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Short Wavelength FELs Using the SLAC Linac*

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Abstract

We have studied the use of the SLAC linac to drive FELs at wavelengths down to a few Angstroms. Lasing would be achieved in a single pass of a low emittance, high peak current, high energy electron beam through a long undulator by Self-Amplified-Spontaneous-Emission (SASE) .

About 10^{13} photons per pulse can be produced in 100 fs pulses at a 120 Hz rate, corresponding to brightness levels of about 10^{22} average and 10^{32} peak. Peak power levels are tens of GW. Electron energies of 10-20 GeV are required. Significant improvement of FEL performance seems possible using harmonic generation techniques according to results from numerical simulations.

1 INTRODUCTION

Two recent developments have opened the possibility to construct linac-based x-ray lasers operating at short wavelengths, down to ≈ 1.5 Å. The first is the development, at Los Alamos and elsewhere, of rf photocathode electron guns which can now deliver low emittance (≤ 3 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 FELs. A long, precise undulator, such as has been made in several 3rd generation light sources, is also required. Several design alternatives are being studied.

Based on these developments we propose to build what we call Linac Coherent Light Source (LCLS), a 4th generation x-ray facility based on the last third of the SLAC linac. In addition to the existing linac, an enclosure to house the undulator exists at the end of the SLAC linac. 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. The characteristics of the light produced by the LCLS at 1.5 Å are projected to be:

Peak Coherent Power (GW)	≥ 10
Pulse Repetition Rate (Hz)	120
Pulse Width (1 sigma - fs)	<130
Photons/pulse	$\geq 10^{12}$
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

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.

2 PARAMETER OPTIMIZATION

The purpose of the optimization is to minimize saturation length at a wavelength of 1.5 Angstrom. The linear theory accurately predicts the growth rate. Based on that, saturation power and saturation length can also be estimated using the simple formulas with reasonable accuracy, which made possible the quick optimization in multi-dimensional parameter space. For a given wavelength,

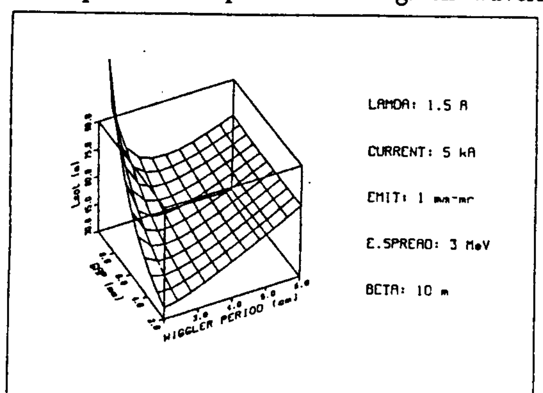

Figure 1: Parameter Optimization

there are six independent parameters included in the model, beam current, emittance, energy spread, undulator gap, undulator period and beta function. All other parameters, such as beam energy and undulator K can be determined from these parameters. A standard hybrid un-

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dulator design is assumed because of the larger field at small gap and undulator period. The optimization is carried out in two steps. First, fix the three beam parameters at nominal values, namely, current at 5 kA, normalized rms emittance at 1 mm-mrad, rms energy spread at 3 MeV, and optimize undulator gap, period and betatron focusing.

As shown in fig. 1, for a given undulator gap, there is an undulator period at which the saturation length is minimized. Thus, the undulator design is limited by the smallest gap allowed. Second, once parameters for the undulator and the focusing are fixed, beam parameters are then parameterized in the neighborhood around their nominal values to show the FEL sensitivity on each beam parameter. Also trade off between these beam parameters can be discussed quantitatively and conveniently. As a example, a 4 mm full gap is picked with a corresponding undulator period of 2.67cm and beta function of 10 meters.

3 SIMULATIONS

Numerical studies have been performed using (primarily) the FRED3D and TDA3D codes as well as the NUTMEG and GINGER codes for the analysis of harmonic generation and startup from noise. 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 40 m with strong focusing provided throughout the undulator.

The calculations have been focussed on schemes that can achieve operation at 1.5 Å: 1) Using the radiation at the fundamental of a single undulator tuned to 1.5 Å, 2) Using the radiation at the third harmonic of a single undulator tuned to 4.5 Å, and 3) Harmonic Generation, i.e. using separate undulators in series, each tuned to the third harmonic of the preceding undulator.

Cases 1) and 3) (in a two undulator arrangement) give about the same total length and output power for helical devices. Case 2) gives about one order of magnitude less power at 1.5 Å, but produces in excess 100 GW of power in the fundamental at 4.5 Å. Suppression at the fundamental could be accomplished with a suitable designed gas absorption cell operating at normal incidence or a movable/disposable grazing-incidence reflection membrane designed to transmit the 3rd harmonic. The system gain, its optimization and tolerance to beam parameter changes, undulator errors and misalignments have been studied.[1]

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 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.

4 TECHNICAL COMPONENTS

4.1 *RF Photocathode Gun*

The injector will consist of an S-band RF gun and accelerator sections. Initially the goal is to produce a single bunch electron beam, with a 1 nc charge, 3 ps FWHM, and normalized RMS emittance of 1 mm-mrad at 50 MeV.We plan to use the robust Cs_2Te cathode with 10 % quantum efficiency recently reported at CERN, and a UV laser for the photocathode. [2]

We have simulated a beamline starting with a 1.6 cell S-band RF gun up to 48 MeV, using SUPERFISH to simulate the electric fields, and PARMELA to simulate the beam dynamics. Preliminary simulations show that we can achieve a normalized rms emittance of 10 mm-mrad for a 1 nC, 10 ps bunch by making use of the space charge emittance compensation technique [3]. Figure 2 shows the rms normalized emittance along the beamline from the gun up to 48 MeV. At 48 MeV the emittance is reduced abruptly to .85 mm-mrad by using a collimator to throw away about 3 % of the charge contained in the "halo". Design work continues to explore the optimum combination of the many parameters. A prototype gun is being developed in collaboration with other labs.

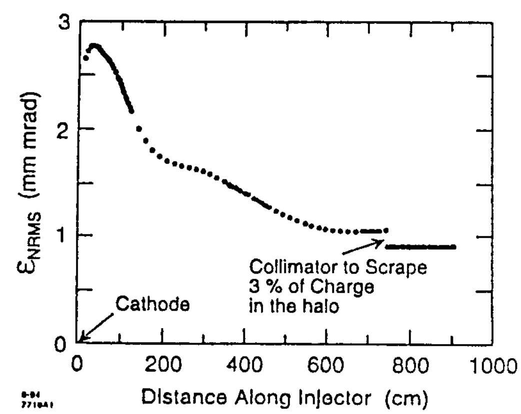

Figure 2: LCLS RF Gun Injector $\epsilon_{n,rms}$ for 1 nC, 10 ps FWHM Beam (Parmela simulations)

4.2 *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 15 GeV using three linear accelerators separated by two compressors[4]. 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 5000 A. The final coherent 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 7 GeV and reduces the length to about 0.05 mm (FWHM). To study the development of longitudinal phase space in the acceleration and compression 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 7 to 15 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.

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.

When the beam passes off-center through the undulator gap, due to the transverse resistive wall wakefield it will experience a transverse kick correlated with the longitudinal position. This effect will cause the effective emittance to grow and sets a tolerance on the accuracy to which the beam must be kept centered in the gap. We call the tolerance to pulse-to pulse offset variations the transverse jitter tolerance. To keep the emittance growth small we take the angular divergence of the beam to be less than 1/4 of the beam divergence, which gives us a jitter tolerance of better then about 8 μm. This tolerance represents about 35 % of the beam size and should not be difficult to achieve.

4.3 Beamlines & Experimental Stations [5]

The extreme brevity and peak intensity of the LCLS output radiation place special restrictions on the design of the beam line system. To minimize the likelihood of surface damage at the expected 10^{12} W/cm^2 normal-incidence power densities, a photon take-off scheme utilizing solid-state mirrors at extreme grazing incidence that could be operated down to $\approx$1 Å has been developed [5]. The necessity of suppressing peak-power damage also leads to the requirement for an ultra-high vacuum environment with provisions for in situ cleaning of all the reflecting surfaces. The diffraction-limited source volume of the LCLS makes possible the use of a simple monochromator configuration utilizing the beam itself to define the entrance aperture. Depending on the LCLS wavelength, alternative dispersion elements and geometries are being considered.

Damage effects may necessitate the use of special techniques such as beam expanders and multi-phase or dynamic optical elements to attain the required spectral filtration, resolving powers, and efficiencies. [6]

5 SCIENTIFIC CASE

In October 1992 [7] and February 1994 [8] workshops were conducted on the scientific uses of a 20-40 Å and 1-2 Å LCLS respectively. The longer-wavelength region is of interest primarily for microscopy and imaging of biological samples. Though the intense, fast pulse of the LCLS could produce an image in a single shot, multiple images would be required to completely characterize a sample, and radiation damage to biological samples would be a major problem. There is much more general scientific interest in the short-wavelength region. Here, the high coherence and ultra-short pulse capabilities of the LCLS would allow fundamentally new types of research to be carried out in chemistry, materials science, and structural biology. Time-resolved studies of crystal lattice motions and fast chemical reactions would be possible. Enough coherent photons would be available to study nonlinear optical properties of materials in the X-ray region. Radiation damage is not seen as an insurmountable problem in this spectral region, due to greater x-ray penetration depths and more robust types of samples.

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