SLAC–PUB–6449
SLAC/SSRL–0068
LBLL–35291
MARCH 1994
(A/SSRL-M)

Prospects for High Power Linac Coherent Light Source (LCLS) Development in the 1000Å-1Å Wavelength Range

R. Tatchyn*, K. Bane*, R. Boyce*, G. Loew*, R. Miller*, H.-D. Nuhn*, D. Palmer*, J. Paterson*, T. Raubenheimer*, J. Seeman*, H. Winick*, D. Yeremian*, C. Pellegrini†, J. Rosenzweig†, G. Travish†, D. Prosnitz◊, E. T. Scharlemann◊, S. Caspi‡, W. Fawley‡, K. Halbach‡, K.-J. Kim‡, R. Schlueter‡, M. Xie‡, R. Bonifacio°, L. De Salvo°, P. Pierini°

**Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309*
†Department of Physics, University of California (UCLA), Los Angeles, CA 90024
◊Lawrence Livermore National Laboratory, Livermore, CA 94550
‡Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
°Istituto Nazionale di Fisica Nucleare, Sezione di Milano, 20133 Milano, Italy

Abstract. Electron bunch requirements for single-pass saturation of a Free-Electron Laser (FEL) operating at full transverse coherence in the Self-Amplified Spontaneous Emission (SASE) mode include: 1) a high peak current, 2) a sufficiently low relative energy spread, and 3) a transverse emittance ε [r-m] satisfying the condition $\varepsilon \le \lambda / 4\pi$, where λ [m] is the output wavelength of the FEL. In the insertion device that induces the coherent amplification, the prepared electron bunch must be kept on a trajectory sufficiently collinear with the amplified photons without significant dilution of its transverse density. In this paper we discuss a Linac Coherent Light Source (LCLS) based on a high energy accelerator such as, e.g., the 3km S-band structure at the Stanford Linear Accelerator Center (SLAC), followed by a long high-precision undulator with superimposed quadrupole (FODO) focusing, to fulfill the given requirements for SASE operation in the 1000Å-1Å range. The electron source for the linac, an RF gun with a laser-excited photocathode featuring a normalized emittance in the 1-3 mm-mrad range, a longitudinal bunch duration of the order of 3 ps, and approximately 10^{-9} C/bunch, is a primary determinant of the required low transverse and longitudinal emittances. Acceleration of the injected bunch to energies in the 5 - 25 GeV range is used to reduce the relative longitudinal energy spread in the bunch, as well as to reduce the transverse emittance to values consistent with the cited wavelength regime. Two longitudinal compression stages are employed to increase the peak bunch current to the 2 - 5 kA levels required for sufficiently rapid saturation. The output radiation is delivered, via a grazing-incidence mirror bank, to optical instrumentation and a multi-user beam line system. Technological requirements for LCLS operation at 40Å, 4.5Å, and 1.5Å are examined.

* Work supported in part by Department of Energy Offices of Basic Energy Sciences and High-Energy and Nuclear Physics and Department of Energy contract DE–AC03–76SF00515.

Invited talk presented at the 4th International Colloquium on X-Ray Lasers
Williamsburg, Virginia, May 16–20, 1994

1. INTRODUCTION

The basic physical mechanisms underlying the onset and exponential amplification of FEL gain have been discussed in prior literature by numerous authors (1,2,3,4,5). From among the many different types and classes of FELs it has proved useful to distinguish those that operate: 1) *with* vs. *without* an external optical cavity, and 2) at beam energies and particle densities at which Coulomb effects within the beam are *negligible* vs. *non-negligible*. Further distinctions may be drawn depending on whether or not an external radiation train is introduced at the beginning of the amplification process (viz., seed light amplification vs. SASE); with respect to the details of the structures employed to guide and enhance the growth of gain (e.g., the Optical Klystron (OK), harmonic generation schemes, etc.); and the source of the particle beam driving the FEL (e.g., storage ring vs. linac). Since the 1970s a wide variety of FELs included in a number of these categories have been developed and operated in the infrared (IR) through the ultraviolet (UV) regimes (6). Heretofore, extension of FEL operation to increasingly higher photon energies has been inhibited by a number of factors critical to the gain process. First, significantly increased particle densities, or beam currents, are required to maintain the interparticle interactions underlying the growth of gain. Second, the energy spread of the particles in the beam must be kept sufficiently small so that the radiation field that they generate and through which they interact remains sufficiently monochromatic (coherent). Third, most of the radiation generated by the particles must be physically confined to the lasing phase-space volume, a condition expressible by the criterion $\varepsilon \leq \lambda / 4\pi$, viz., the emittance of the particle beam must be substantially dominated by the wavelength of the amplified light.

In recent years, a number of technical developments has made it possible to consider FEL schemes wherein these and other factors could be satisfied down to x-ray wavelengths of the order of 1Å (7). First, RF electron guns with laser-driven photocathodes and normalized emittances in the 1-3 mm-mrad range have been designed and operated. Assuming particle beam energies E as high as 50 GeV, viz., γ factors ($\gamma = E / m_e c^2$) approaching 10^5, the possible fulfillment of the emittance criterion with the use of, e.g., a high energy linac is evident. Second, assuming that the energy spread, σ_E, of the particle bunch emitted from the cathode stays relatively constant, the multi-GeV acceleration following the gun can be used to significantly reduce the relative energy spread, σ_E / E, of the beam to values required for efficient gain amplification. Third, longitudinal compression stages in the acceleration cycle, such as have been developed and utilized, e.g., at the Stanford Linear Collider (SLC) at SLAC (8), can be employed to increase the peak current (i.e., the particle density within the bunch) to values required for efficient gain stimulation. Finally, progress in undulator and focusing lattice technologies, in particular at 3rd Generation Synchrotron Radiation

Sources (9), can now yield insertion devices of sufficient length and quality to maintain the cited beam conditions during the FEL amplification process.

Given these developments, a multi-institutional collaboration has been established to study the feasibility of utilizing a portion of SLAC's 3 km linac as a driver for an x-ray FEL. Since highly efficient reflector arrays are presently unavailable in this spectral regime, the basic operating mode assumed for this FEL has been either SASE or seed-light amplification designed to saturate the gain in a single pass through the undulator. The design of this x-ray source, referred to as the LCLS ("Linac Coherent Light Source"), has been structured as an R&D facility for the development and utilization of x-ray lasers (see Fig. 1).

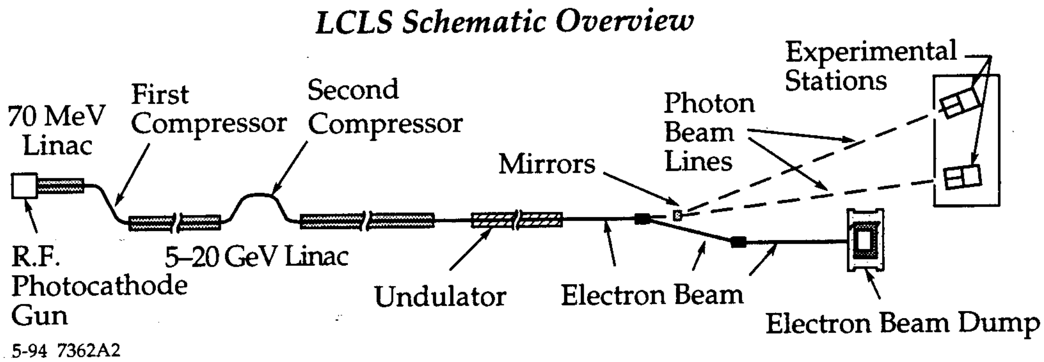

FIGURE 1. Proposed component layout of the LCLS experimental facility at SLAC.

The activities of the research group have focused on a number of areas associated with the various systems indicated in the layout. These include theoretical and design studies of: 1) the FEL gain process in the insertion device; 2) emittance control and beam transport in the RF gun, the longitudinal bunch compressors, and the linac acceleration sections; 3) the insertion device and its auxiliary beam focusing and monitoring systems; and 4) the optical beam line instrumentation. In the following sections we will review selected aspects of these studies.

2. PHYSICAL CHARACTERISTICS OF THE LCLS

The basic energy transfer mechanism in the SASE FEL is dependent on the interaction of the free electrons with the combined undulator and radiation fields. At the proper phase the kinetic energy of electron motion induced by the undulator is transferred to the radiation field. Once this energy exchange begins favoring a particular wave field (out of the large aggregate of waves generated by the randomly distributed electrons) the process becomes regenerative; viz., an initially weak bunching fluctuation coherently enhances the field, which in turn induces stronger bunching, etc., until limiting effects lead to saturation. In the multi-GeV energy regime of the SLAC LCLS, Coulomb effects play a minor role in this process. For an N-period undulator of length L_u and a peak bunch current I_p, an analysis of gain amplification in the bunch (5) leads to an estimated total output power of $P_{tot}[GW] \cong 1000 E I_p / N$, from which the potential performance of the SASE FEL can be assessed.

Theoretical and numerical studies of the LCLS have focused on the various factors and mechanisms underlying the growth of the bunching process. Using the codes FRED and GINGER (10), FRED3D and TDA3D (11), and NUTMEG (12), gain in both transverse and helical undulators, including the effects of external focusing, beam phase space distributions, and field errors, has been simulated for various FEL schemes. These include: 1) SASE on the 1st and 3rd harmonics of a single undulator, 2) SASE on the 1st harmonic of an Optical Klystron (OK) configuration, and 3) harmonic amplification of seeded light and SASE through a series of harmonically tuned undulators. Theoretical analyses and code development for increasingly refined simulations of gain startup from noise, field tapering, and the effects of undulator field harmonics on gain are also in progress. Basic parameter sets from three single-undulator case studies are listed in Table 1.

Table 1. Parameters for three LCLS cases:

	FEL1 (40Å)	FEL2 (4.5Å)	FEL3 (1.5Å)
Normalized emittance $\gamma\varepsilon$ [mm-mrad]	3.5	1	1
Peak current I_p [kA] *	2.5	5	5
Electron beam energy E [GeV]	7	15	25
σ_E / E [%]	0.02	0.02	0.02
Pulse duration $\sqrt{2\pi}\sigma_\tau$ [fs]	300	150	150
Repetition rate [Hz]	120	120	120
Undulator period λ_u [cm]	8.3	4.0	4.0
Peak field B_u[T]	0.76	1.6	1.6
Saturation length L_u [m]	60	40	70
Peak coherent power [GW]	10	100	40
Average coherent power [W]	0.4	1.4	1.6
Energy/pulse [mJ]	3	12	5
Coherent photons/pulse ($\times 10^{13}$)	6.6	3.3	0.5
Approximate Bandwidth (BW) [%]	0.1	0.1	0.1
Peak brightness** ($\times 10^{31}$)	5	500	500
Average brightness** ($\times 10^{21}$)	2	100	100
Transverse size [microns, FWHM]***	80	30	20
Divergence angle [μrad, FWHM]***	25	10	5

*Bunch charge in all cases is 1 nC; **Photons/s/mm^2/mrad^2/0.1%BW; ***At exit of undulator

3. RF GUN AND BEAM TRANSPORT

A typical RF gun/injector design under present study at SLAC consists of a UV laser-excited Cs_2Te photocathode (13) followed by a 1.6 cell S-band cavity and acceleration of the bunch up to 50MeV. The development of a working prototype using codes such as SUPERFISH (14), ITACA, and PARMELA (15) to study the effects of cavity geometry on beam transport is in progress in collaboration with groups at the University of California at Los Angeles (UCLA), the Los Alamos National Laboratory (LANL), and the Brookhaven National Laboratory (BNL). Emission parameters anticipated for the final structure include a 1nC charge, a 3ps (FWHM) length, and a 1mm-mrad normalized emittance.

Following injection, the bunch passes through a first (2.5x) compressor at 70MeV, an acceleration up to about 7GeV, a second (4x) compressor , and a final acceleration up to the LCLS operating energy. The number of compressions, their energies, and the compression factors are selected to minimize the bunch's energy spread, emittance growth, and time and intensity jitters (16). In simulations of the beam acceleration and compression, a number of known emittance degradation effects and possible methods for their control are under continuing study. These include: 1) transverse and longitudinal wakefield effects associated with the RF and passive accelerator components, 2) optical dispersion effects, and 3) the effects of random misalignments of the transport lattice components.

4. THE LCLS INSERTION DEVICE

Use of a linac allows for a minimal aperture in the LCLS insertion device, in principle down to a few millimeters. Limiting factors include: 1) the proximity of the magnetic material and vacuum duct walls to the e-beam's bremsstrahlung and synchrotron radiation cones; 2) complications associated with Beam Position Monitor (BPM) and vacuum engineering; and 3) undulator type (helical vs. transverse). For the undulator parameter ranges studied for various LCLS cases, viz., $2 \le K \le 6$ and $2.5cm \le \lambda_u \le 10cm$, the available gap range and the sub-KHz repetition rate allow a wide range of candidate technologies to be considered (see Fig. 2, left). Practical issues associated with the various technologies include: 1) cost factors such as, e.g., undulator materials and device length; 2) the attainability of 0.1%-0.2% field errors within a single gain length; and 3) constraints on the external focusing lattice design. In recent studies, e.g., it has been found that: 1) helical superconducting configurations (bifilar (17) or linear (18)) lead to the shortest structures; and that 2) a transverse pure permanent magnet (PM) design with adequate field quality and sufficiently strong focusing (19,20) could be developed from proven 3rd generation storage ring technology (Fig. 2, right). Substantial experience in the design and operation of transverse FEL undulators based on electromagnetic (E&M) DC technology has been acquired at LLNL (21). Other important factors in the construction and operation of LCLS insertion devices include field control, metrology, and alignment. These issues are being studied and are likely to entail the development of novel or improved techniques (22,23) for reliable operation. A vital aspect of the LCLS as an x-ray source is the tunability of its spectral and polarization properties. In

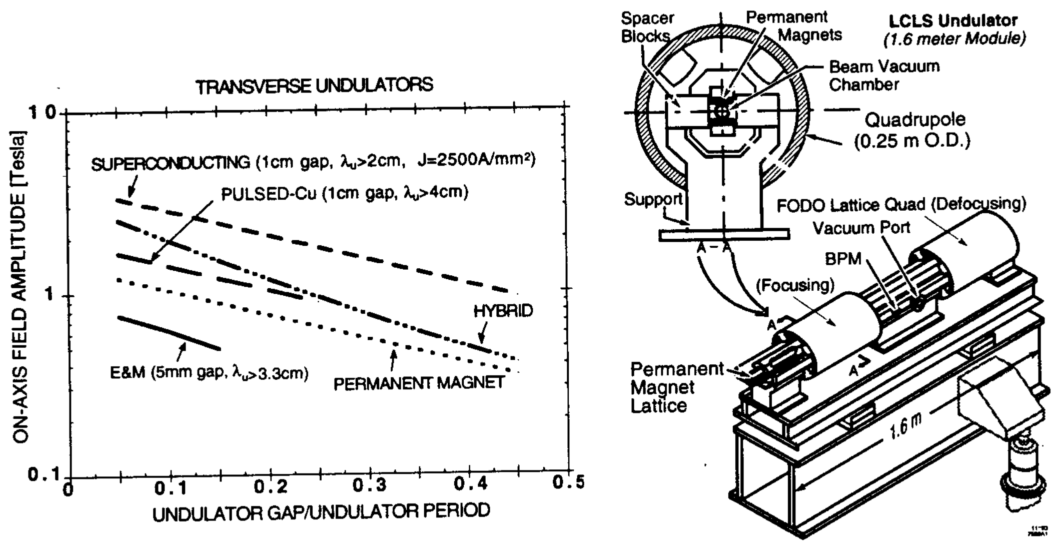

FIGURE 2 . Candidate LCLS undulator technologies and parameter regimes (left) and a section of a 60m PM insertion device (gap=1.5cm; period=8cm) for a 40Å LCLS (right).

addition to being tunable with the linac energy, the lasing frequency, as well as the polarization, can be controlled by the undulator. A possible mode of operation would be to induce bunching in an initially transverse insertion device, and then pass the beam through the final few gain lengths in a field-controllable structure such as, e.g., a pulsed-Cu field synthesizer (18).

5. LCLS BEAM LINE OPTICS

The temporal, peak power, brightness, and spectral-angular parameters of the LCLS are all critical to its beam line and end-use experimental designs (24). A graphical display of both the spontaneous and coherent (angle-integrated) photon flux distributions generated by the three LCLS cases of Table 1 is shown in Fig. 3. The opening angle of the coherent FEL peaks ($\left[(1+K^2)/N_i\right]^{1/2}/\gamma_i$ for the 1st harmonic) is at least a factor $\sqrt{N_i}$ smaller than that of the spontaneous background. For $K = 6$ the total power in the spontaneous spectrum, which is seen to extend out to the vicinity of the 100th harmonic, can be comparable to or even greater than the power under the coherent peaks. Due to the low average linac current, the time-averaged LCLS power is relatively small, of the order of 1W.

From the output parameters in Table 1 it is evident that a coherent photon pulse at normal incidence can deposit of the order of 1eV per atom for absorptivities (25) and penetration depths typical of solid state materials in the x-ray range. This level of energy loading, which can be shown to lead to the enhanced probability of lattice damage, can be reduced by decreasing the angle of incidence, θ_i, on the optical surface (see Fig. 4, left). This leads to the notion of

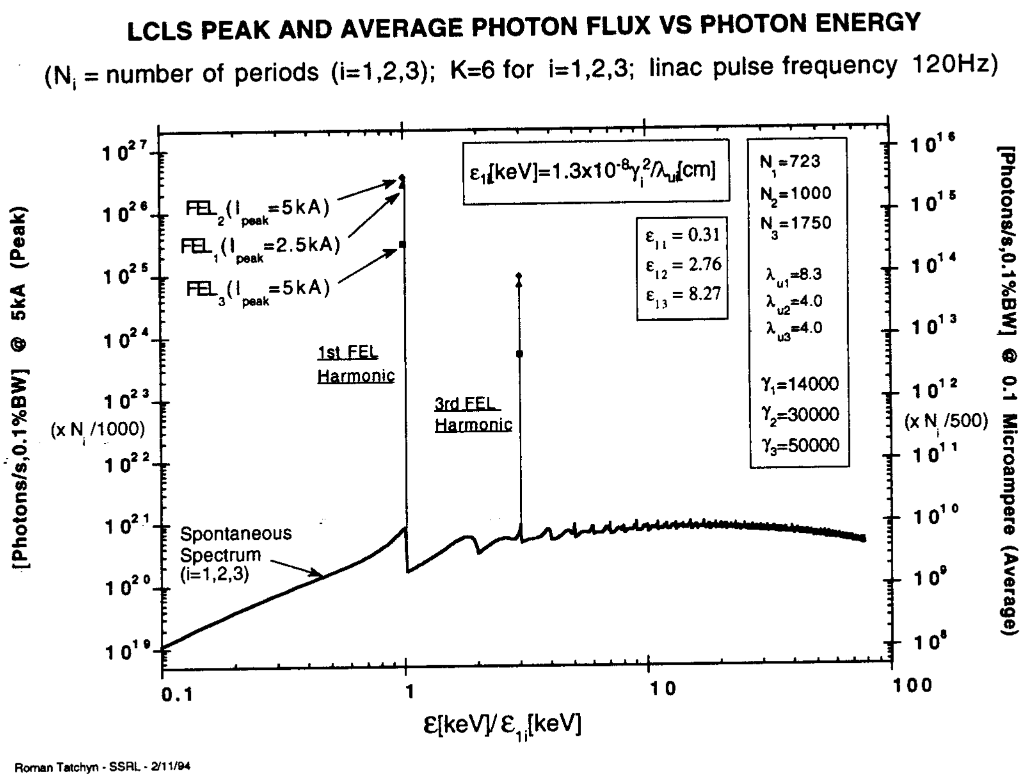

FIGURE 3. Energy-normalized spectral flux curves for three LCLS undulators.

multiple reflections at grazing incidence to deflect the LCLS beam by a total angle θ_T. For m reflectors with equal reflectivities R ($R \cong 1$), indices of refraction $n = 1 - \delta + ik$, atomic densities $\#[\mathrm{cm}^{-3}]$, and vertical penetration depths δ_P[cm] of the order of $\lambda / 4\pi k$, an absorbed-energy parameter, η_A[eV/atom], can be defined for a given peak power, P_{peak}[W], and incident beam diameter D_w[cm]:

$$\eta_A = \frac{P_{peak}\sqrt{2\pi}\sigma_\tau}{q}\left[\frac{\theta_i}{D_w^{\ 2}}\right]\left[\frac{1-R}{\delta_p \#}\right] << 1. \qquad (1)$$

Selecting, e.g., $\eta_A \leq 0.01$, a criterion suggested by earlier experimental work at SSRL (26), parameter studies of eq. (1) indicate that grazing incidence arrays (Fig. 4, right) of practical size and economy can be designed for the coherent peaks of the LCLS down to 1Å wavelengths.

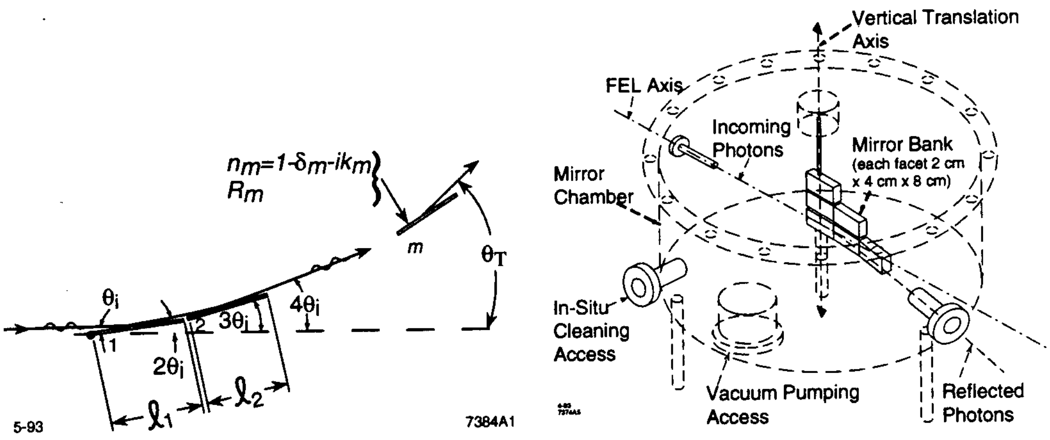

FIGURE 4. Multiple grazing incidence geometry (left) and practical configuration (right).

The design of beam line instrumentation for experimental applications (e.g., monochromators, beam splitters, delay lines, etc.) to further control the spectral-angular, temporal, and coherence properties of the LCLS beam is expected to present both significant challenges and opportunities. As an example, the diffraction-limited source volume of the LCLS should allow the use of efficient monochromator configurations in which the beam itself is the entrance aperture. Due to potential damage effects and the extreme brevity of the radiation pulses, however, special techniques such as beam expansion and compression, or novel elements such as multi-phase or dynamical optics, may need to be developed to attain the desired spectral profiles, resolving powers, and efficiencies (27).

6. SUMMARY

As indicated in Fig. 5, the peak power, brightness, and temporal properties of the LCLS are expected to open important new regimes for x-ray science and technology. Two workshops for exploring such possibilities have recently been held at SLAC (27, 28). The first focused on an LCLS and various applications in the 40Å range, with an emphasis on imaging techniques such as, e.g., single-shot holography of biological samples. The subsequent workshop, emphasizing LCLS sources and applications in the 4.5Å-1.5Å regime, has generated significant interest in areas such as surface and liquid-phase chemistry, materials science, structural biology, and non-linear physics. New techniques and extended parameter ranges in time-resolved, structural, and coherence studies have been considered. These include the possibility of real-time studies of fast chemical reactions and phase transitions; real-time lattice dynamics studies using speckle interferometry; structural analysis using the spontaneous LCLS spectrum for Laue diffraction; and multiple-beam techniques for holographic tomography. Studies

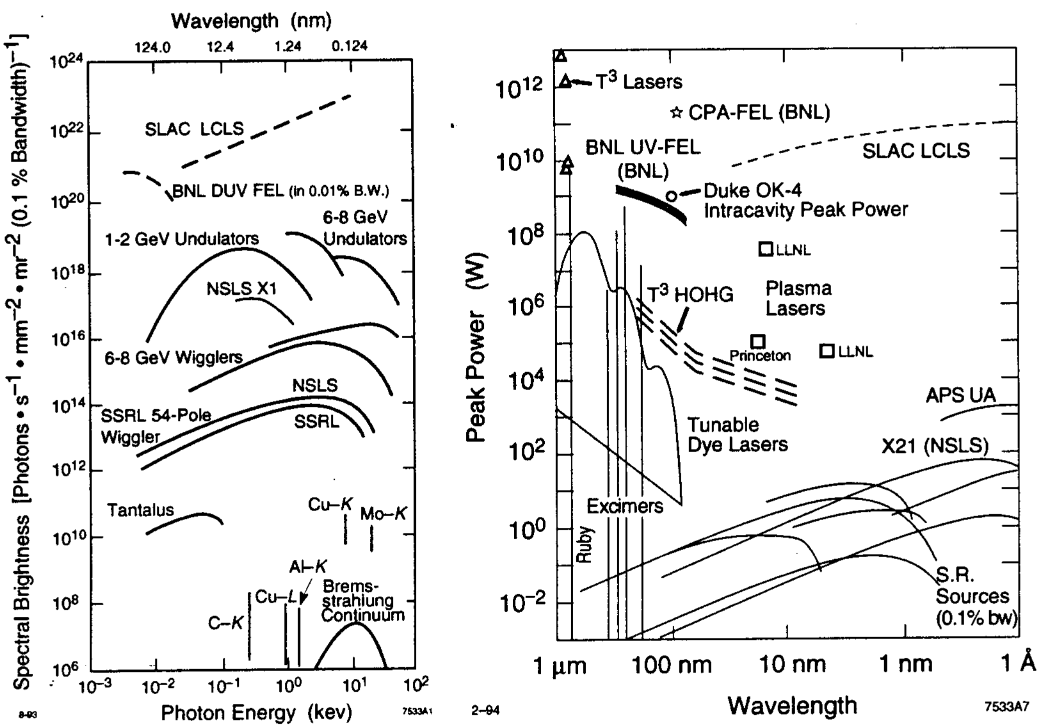

FIGURE 5. Comparison curves contrasting the average spectral brightness (left) and the peak coherent output power (right) of the LCLS with alternative coherent and quasi-coherent sources spanning the visible through the sub-100keV x-ray regimes.

of these and other possibilities, including issues related to sample damage, are currently in progress.

ACKNOWLEDGMENTS

Work supported in part by the Department of Energy Offices of Basic Energy Sciences and High Energy and Nuclear Physics and Department of Energy Contract DE-AC03-76SF0015.

REFERENCES

1. Madey, J. , "The Development of the Free Electron Laser," in *Near Zero: New Frontiers of Physics*, Fairbank, J. D., Deaver, Jr., B. S. , Everitt, C. W. F., and Michelson, P. F., eds., New York: W. H. Freeman and Company, 1988, pp. 431-441.
2. Murphy, J. B., and Pellegrini, C., "Introduction to the Physics of the Free Electron Laser," in *Lecture Notes in Physics No. 296*, Month, M., and Turner, S., eds., Berlin: Springer-Verlag, 1988, pp. 163-219.
3. Colson, W. B., *SPIE Proceedings* **738,** 2-27(1988).
4. Pellegrini, C., *Nuclear Instruments and Methods* **A272**, 364-367(1988).
5. Kim, K.-J., *Physical Review Letters* **57(13),** 1871-1874(1986).

6. Van Amersfoort, P. W., Van Der Slot, P. J. M., and Witteman, W. J., eds., *Nuclear Instruments and Methods* **A341,** 1994, Part II, pp. ABS3-ABS140.
7. Winick, H., Bane, K., Boyce, R., Cobb, J., Loew, G., Morton, P., Nuhn, H.-D., Paterson, J., Pianetta, P., Raubenheimer, T., Seeman, J., Tatchyn, R., Vylet, V., Pellegrini, C., Rosenzweig, J., Travish, G., Prosnitz, D., Scharlemann, E. T., Halbach, K., Kim, K.-J., Schlueter, R., Xie, M., Bonifacio, R., DeSalvo, L., Pierini, P., "Short wavelength FELs using the SLAC linac," presented at the 8th Synchrotron Radiation Instrumentation Conference, Gaithersburg, MD, August 23-26, 1993.
8. Raubenheimer, T., Emma , P., and Kheifets, S., "Chicane and Wiggler Based Bunch Compressors for Future Linear Colliders," in *Proceedings of the 1993 Particle Accelerator Conference*, Washington D.C., May 17-20, 1993, pp. 635-637.
9. Cornacchia, M., and Winick, H., eds., *Proceedings of the Workshop on Fourth Generation Light Sources,* SSRL Pub. 92/02, pp. 385-616.
10. Scharlemann, E. T., and Fawley, W. M., *SPIE Proceedings* **642**, 2-9(1986).
11. Kim, K.-J., Xie, M., Scharlemann, E. T., Pellegrini, C., and Travish, G., "Performance Characteristics, Optimization, and Error Tolerances of a 4-nm FEL Based on the SLAC Linac," in *Proceedings of the 1993 Particle Accelerator Conference*, Washington D.C., May 17-20, 1993, pp. 1533-1535.
12. Bonifacio, R., DeSalvo, L., Pierini, P, and Scharlemann, E. T., *Nuclear Instruments and Methods* **A296**, 787-790(1990).
13. Chevallay, E., Durand, J., Hutchins, S., Suberlacq, G. , and Wurgel, M., Nuclear Instruments and Methods A340, 146-149(1994).
14. Menzel, M. T., and Stokes, H. K., "User's guide for the POISSON/SUPERFISH group of codes," January, 1987, LANL Report LA-UR-87-15.
15. Rosenzweig, J., Smolin, J., and Serafini, L., "Design of a High Brightness RF Photoinjector for the SLAC X-Ray Linear Coherent Light source," in *Proceedings of the 1993 Particle Accelerator Conference*, Washington D.C., May 17-20, 1993, pp. 3024-3026.
16. Bane, K., Raubenheimer, T., and Seeman, J., "Electron Transport of a Linac Coherent Light Source (LCLS) Using the SLAC Linac," ibid., pp. 596-598.
17. Brau, C. A., *Free-Electron Lasers*, Boston: Academic Press, Inc., 1990, ch. 6, pp. 269-271.
18. Tatchyn, R., and Cremer, T., *IEEE Transactions on Magnetics* **26(6)**, 3102-3123(1990).
19. Tatchyn, R., Boyce, R., Halbach, K., Nuhn, H.-D., Seeman, J., Winick, H., and Pellegrini, C., "Design Considerations for a 60 Meter Pure Permanent Magnet Undulator for the SLAC Linac Coherent Light Source (LCLS)," in *Proceedings of the 1993 Particle Accelerator Conference*, Washington D.C., May 17-20, 1993, pp. 1608-1616.
20. Tatchyn, R., *Nuclear Instruments and Methods* **A341,** 449-453(1994).
21. Deis, G. A., Burns, M. J., Christensen, T. C., Coffield, F. E., Kulke, B., Prosnitz, D., Scharlemann, E. T., and Halbach, K., *IEEE Transactions on Magnetics* **24(2)**, 986-989(1990).
22. Warren, R. W., *Nuclear Instruments and Methods* **A272**, 257-260(1988).
23. Ben-Zvi, I., and Qiu, X. Z., *SPIE Proceedings* **2013**, 44-53(1993).
24. Tatchyn, R., and Pianetta, P., "X-Ray Beam Lines and Beam Line Components for the SLAC Linac Coherent Light Source (LCLS)," in *Proceedings of the 1993 Particle Accelerator Conference*, Washington D.C., May 17-20, 1993, pp. 1536-1538.
25. Henke, B. L., Lee, P., Tanaka, T. J., Shimabakuro, R. L., and Fujikawa, B. K., *American Institute of Physics Proceedings* **75**, 340-388(1982).
26. Tatchyn, R., Csonka, P., Kilic, H., Watanabe, H., Fuller, A., Beck, M., Toor, A., Underwood, J., and Catura, R., *SPIE Proceedings* **733**, 368-376(1986).
27. Spicer, W., Arthur, J., and Winick, H., eds., *Workshop on Scientific Applications of Short Wavelength Coherent Light Sources*, Stanford, CA, October 21, 1992, SLAC Report 414.
28. Arthur, J., Materlick, G., and Winick, H., eds., *Workshop on Scientific Applications of Coherent X-Rays*, Stanford, CA, February 12, 1994, SLAC Report 437.