelengths around 10 nm or longer. At these wavelengths certain tolerances are more manageable. As experience is gained and tighter tolerances met, operation down to about 3 nm can be expected, still using electrons below the 10 GeV that will be available in the proposed facility. The characteristics of the light produced by the LCLS at 4 nm are projected to be:

Peak Coherent Power (GW)	≥ 10
Pulse Repetition Rate (Hz)	120
Pulse Width (1 sigma - fs)	<160
Photons/pulse	$\geq 10^{14}$
Energy/pulse (mJ)	3
Bandwidth (1 sigma)	0.1-0.2%
Peak Brightness *	$\geq 10^{31}$
Average Brightness *	$\geq 10^{21}$

* photons/(s,mm^2,mrad^2) within 0.1% bandwidth

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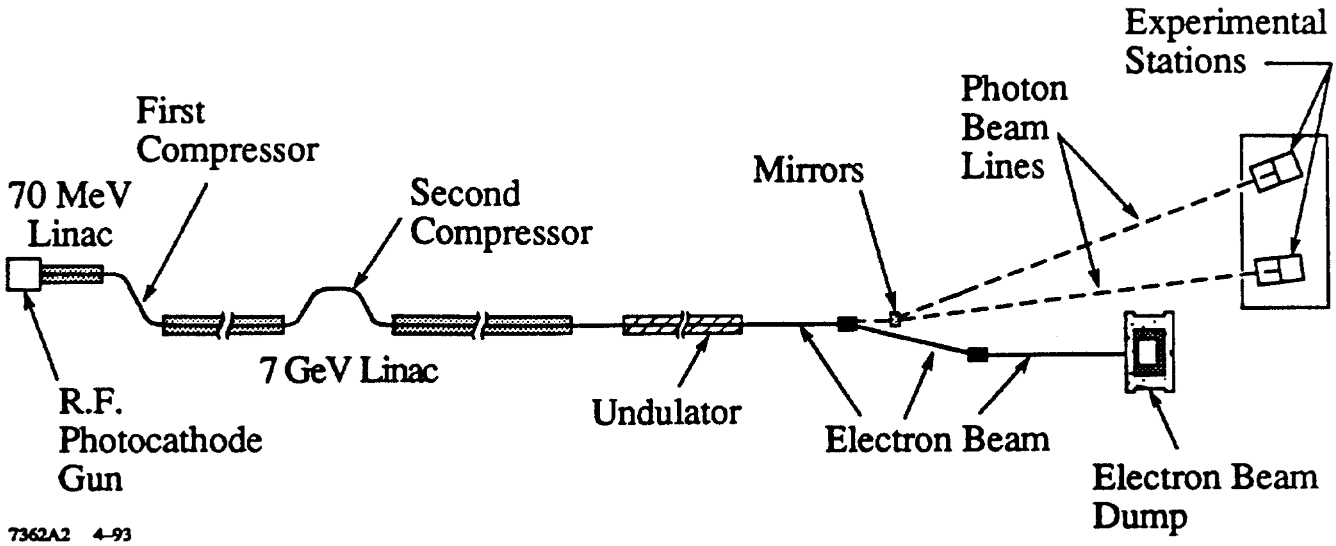

Figure 1
LCLS Schematic Overview

The average values of brightness and coherent power are about 3 orders of magnitude greater than projected for 3rd generation light sources such as the ALS and the peak values are about 9 orders of magnitude higher. Photon beams with this extraordinarily high brightness, coherence and peak power will make possible a wide range of experimental studies in many scientific and technical fields including x-ray imaging of biological specimens in and around the "water window" (including producing x-ray holograms of live biological specimens in a single sub-picosecond pulse); time resolved studies of condensed matter systems and chemical reaction dynamics; and non-linear processes. Because the properties of this light source go many orders of magnitude beyond that available from any other source in operation or construction, it is likely that entirely new scientific applications will be opened up. Exploratory experiments will be carried out on two diagnostic/experimental stations. With two experiments able to receive pulses, techniques will be developed for the rapid switching of the beam, as well as rapid changing of beam parameters such as wavelength and intensity to meet different experimental needs. An FY 1996 Short Form Construction Project Data Sheet has been submitted to DOE for this project. The total estimated cost is $29.45M.

II. SIMULATIONS

Extensive numerical studies have been performed using (primarily) the FRED3D and TDA3D codes. In agreement with simple models, the simulations predict that the LCLS can provide in excess of 10 GW of peak power in a sub-picosecond pulse. The saturation length is about 60 m with strong focusing provided throughout the undulator. The system gain, its optimization and tolerance to beam parameter changes, wiggler errors and misalignments have been studied.[1]

The operating parameters chosen provide relative insensitivity to beam current and emittance fluctuations. By running to saturation, variations in the output radiation due to changes in the beam parameters are minimized. The requirements on the uncorrelated energy spread of the beam are tight (<0.04% rms) and are determined primarily by the desire to maintain a narrow bandwidth and maximum gain. Energy spreads twice as large as specified do not seriously degrade the (single frequency) performance. This, along with the high power (brightness) of the optical pulse, suggests that filtering could be used to narrow the line width.

According to the simulations (using a random walk), the wiggler field errors required are small (<0.2% rms) but within state of the art. Steering and alignment requirements are also tight (30 μms rms), yet less stringent than required for many future linear collider designs.

III. TECHNICAL COMPONENTS

A. RF Photocathode Gun

We have studied the design of an rf photocathode gun which can produce the beam characteristics required for reliable operation of the LCLS. The dynamics of the photoelectron beam have been modelled using both PARMELA, and an axisymmetric particle-in-cell code, ITACA. These simulations show that a one nC, 10 MeV electron beam can be produced in a 3+1/2 cell, 2.856 GHz structure, which has a pulse length of 2 psec and a normalized rms emittance of 3 mm-mrad. The major challenge in designing this source concerns reproducibility of the beam properties. In particular, due to wake-fields in the transport, it is critical that the jitter in the total charge per pulse and the injection timing be minimized [2]. We believe that a solution to these problems exists based on choice of a rugged cathode material and a commercial diode-pumped laser system with timing stabilization [3].

B. Transport, Acceleration & Compression

The bunch produced by the LCLS photo-injector must be accelerated and length compressed before injection into the undulator. In the present scheme the bunch is accelerated from 10 MeV to about 7 GeV using three linear accelerators separated by two compressors[2]. The final bunch length is about 0.05 mm (FWHM) (over a factor of 10 smaller than that produced by the photocathode gun) yielding a peak current of 2500 to 3500 A. The final energy spread is less than 0.2 % (rms).

The choices of energies at which to compress are influenced by the need to 1) control longitudinal wakefields for energy spread minimization, 2) minimize emittance growth from transverse forces, and 3) reduce the effects of time-phase jitter as well as beam intensity jitter from the injector and in the compression process.

The first compression is performed at 70 MeV where the bunch length is reduced from 0.5 mm to 0.2 mm (rms). The second compression is near 2 GeV and reduces the length to about 0.05 mm (FWHM). To study the development of longitudinal phase space in this process, a computer program is used which considers the effects of longitudinal wakefields, curvature of the RF wave, and phase and intensity jitter. The second compression is made to deliberately over-compress the bunch length beyond the 0.003 mm (rms) minimum. This over-compression and acceleration from 2 to 7 GeV allows approximate cancellation of upstream errors with downstream errors, thus providing significantly relaxed timing and intensity jitter tolerances of the injector and accelerator RF. Bunch intensity fluctuations up to ± 2 % and injection phase jitter of roughly ± 0.5 degree can be tolerated[2]. After the first compression the bunch length is still nearly gaussian, but after the second compression the beam distribution is more sharply spiked and has long tails.

A second set of parameters for this length compression scheme is being studied which would provide a distribution that is more flat topped. Both distributions produce the peak current and energy spread needed to satisfy the FEL requirements.

The emittance dilution effects due to transverse wakefields, RF deflections, and dispersive effects have been modeled in the SLAC linac for this configuration assuming 150 μm random misalignments of the quadrupoles and BPMs, 300 μm rms random misalignments of the accelerating structures, and a random transverse-longitudinal coupling of $g_{rms} = 2 \times 10^{-4}$ for the RF deflections. A transverse beam jitter equal to the rms beam size was also assumed. At a bunch length of 200 μm (rms), we find 25 % emittance growth along the linac. Emittance growth after the second compression is negligible due to the short bunch length and small energy spread.

An experimental test of the second bunch compressor including longitudinal and transverse effects has been designed and is under consideration. [4]

C. Undulator [5]

Based on 3D simulations of a continuous single-pass field structure, the following parameter set has been established for the LCLS (water window) insertion device: 1) period = 8 cm; 2) peak field amplitude = 0.8 T; 3) K = 6; 4) total length = 60 m; 5) focussing betatron wavelength = 60 m. Design work has concentrated on a pure permanent magnet undulator structure with a superimposed focussing (FODO) field lattice generated by 40 cm long 15 T/m quadrupoles placed at 80cm intervals. To facilitate orbit and phase correction, beam position monitors are spaced at 1.6 m intervals, with corrector coils located every 3.2 m. Work on a short prototype section is in progress to help resolve selected engineering, magnet tolerance, and field measurement issues.

D. Beam Lines & Experimental Stations [6]

Due to the extreme brevity and peak intensity of the LCLS output radiation, special emphasis has been placed on the design of the beam line system. To minimize the likelihood of sustaining damage at the expected 10^{12} W/cm^2 normal-incidence power densities, a deflection scheme utilizing solid-state mirrors at grazing incidence has been developed [6]. Furthermore, the necessity of maintaining high reflectivity to avoid peak-power damage leads to the need for an ultra-high vacuum environment with provisions for in situ cleaning of all the reflecting surfaces. To exploit the diffraction-limited source size of the LCLS, the use of a simple monochromator configuration utilizing a single grating in a conical diffraction geometry, with the source as the effective entrance slit, is under consideration.

IV. Acknowledgements

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