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RESEARCH AND DEVELOPMENT TOWARD A 4.5-1.5 Å LINAC COHERENT LIGHT SOURCE (LCLS) AT SLAC

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Abstract

In recent years significant studies have been initiated on the feasibility of utilizing a portion of the 3km S-band accelerator at SLAC to drive a short wavelength (4.5-1.5 Å) Linac Coherent Light Source (LCLS), a Free-Electron Laser (FEL) operating in the Self-Amplified Spontaneous Emission (SASE) regime. Electron beam requirements for single-pass saturation in a minimal time include: 1) a peak current in the 7 kA range, 2) a relative energy spread of <0.05%, and 3) a transverse emittance, ε[r-m], approximating the diffraction-limit condition $\varepsilon = \lambda / 4\pi$, where λ[m] is the output wavelength. Requirements on the insertion device include field error levels of 0.02% for keeping the electron bunch centered on and in phase with the amplified photons, and a focusing beta of 8 m/rad for inhibiting the dilution of its transverse density. Although much progress has been made in developing individual components and beam-processing techniques necessary for LCLS operation down to ~20 Å, a substantial amount of research and development is still required in a number of theoretical and experimental areas leading to the construction and operation of a 4.5-1.5 Å LCLS. In this paper we report on a research and development program underway and in planning at SLAC for addressing critical questions in these areas. These include the construction and operation of a linac test stand for developing laser-driven photocathode rf guns with normalized emittances approaching 1 mm-mr; development of advanced beam compression, stability, and emittance control techniques at multi-GeV energies; the construction and operation of an FEL Amplifier Test Experiment (FATE) for theoretical and experimental studies of SASE at IR wavelengths; an undulator development program to investigate superconducting, hybrid/permanent magnet (hybrid/PM), and pulsed-Cu technologies; theoretical and computational studies of high-gain FEL physics and LCLS component designs; development of x-ray optics and instrumentation for extracting, modulating, and delivering photons to experimental users; and the study and development of potential scientific experiments that would be made possible by the source properties of the LCLS.

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DISCLAIMER

1. Introduction

In recent years, various technical developments have made it possible to consider FEL schemes wherein a number of essential requirements for the stimulation and growth of gain could be satisfied down to x-ray wavelengths on the order of 1 Å [1,2,3,4,5,6]. First, RF electron guns with laser-driven photocathodes and normalized emittances, $\gamma\varepsilon$, in the 3 mm-mrad range have been designed and operated [7]. With particle beam energies E on the order of 15 GeV, viz., γ factors ($\gamma = E/m_e c^2$) of 3x10^4, substantial approximation to the emittance criterion, $\varepsilon = \lambda/4\pi$, with the use of, e.g., a high energy linac can be realized. 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 SLAC Linear Collider (SLC) [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 necessary beam density during the FEL amplification process.

In parallel with these developments, a multi-institutional collaboration has been studying the feasibility of utilizing a portion of SLAC's 3 km linac as a driver for an x-ray FEL. Stimulated by continuing technical progress and scientific interest over the 1993-1995 period, the group's emphasis has evolved from an initial effort on a 40 Å FEL [10] to a current focus on the 4.5-1.5 Å range. Since adequate x-ray cavities are presently unavailable in this spectral regime, the basic operating mode assumed for this "Linac Coherent Light Source (LCLS)" has been either SASE or seed-light amplification designed to saturate the gain in a single pass through the undulator. At present, the proposed siting for this 4th generation x-ray source - to be developed as an R&D facility for the development and utilization of x-ray lasers - is on the last kilometer of the 3 km linac, which is expected to become available following the commissioning of SLAC's B-Factory sometime in 1998-1999 (see Fig. 1). To date, the activities of the research group have focused on a number of areas associated with the various components and 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 accelerator sections; 3) the insertion device and its auxiliary beam focusing and monitoring systems; and 4) the optical beam line instrumentation. Over the last year, a research and development (r&d) program [11] based on these activities has been formulated to help define and structure ongoing and future efforts towards the engineering design, construction, and operation of the proposed facility. The basic components of this program, which has recently been expanded to include the development of an infra-red (IR) FEL Amplifier Test Facility

(FATE) for studying SASE physics at longer wavelengths, are listed in Table 1. In the following sections selected ongoing and projected activities associated with the tabulated r&d areas will be reviewed.

2. Photocathode RF Gun and Test Stand

Since the early part of 1994 a major LCLS collaborative development effort has centered on a minimal-emittance pc rf gun [12,13,14,15]. This program presently consists of four areas: 1) conceptual, theoretical, and computer development of gun/injector structures and emittance compensation schemes; 2) fabrication of gun structures and injector components followed by initial tests at BNL, UCLA, or SLAC; 3) construction of a pc rf gun test facility in the SSRL booster ring building and injection linac enclosure [16]; and 4) development of a high power laser system for photocathode excitation, initially for the pc rf gun development, and ultimately for driving the 1.5 Å LCLS photocathode.

The RF gun/injector design under present study at SLAC consists of a 1.6 cell S-band cavity with a solenoidal emittance compensation scheme followed by initial acceleration of the bunch up to 50MeV [17]. Although the present emphasis is on Cu photocathodes, alternative materials (e.g., Cs_2Te [18]) are also being assessed. In the initial ("BNL/SLAC/UCLA #3") design (see Fig. 2, left) basic strategies for minimizing transverse emittance growth have included: 1) symmetrization of the structure in order to reduce the multipole contributions to the longitudinal (E_z) field asymmetries [19]; 2) special tailoring of the transverse and longitudinal profiles of the pc laser pulse [20]; and 3) optimization and implementation of a solenoidal emittance compensation scheme [21]. The cavity design studies were carried out using codes such as SUPERFISH [22] and PARMELA; the magnet studies with the POISSON and PARMELA codes. To date, an initial brass model for cold testing has been machined and tested at BNL. The final Cu version of this first model structure has been machined at UCLA, and E_z has been measured at BNL as a function of azimuthal angle in the full cell using a needle rotation/frequency perturbation technique [23,24]. The multipole contributions to the longitudinal field asymmetry have been calculated using standard Fourier series techniques [19]. The tested gun parts have recently been delivered to SLAC for final cold testing, brazing, and final tuning. In 1996, tests including acceleration and emittance compensation will be conducted and further gun structures (e.g., employing High Isostatic Pressure (HIP) Cu) and emittance minimization schemes [7] will be developed. Emission parameters anticipated for a final optimized structure include a 1 nC charge, an 2-3 ps (FWHM) length, and a $\gamma\varepsilon$ (following compensation and acceleration) of ≤ 1 mm-mrad (Fig. 2, right).

The near-term purpose of the pc rf gun test stand facility is to support low-emittance gun development at SSRL; in the longer term, expansion to support the FEL Amplifier Test

Experiment (FATE) system (to be described in Section 8) is planned. Ongoing construction activities include: 1) installation of a new linac section, rf gun test stand, and control and diagnostics systems inside SSRL's injector linac enclosure; 2) upgrading and conversion of the existing rf system (replacing the second of three existing XK-5 klystrons with a SLAC 5045, freeing up the 1st klystron to power the new test stand linac section); and 3) fabrication of a new laser enclosure inside the booster ring building to house the pc drive laser (see Fig. 3). The initial laser system, to be used for low-emittance gun development, will consist of a CW mode-locked Nd:YLF oscillator followed by a Nd: Glass regenerative amplifier with 4th harmonic up-conversion prior to the pc. Due to bandwidth constraints associated with the required pulse profile tailoring, a second laser for the final LCLS system based on a Ti:Sapphire oscillator and amplifier will need to be developed. Both of these systems are presently being studied under the LCLS r&d program [11] in collaboration with UR.

3. Transport, Acceleration and Compression

Following injection from the rf gun, the current design of the LCLS transport system comprises: 1) a first (2.5x) compression at 70 MeV; 2) an acceleration up to about 7 GeV; 3) a second (4x) compression, and 4) a final acceleration up to the peak operating energy (see Fig. 1). The compression is performed by introducing an energy deviation δ, correlated with the longitudinal position z in the bunch, and then passing the bunch through a magnet system in which the path length is energy dependent. The number of compressions, their energies, and the compression factors have been designed to minimize the bunch's energy spread, emittance growth, and time and intensity jitters [25]. In simulations of the beam transport, acceleration, and compression, a number of known emittance dilution effects and possible methods for their control are under continuing study. Primary causes of transverse emittance degradation include focusing mismatches and transverse coupling, dispersive and chromatic errors, transverse wakefields and RF deflections, and space charge forces [26]. Current assessments indicate that most of these effects can be minimized or corrected, both at low and high [27,28] energies, primarily by the use of highly accurate beam diagnostics (e.g., BPMs) and control of random misalignments of both the passive and active (rf) transport lattice components. To date these studies have been primarily analytical and numerical; selected experimental tests of emittance control and compression techniques at low energies are planned for 1996, followed by high energy tests on the SLAC linac for the 1996-1997 period.

4. LCLS Gain and Insertion Device Modeling

From the outset of the LCLS research effort, gain and insertion device modeling has been based on the theoretical and numerical investigation of the various factors and mechanisms underlying the origination, exponential growth, and saturation of the (high-gain) FEL bunching process. Various methods of gain start-up and growth, including SASE, signal amplification (seeding), and bunching on the fundamental or higher harmonics have been proposed and analytically investigated [29,30,31,32,33,34]. In parallel, selected analytical solutions of restricted 3-D gain models have been applied to the problem of LCLS parameter optimization [35]. In addition, special studies of selected aspects of LCLS performance such as, e.g., the mode and spectral-temporal [36] structure of the output radiation, the effects of coherent infra-red (IR) emission [37], or the introduction of drift spaces into the undulator [38], have been conducted. In combination with these studies, computer codes of varying degrees of realism, including FRED and GINGER [39], FRED3D and TDA3D [40], and NUTMEG [31], have been used to simulate and optimize the performance of different LCLS configurations [41] and undulators [42,43]. Most of these simulations, to a greater or lesser extent, incorporate details of the external focusing scheme, beam emittance, beam phase-space distribution, and undulator field errors. For example, FRED3D simulations of the sensitivity of FEL gain to undulator field and steering errors, revealing field error requirements of <0.2% for a 30 meter long superconducting 1.5 Å LCLS, are shown in Fig. 4. In Table 2, parameters for three LCLS cases optimized for SASE operation in the 40-1.5 Å range are shown.

In the projected LCLS r&d program, further development and improvement of both the analytical and computer models of gain amplification mechanisms, configurations, and the associated undulator structures will continue, with emphasis on the 4.5-1.5 Å wavelength range. Specific goals include: 1) the development of more sophisticated models of gain startup from noise to support more realistic SASE simulations; 2) the incorporation of more realistic e-beam phase-space distributions; 3) a better understanding of the effects and control of structural and field errors; and 4) the incorporation of more realistic undulator models into existing codes, or the development of improved codes, for supporting engineering design studies.

5. LCLS Undulator

For a low emittance, single pass device, a small aperture in an insertion device can be tolerated, in principle down to a few millimeters. In practice, the gapsize is limited by: 1) the proximity of the magnetic material and vacuum duct walls to the e-beam (wakefield effects) and its bremsstrahlung and synchrotron radiation cones; 2) complications associated with Beam

Position Monitor (BPM) and vacuum engineering; and 3) geometrical constraints associated with the undulator type (helical vs. transverse). For the undulator parameter ranges studied for various LCLS cases, viz., $2 \leq K \leq 6$ and $2.5cm \leq \lambda_u \leq 10cm$, the sub-centimeter gaps and the sub-KHz repetition rate allow for a wide range of undulator technologies to be considered [6]. These include: 1) pure superconducting (SC), 2) SC ferric [44] and superferric [45], 3) hybrid/permanent magnet (hybrid/PM), 4) pure-PM, 5) DC electromagnetic (E&M) [46], and 6) pulsed E&M [47]. In general, for any technology a helical structure will lead to a 30-45% shorter L_{sat} and a higher output than a transverse one, but the relative feasibility of implementing a helical design is strongly dependent on technology. A fundamental aspect of LCLS undulator design common to all technologies is the requirement for a superimposed focusing field substantially stronger than the undulator's natural focusing.

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) performance constraints associated with the external focusing lattice design. Designs considered for the 40 Å LCLS have included a pure-PM undulator [48] and the LLNL PALADIN (PM-assisted DC E&M) structure [49]. In more recent studies involving the 4.5-1.5 Å range, emphasis in the LCLS r&d program has been placed on SC, hybrid/PM, and pulsed-Cu technologies [50] . The first option (Fig. 5, top left), under study at LBL by S. Caspi and collaborators [51], proposes to utilize a pure SC structure using SC "cos2θ" coils as focusing elements. Exploratory numerical studies of potential quenching problems in this structure have also been started recently using the EGS4 particle-tracking code at SLAC [52].

An elegant version of the second, hybrid/PM technology (Fig. 5, top right), introduced by R. Schlueter at LBL, derives the undulator's dipole and quadrupole (focusing) fields from a monogenic potential generated by wedged/canted permeable pole surfaces [53]. Two alternative versions are based on combining a simple weak-focusing hybrid/PM structure with a superimposed strong-focusing field generated either by side-mounted [54] or planar-multipole [55] PM elements (Fig. 5, bottom left). An implementation of the latter option, featuring a fully open horizontal gap and means for active correction of multipole axis misalignments [56,57] is shown in Fig. 5 (bottom right). For all implementations of hybrid/PM technology, the question of radiation damage to the magnets is critical, and EGS4 simulations of SLAC's linac environment are planned as part of the LCLS r&d program.

Current assessments of pulsed-Cu technology indicate that power-supply, control, and thermal requirements for running up to a 100 m LCLS could be met, but that substantial r&d would be required to assess and resolve both impulsive and longer-term field quality issues. Other important factors in the construction and operation of LCLS insertion devices include field control, metrology, and alignment. These issues are an integral part of the LCLS undulator r&d program and are likely to entail the development of novel or improved techniques [58].

Additional r&d issues involve the tunability of the LCLS' spectral and polarization properties, both of which can be accomplished with the undulator field. For example, 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 of a variable-field device such as, e.g., a pulsed-Cu field synthesizer [59].

6. LCLS X-Ray Optics

Designs for LCLS beam line optics, end-use experimental structures, and optical instrumentation are governed by the peak power, brightness, temporal, spectral-angular, and polarization parameters of the LCLS light [60,61]. Displays of both the spontaneous and coherent angle-integrated photon flux distributions generated by the three LCLS cases of Table 1 are shown in Fig. 6. The opening angle of the coherent FEL peaks (e.g., $[(1+K^2)/N_i]^{1/2}/\gamma_i$ for the 1st harmonic) is at least a factor $\sqrt{N_i}$ smaller than that of the spontaneous background. For the 15 GeV energies and 0.75-1.6 T fields of the three cases, the total power in the spontaneous spectrum, both for K=6 (up to the 100th harmonic) and K=3.7 (up to the 30th harmonic), can be comparable to or substantially greater than the coherent 1st harmonic power. Due to the low average linac current, the time-averaged power is relatively small, of the order of 1W.

From the output parameters listed in Table 1 it is evident that a coherent photon pulse at normal incidence can deposit of the order of 10-100 eV per atom for absorptivities [62] and penetration depths typical of solid state materials in the x-ray range. This level of energy loading, which can be shown to enhance the probability of lattice damage, can be reduced by decreasing the angle of incidence, θ_i, on the optical surface (see Fig. 7, left). This leads to the notion of multiple grazing-incidence reflections to deflect the beam by a total angle θ_T. For m facets with equal reflectivities R ($R \cong 1$), complex indices of refraction $\hat{n} = 1 - \delta + ik$, atomic densities #[cm^{-3}], 1/e vertical penetration depths $\delta_P = \lambda\rho/4\pi k$ (where $\rho \cong \{[\theta_i^2 - 2\delta + \sqrt{(\theta_i^2 - 2\delta)^2 + 4k^2}]/2\}^{1/2}$), 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]:

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

Selecting, e.g., $\eta_A \leq 0.01$, a criterion suggested by earlier experimental work at SSRL [63], parameter studies of eq. (1) indicate that grazing incidence arrays (Fig. 6, right) of practical size and economy can be designed for the coherent peaks of the LCLS down to 1 Å wavelengths.

The design of beam line instrumentation for experimental applications (e.g., monochromators, beam splitters, delay lines, etc.) to further control the spectral-angular, temporal, polarization, and coherence properties of the LCLS beam is expected to present both significant challenges and opportunities. For example, the diffraction-limited source volume of the LCLS should allow the development of monochromator configurations in which the beam source serves as the entrance aperture. As another example, the development of FEL resonator cavities based on specular reflectors, multilayer structures, and crystals [64], while difficult, could substantially reduce the cost and size of future LCLS systems. Due to potential damage effects and the extreme brevity of the radiation pulses, special techniques such as beam expansion and compression, spectral filtering, 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. Current and projected r&d activities in this area include: 1) theoretical and computer investigations of short-pulse effects, instrumentation concepts and systems; and 2) experiments on optical components, materials, and systems to investigate limiting effects related to coherence, specular and interfacial scattering, and peak power damage. A number of valid experiments in these areas could be performed at 3rd and earlier generation SR facilities.

7. Scientific Applications

Both the average and peak brightness of the LCLS significantly exceed those of alternative coherent and quasi-coherent sources in the 60-1 Å range, the latter by more than 8 orders of magnitude (see Fig. 8). This level of coherent output, together with the peak power (Fig. 9) and temporal parameters (Table 2) 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 [65,66]. The first focused on an LCLS and various applications in the 40 Å range, with an emphasis on imaging techniques such as, e.g., single-shot holography of biological samples. Exploratory assessments of potential damage mechanisms and problems associated with biological and non-biological samples were undertaken [67]. The subsequent workshop, emphasizing LCLS sources and applications in the 4.5-1.5 Å regime, has generated significant interest in a number of areas, including 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 dynamics studies using speckle interferometry [68]; structural analysis using the spontaneous LCLS spectrum for Laue diffraction; and multiple-beam techniques for holographic tomography. Studies of these and other possibilities, aimed at developing a structured scientific case and program for the LCLS r&d facility, are currently in progress [69].

8. The FEL Amplifier Test Experiment (FATE)

Although a substantial body of theoretical work on the SASE process is now extant, existing direct or indirect experimental studies have been confined to the mm and deep-IR wavelength regimes [70,71]. In view of this, a program to develop a 10-1 μ FEL Amplifier Test Experiment ("FATE") based on the SSRL injector linac and pc rf gun test stand facility for studying the physics of SASE vs. seed-light amplification at intermediate wavelengths has been proposed [72]. Plans for this facility presently include: 1) use of the existing thermionic rf gun and alpha magnet bunch compression system to prepare high-current bunches; 2) use of the existing injector linac sections for acceleration up to 120 MeV; and 3) the development of an achromatic and isochronous transport system based on a double bend achromat with a reverse bend at the center, followed by the installation of a long (6 m) undulator (see Fig. 3). Recent activities on this project have included preliminary measurements of the linac's beam emittance and peak current, modeling of the SASE gain for different beam and undulator parameters, and preliminary assessments of alternative undulator designs. Recent observations of SASE-like signal growth by Bocek et al on a similar (but lower-energy) gun/linac/undulator system at Stanford University [73] have stimulated an interest in exploring similar possibilities for initial experiments on FATE.

9. LCLS Theory

Recently, significant progress has been made in the theoretical understanding of the three basic regimes of SASE: 1) startup [74,75,76], 2) exponential growth [36,77], and 3) saturation [6]. Theoretical analyses have been extended to the calculation of the optical mode structure and undulator optimization of the LCLS [35,78]. To a greater or lesser extent, the cited work has utilized idealizations or simplifications of the physical parameters of the electron beam and undulator structures. In view of this, the principal directions for future theoretical research under the LCLS r&d program are threefold. First, analyses of more realistic physical models of the electron beam and undulator (e.g., beams with phase space distributions generated by the SLAC gun/compression/linac system, undulators with realistic types of errors, etc.) in SASE will be developed. Second, theoretical studies of alternative (non-SASE) FEL schemes will be continued. Finally, numerical (computer) studies will be performed to augment and verify analytical results. The goal of this research will be to provide improved theoretical understanding of the SASE and alternative FEL processes and to improve existing computer codes for supporting LCLS engineering design efforts.

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Tables

Table 1. 4.5-1.5 Å LCLS r&d areas (facility to use last 1/3 of SLAC 3km linac, FFTB[a] tunnel).

R&D Area	Current Status	Collaborating Groups
Photocathode RF Gun and Test Stand	- analytical & computer studies - fabrication & testing - facility construction	SSRL[b], SLAC, BNL[c], UCLA, UR, et al
Transport, Acceleration and Compression	- theoretical & computer studies	SLAC, BNL, et al
LCLS Gain and Undulator Modeling	- theoretical & computer studies	SSRL, LLNL, LBL, UCLA, UM[d], et al
LCLS Undulator	- analytical & computer studies - some prototype development	SSRL, LBL, UCLA, et al
LCLS X-Ray Optics	- conceptual & computer studies	SSRL, DESY[e], et al
Scientific Applications	- conceptual & feasibility studies	SSRL, DESY, LBL, SU[f], BNL, et al
FEL Amplifier Test Experiment (FATE)**	- theoretical & experimental studies - some facility construction	SSRL, LBL, SU, UR, UM, et al
LCLS Theory	- analytical & computer studies	LBL, UCLA, SSRL, LLNL, UM, et al

**for studying SASE physics in the 10-1μ wavelength range; [a]Final Focus Test Beam; [b]Stanford Synchrotron Radiation Laboratory; [c]Brookhaven National Laboratory; [d]University of Milan; [e]Deutsches Elektronen-Synchrotron (Hamburg); [f]Stanford University

Table 2. Parameters for three LCLS cases:

Parameter	FEL1 (40 Å)[a]	FEL2 (4.5 Å)[a]	FEL3 (1.5 Å)[b]
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	15
σ_E / E [%]	0.02	0.02	0.02
Pulse duration $\sqrt{2\pi}\sigma_\tau$ [fs]	300	150	250
Repetition rate [Hz]	120	120	120
Undulator period λ_u [cm]	8.3	4.0	3.0
Peak field B_u [T]	0.76	1.6	1.3
Saturation length L_u [m]	60	40	55
Focusing beta [m/rad]	10	6.5	4.9
Peak spontaneous power [GW]	26	72	66
Peak coherent power* [GW]	10	100	50
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 [mrad, FWHM]***	25	10	5

[a]Bunch charge 0.75 nC; [b]Bunch charge 1.25 nC; *Sufficiently small field errors assumed; **Photons/s/mm^2/mrad^2/0.1%BW; ***At exit of undulator

Figure Captions

Figure 1. Component layout of the 4.5-1.5 Å LCLS within SLAC's B-factory/linac system.

Figure 2. SLAC/BNL/UCLA #3 photocathode rf gun (left) symmetrized by a vacuum pump-out port installed directly opposite the RF feed-in port; and a PARMELA simulation of its minimal attainable emittance (right) using a solenoidal magnetic compensation scheme. The discontinuous drop results from energy-tail halo scraping of the electron beam.

Figure 3. Schematic top view of SSRL's linac booster ring and linac enclosure showing the layout of the photocathode rf gun test stand and photocathode laser room.

Figure 4. FRED-3D simulations showing the effects of rms magnet field (left) and steering (right) errors on the peak output power of a 30m superconducting LCLS. Steering-corrector intervals ("dzsteer") of 2 vs. 2.5 m are contrasted in the right hand graph.

Figure 5. Selected design features of candidate LCLS undulator technologies: 1) SC coil structure with minimized field harmonics (top left); 2) hybrid/PM design with a monogenic dipole+quadrupole potential generated by wedged/canted poles (top right); 3) planar PM (open-gap) and side-magnet PM strong-focusing schemes (bottom left); and 4) planar PM quadrupoles affixed to a vacuum duct and interleaved with the poles of a hybrid/PM undulator (bottom right). Correction of quad axis displacement errors is provided by four variable currents.

Figure 6. Energy-normalized spectral flux curves for three LCLS undulators. K=6 for FEL1 and FEL2, and K=3.7 for FEL3.

Figure 7. Multiple grazing incidence geometry (left) and practical configuration (right) for a 4nm LCLS..

Figure 8. Comparison curves contrasting the average (left) and peak (right) spectral brightness of the LCLS with alternative coherent and quasi-coherent sources spanning the visible through the sub-100 keV x-ray regimes.

Figure 9. Peak coherent LCLS power over the 100-1Å wavelength range contrasted with alternative sources.

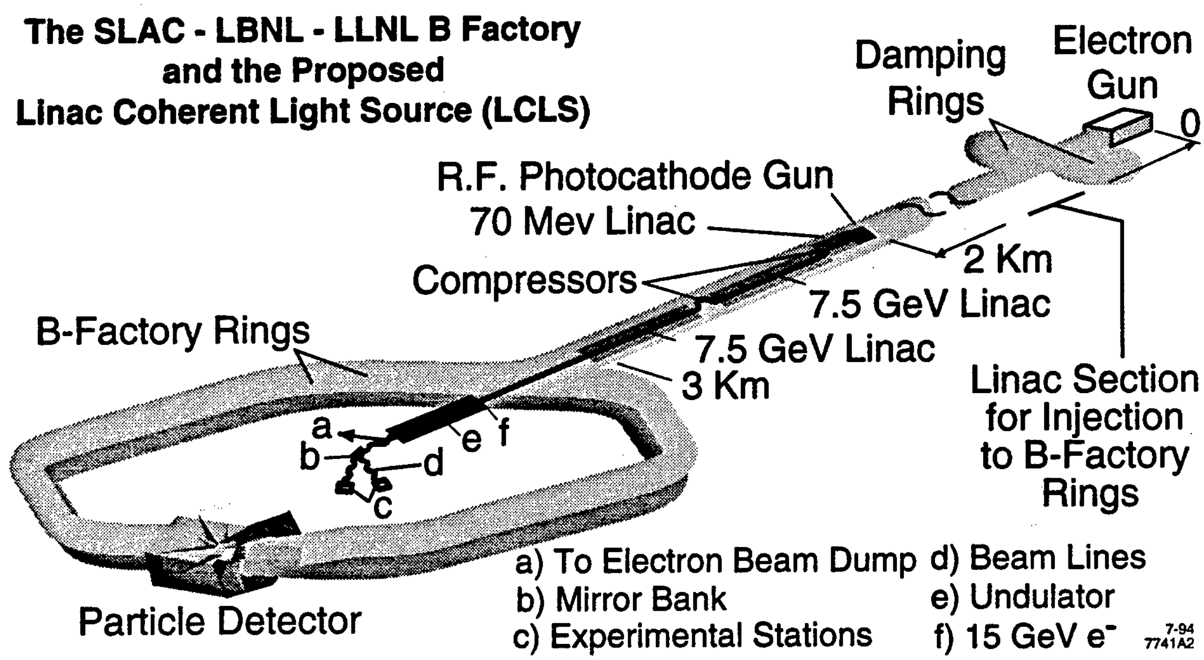

The SLAC - LBNL - LLNL B Factory
and the Proposed
Linac Coherent Light Source (LCLS)
Damping
Rings
Electron
Gun
0
R.F. Photocathode Gun
70 Mev Linac
2 Km
Compressors
7.5 GeV Linac
B-Factory Rings
7.5 GeV Linac
3 Km
Linac Section
for Injection
to B-Factory
Rings
a
b
d
c
e
f
Particle Detector
a) To Electron Beam Dump
b) Mirror Bank
c) Experimental Stations
d) Beam Lines
e) Undulator
f) 15 GeV e⁻
7-94
7741A2

Fig 1

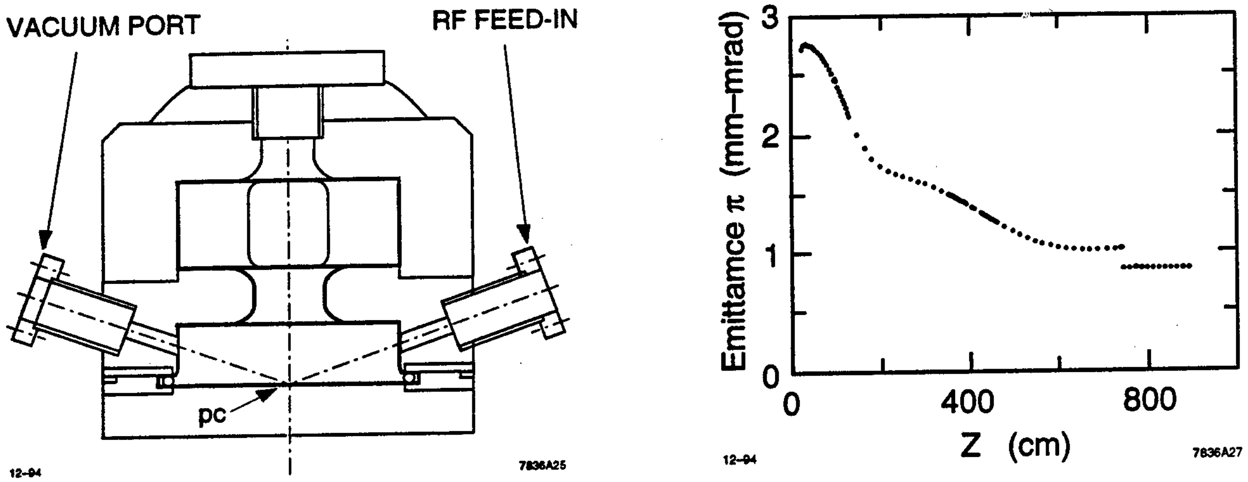

VACUUM PORT
RF FEED-IN
pc
12-94
7836A25
Emittamce π (mm–mrad)
Z (cm)
0
1
2
3
0
400
800
12-94
7836A27

Fig. 2

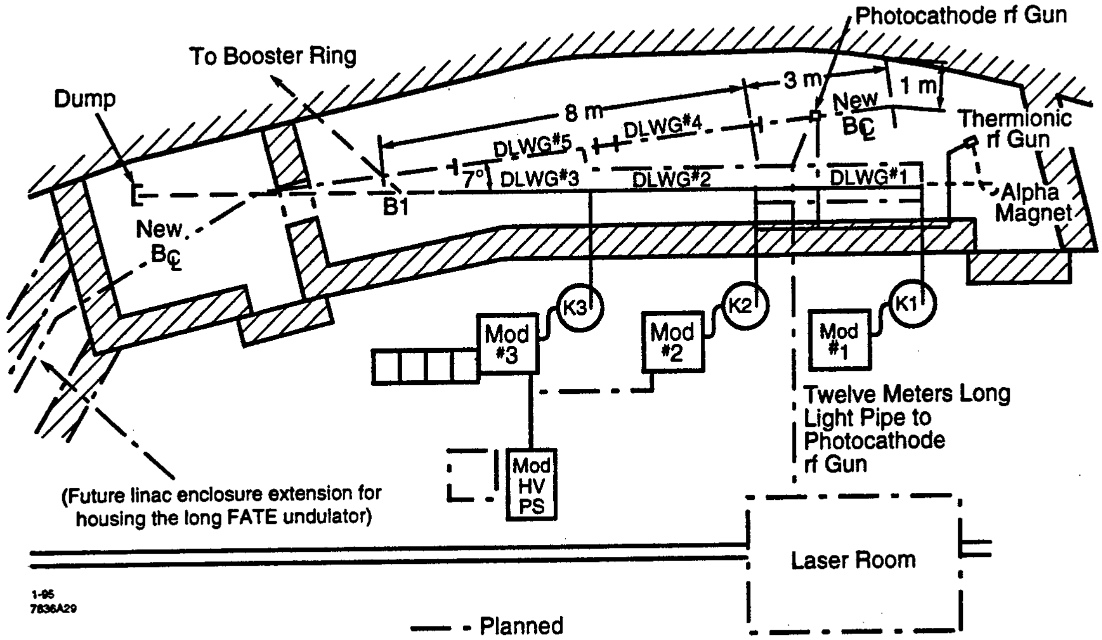

Photocathode rf Gun
To Booster Ring
Dump
3 m
1 m
8 m
New
BC
Thermionic
rf Gun
DLWG#5
DLWG#4
7°
DLWG#3
DLWG#2
DLWG#1
Alpha
Magnet
B1
New
BC
K3
K2
K1
Mod
#3
Mod
#2
Mod
#1
Twelve Meters Long
Light Pipe to
Photocathode
rf Gun
Mod
HV
PS
(Future linac enclosure extension for
housing the long FATE undulator)
Laser Room
1-95
7836A29
Planned

Fig. 3

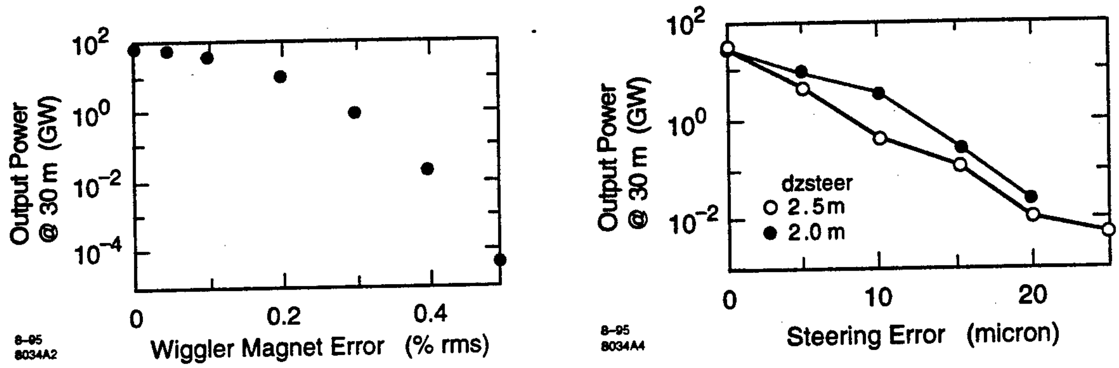

Output Power @ 30 m (GW)
10^2
10^0
10^{-2}
10^{-4}
0
0.2
0.4
Wiggler Magnet Error (% rms)
8-95
8034A2
Output Power @ 30 m (GW)
10^2
10^0
10^{-2}
dzsteer
○ 2.5m
● 2.0m
0
10
20
Steering Error (micron)
8-95
8034A4

Fig. 4

SLAC-PUB-95-6994
August 1995

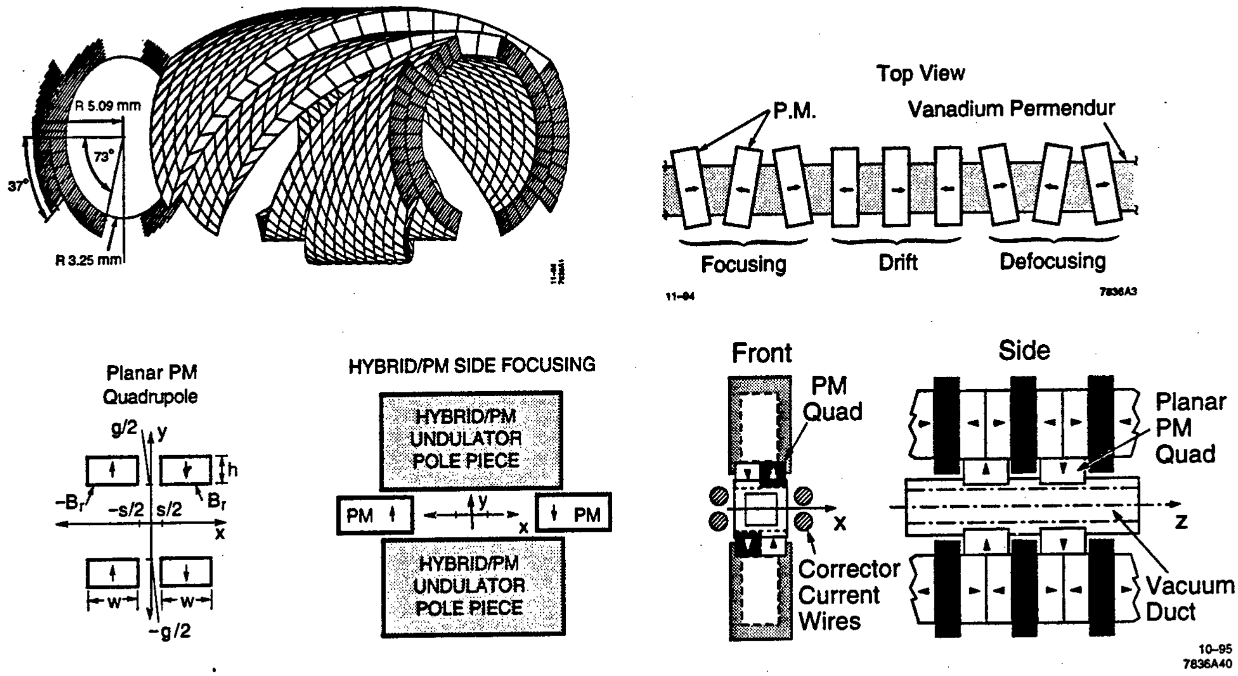


Fig. 5

LCLS PEAK AND AVERAGE PHOTON FLUX VS PHOTON ENERGY

(N_i = number of periods; K=6 for i=1,2; K=3.7 for i=3; linac pulse frequency 120Hz)

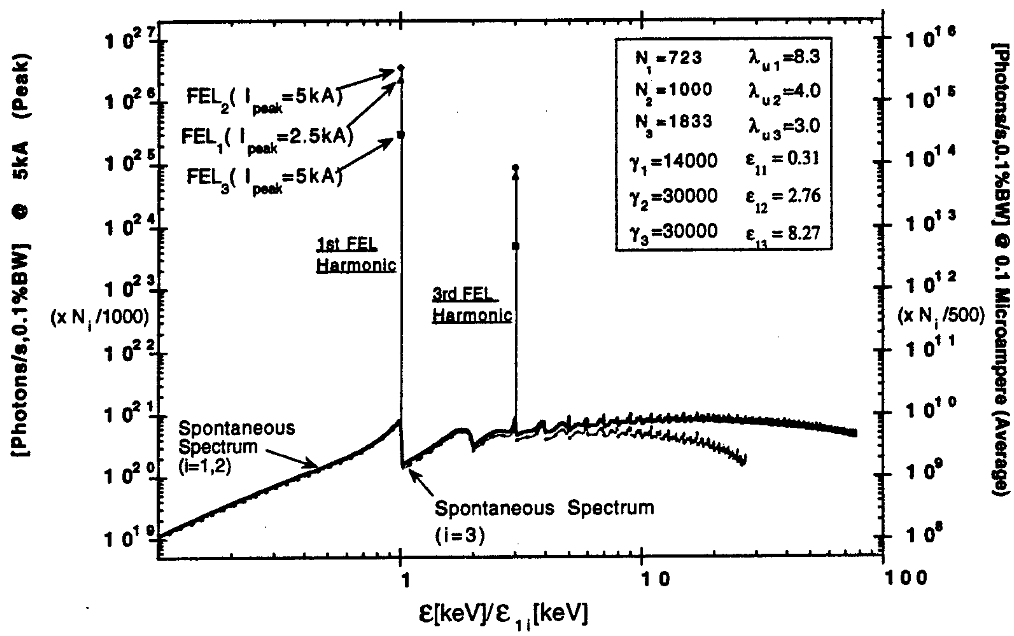
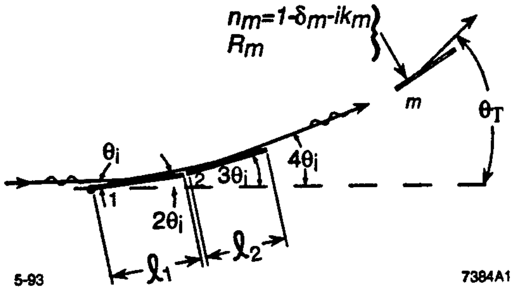


Fig. 6

SLAC-PUB-95-6994
August 1995



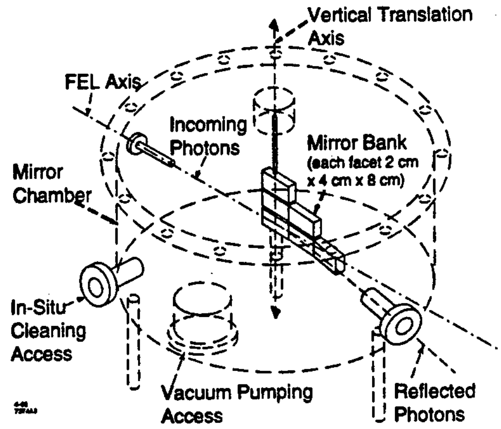


Fig. 7

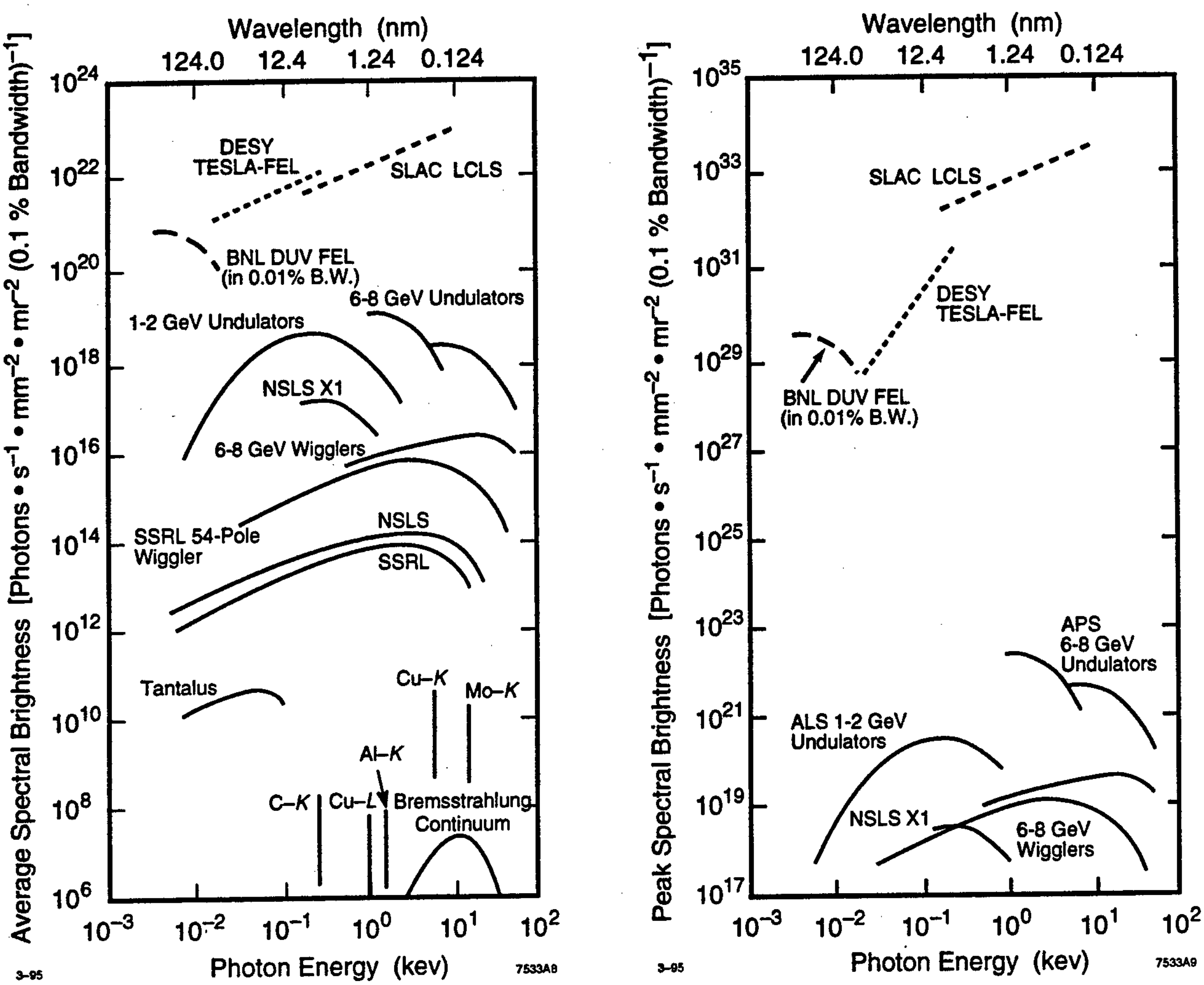

Wavelength (nm)
124.0 12.4 1.24 0.124
Average Spectral Brightness [Photons • s^{-1} • mm^{-2} • mr^{-2} (0.1 % Bandwidth)$^{-1}$]
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
DESY
TESLA-FEL
SLAC LCLS
BNL DUV FEL
(in 0.01% B.W.)
6-8 GeV Undulators
1-2 GeV Undulators
NSLS X1
6-8 GeV Wigglers
SSRL 54-Pole
Wiggler
NSLS
SSRL
Tantalus
Cu–K
Mo–K
Al–K
C–K
Cu–L
Bremsstrahlung
Continuum
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Photon Energy (kev)
3-95
7533A8
Wavelength (nm)
124.0 12.4 1.24 0.124
Peak Spectral Brightness [Photons • s^{-1} • mm^{-2} • mr^{-2} (0.1 % Bandwidth)$^{-1}$]
10^{35}
10^{33}
10^{31}
10^{29}
10^{27}
10^{25}
10^{23}
10^{21}
10^{19}
10^{17}
SLAC LCLS
DESY
TESLA-FEL
BNL DUV FEL
(in 0.01% B.W.)
APS
6-8 GeV
Undulators
ALS 1-2 GeV
Undulators
NSLS X1
6-8 GeV
Wigglers
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Photon Energy (kev)
3-95
7533A9

Fig. 8

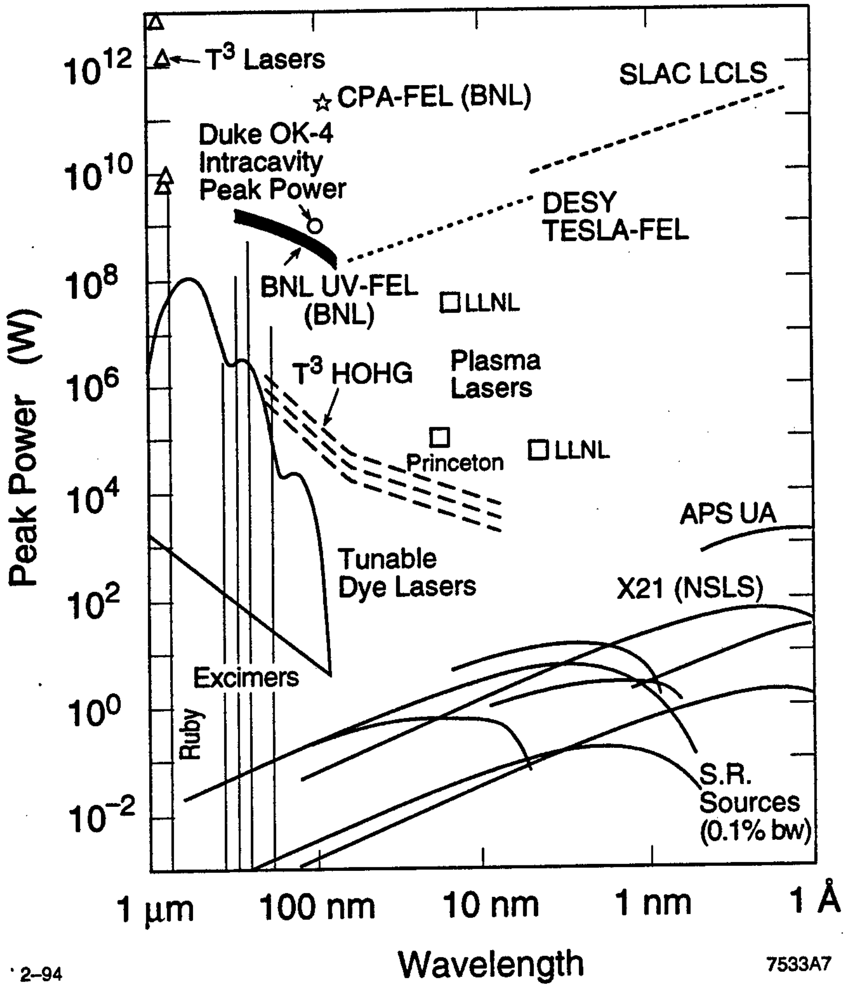

T3 Lasers
CPA-FEL (BNL)
SLAC LCLS
Duke OK-4
Intracavity
Peak Power
DESY
TESLA-FEL
BNL UV-FEL
(BNL)
LLNL
T3 HOHG
Plasma
Lasers
Princeton
LLNL
APS UA
Tunable
Dye Lasers
X21 (NSLS)
Excimers
Ruby
S.R.
Sources
(0.1% bw)
Peak Power (W)
10^12
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
1 μm
100 nm
10 nm
1 nm
1 Å
Wavelength
2–94
7533A7

Fig. 9

M97009078

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