STATUS OF THE LINAC COHERENT LIGHT SOURCE*

John N. Galayda, SLAC, Menlo Park, CA, 60439, USA

Abstract

The Linac Coherent Light Source (LCLS) is a free-electron laser facility in construction at Stanford Linear Accelerator Center. It is designed to operate in the wavelength range 0.15-1.5 nanometers. At the time of this conference, civil construction of new tunnels and buildings is complete, the necessary modifications to the SLAC linac are complete, and the undulator system and x-ray optics/diagnostics are being installed. The electron gun, 135 MeV injector linac and 250 MeV bunch compressor were commissioned in 2007. Accelerator commissioning activities are presently devoted to the achievement of performance goals for the completed 14 GeV linac.

LCLS DESCRIPTION

Performance Goals

The Linac Coherent Light Source[1,2] will be an x-ray free-electron laser operating in the wavelength range 0.15-1.5 nanometers (8,000 – 800 eV photons). It will produce pulses of x-rays with duration 200 femtoseconds or less, each with at least 10^{12} photons. A selection of experiment concepts that formed the justification for building the LCLS were reviewed by the U. S. Department of Energy Office of Science in 2001. This report[3] still provides a good overview of LCLS capabilities and research goals.

Facility Layout

The LCLS will make use of the downstream 1/3 of the 3 km SLAC s-band linac. In 2006 a new 135 MeV injector linac was installed in a vault located adjacent to the linac tunnel. The linac itself has been modified to incorporate bunch compressors (BC-1 and BC-2 in figure 1), located at the 250 MeV and 4.3 GeV points in the accelerator. Electrons from the LCLS linac are transported through the SLAC beam switchyard to a new Beam Transport Hall, and thence to an underground tunnel housing a 130 meter long undulator system designed and built by Argonne National Laboratory. Pulses of x-rays from the undulator are transported 90m to a "front end enclosure" (FEE) just upstream of the first experiment station. Specialized optics and diagnostics in the FEE, developed by Lawrence Livermore National Laboratory, will be used to control and characterize the x-ray beam. It will then be delivered to three 10m x 15m experiment hutches in the Near Experiment Hall (NEH). Three more experiment hutches will be located 200m beyond the NEH in the Far Experiment Hall (FEH), a 14m x 64m cavern located 30m below ground on the SLAC site.

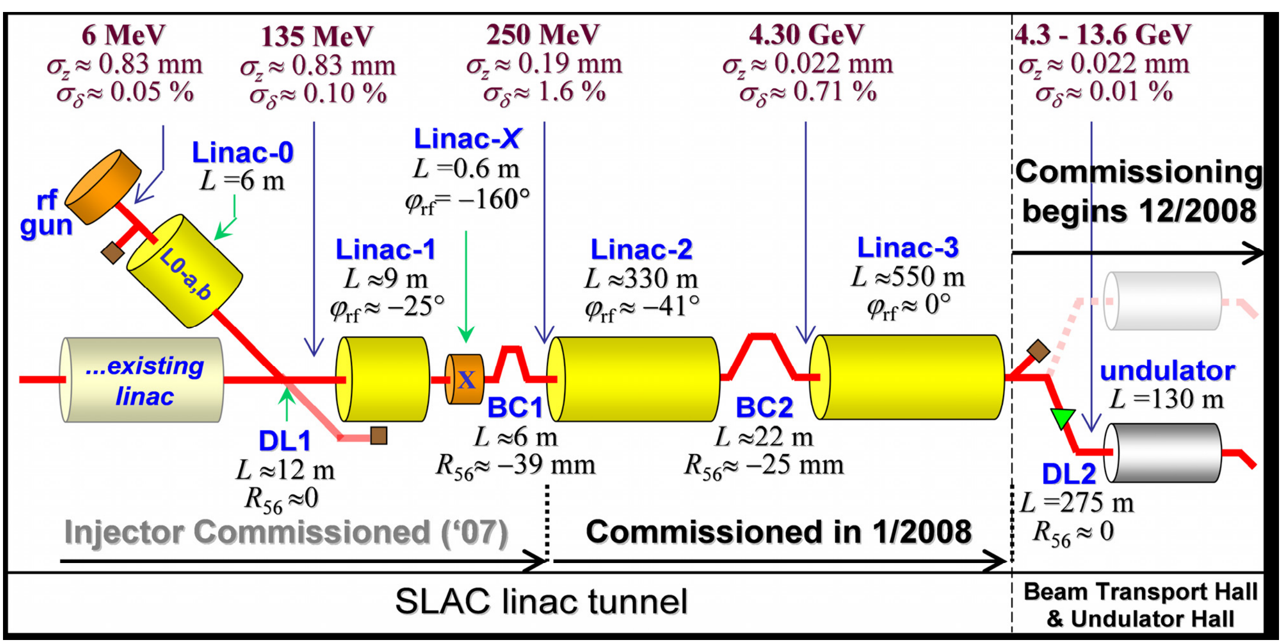

Figure 1: Schematic diagram of major LCLS accelerator systems, including physical lengths (L) of each segment of the linac and nominal conditions for operation with a 1 nC electron bunch. The symbols "DL1" and "DL2" refer to "dogleg" bends. "BC1 and "BC2" are four-magnet chicane bunch compressors. "Linac-X" is an X-band accelerating structure.

*Work supported in part by US Department of Energy contract DE-AC02-76SF00515

Table 1: LCLS Performance Goals

Parameter	Lower Limit	Upper Limit	Units
Photon wavelength	1.5	0.15	10^{-9} m
Photon Energy	800	8,000	eV
Peak FEL power	5	8	GW
Bandwidth	0.2		%
Energy per Pulse	2	2	mJ
Pulse duration	<200 x 10^{-15}		Sec
Flux	$1x10^{13}$	1×10^{12}	Photons/(0.1% BW)
Peak Brightness	$3x10^{31}$	$1.5x10^{32}$	$\frac{Photons}{mm^2 mr^2 \sec(0.1\% BW)}$
Repetition	120		Hz
Average Brightness	$2x10^{21}$	$4.5x10^{22}$	$\frac{Photons}{mm^2 mr^2 \sec(0.1\% BW)}$

INJECTOR

Injector Description

The Injector linac must produce an electron beam with very low transverse emittances and small energy spread. The photocathode electron gun[4] and associated laser are the result of years of work at SLAC and other labs. It is a 1 ½ -cell s-band (2856 MHz) structure with a copper photocathode and solenoid focusing for compensation of linear space charge forces. The gun design has been changed from the original "BNL-SLAC-UCLA" design[5] in several important aspects to achieve LCLS performance. Tests have verified that the gun can operate at 120 Hz with 120 MV/m at the cathode.

The injector will include a "laser heater"[6], scheduled for test in January 2009. This device is a short undulator in which a 800 nm laser pulse derived from the gun laser is superimposed on the passing electron bunch to modulate the electron beam energy. Although the modulation has well-defined wavelength, the purpose of the "heater" is to provide a controllable and effectively incoherent energy spread to damp coherent synchrotron instability effects during the bunch compression process.

Injector Commissioning

The Thales laser system[7] for the gun photocathode has performed very well. Its availability during months of continuous operation has been 99.5%. The temporal and spatial profile of the laser pulse has likewise been satisfactory.

First studies of the performance of the LCLS Injector and Bunch Compressor 1 were conducted April-September 2007. A comprehensive description of the 2007 commissioning run has been published[8]. Degradation of the horizontal emittance, brought on by bunch compression, was observed. This degradation was predicted in simulations, and is attributed to energy modulation of the electrons induced by coherent synchrotron radiation (CSR) forces during the bunch compression process. Profiles measured with OTR diagnostics downstream of DL1 are distorted by coherent OTR from the beam at micron- and sub-micron wavelengths. Emittance measurements from scanning wires after BC1 and at the end of the linac are, of course, unaffected by COTR.

LINAC

Linac Description

Electrons from the LCLS Injector are brought into the SLAC linac via a dogleg bend (DL1 in figure 1) and accelerated from 135 MeV to 250 MeV before passing though the first bunch compressor (BC1 in figure 1). An X-band accelerating structure (Linac-X in figure 1), located immediately upstream of BC1, is used to remove quadratic dependence of electron energy on longitudinal position within the electron bunch. A second bunch compressor (BC2 in figure 1) further compresses the beam after it is accelerated to 4.3 GeV. The FEL wavelength will be varied by changing the electron beam energy downstream of BC2. The bunch compressor magnets and the vacuum pipe for the electron beam are mounted on motorized stages. Much of the linac is unchanged since it provided beam to the Stanford Linear Collider. However the RF reference, the low-level RF and electronics for the beam position monitors in the vicinity of the bunch compressors have been upgraded to meet LCLS specifications[9].

Linac Commissioning

Bunch compressor 2 was installed in the fall of 2007, and commissioning studies resumed in January 2008. The first part of the 2008 commissioning period has been devoted to careful study of a very promising operating configuration with 0.25 nC electron bunches.

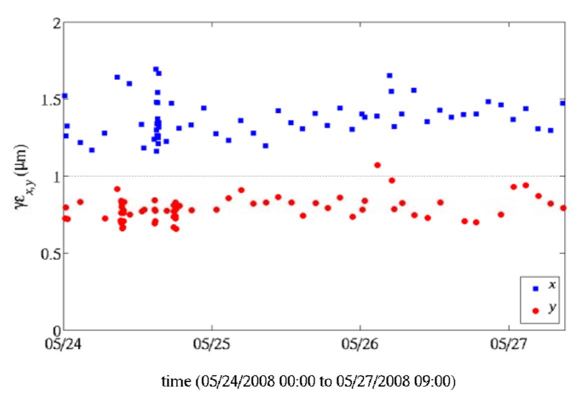

Figure 2: Projected emittance of a 0.25 nC bunch at the 10 GeV point of the SLAC linac, over three days of operation.

This configuration can achieve the design performance goals of Table 1. The shorter pulse duration (75 fs) is considered desirable by prospective LCLS users. The lower charge is also favorable because it minimizes the negative impact of wake fields and CSR effects.

This is likely to be the configuration used for commissioning and first experiments in summer 2009. For this reason, recent commissioning activities have been devoted to investigating the stability of the linac in this configuration. Figures 2 and 3 demonstrate that the LCLS linac is capable of extended running at performance levels necessary for FEL operation. It has also been possible to measure the fast jitter in x, y and arrival time of the electron bunch at the output of the LCLS linac.

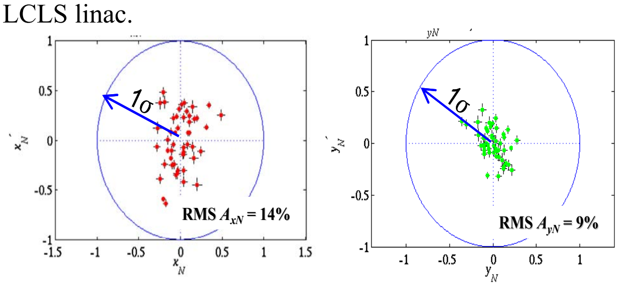

Figure 3: “fast” x-y jitter of the bunch at the end of the linac.

Positional stability in y meets the desired 0.1σ tolerance. Stability in x is 0.14σ; efforts are underway to reduce x jitter further.

Temporal characteristics of the electron bunch were measured using an s-band transverse deflecting cavity[10] synchronized to the linac RF. This system provides a time-dependent transverse kick to electrons as they pass through the cavity, which results in a time-dependent displacement of the electron at a profile monitor downstream. A 1 picosecond change in time of arrival at the deflecting cavity results in a 2.4mm displacement at the profile monitor. The deflecting cavity has been used to measure the bunch length (50 fs) and the timing jitter of the bunch relative to the deflecting cavity RF. The rms “fast” timing jitter of the bunch relative to the RF system is 46 femtoseconds, a very good result will be important to the success of pump/probe experiments that require precise synchronization of the LCLS to an external laser.

UNDULATOR

The undulator system is a simple FODO lattice with one quadrupole for each of 33 undulators. The LCLS undulators are hybrid permanent magnet devices with period=3 cm, gap=6.8mm, length=3.4m and peak field of 1.25 T. A total of 33 devices will be installed in the LCLS. The undulators themselves have negligible effect on the electron focusing and, ideally, no steering effects as well.

Steering effects in the undulators have been reduced below the required tolerances on field integral (0.4 gauss-meter) and second integral(0.5 gauss-meter^2) per undulator, over their “good field” regions. The undulators also meet the tolerance requirements for phase-shake in the ponderomotive “bucket” of the SASE radiation, +/- 10 degrees rms.

Every aspect of the transverse alignment of the undulator system is critical for 0.15 nm FEL operation. The electron beam trajectory must be straightened to a tolerance of 2 microns over 5-10 meters. Unless alignment of the undulators and electron optics is corrected continuously, it will degrade in hours or days due to natural motions of the earth, concrete shrinkage, thermal effects, etc., and must be corrected continuously using diagnostic devices and motorized movers.

Each undulator will be placed on a girder assembly designed to hold the vacuum chamber, quadrupole magnet, high-precision resonant cavity RF beam position monitor (RFBPM)[11] and “beam finder wire” (described below) in alignment.

The undulator vacuum chamber is an aluminum extrusion providing a 5mm vertical aperture for the electron beam. Aluminum appears to offer some advantage over copper when AC effects are taken into account[12,13,14] in evaluating resistive wall impedance. The interior of the chamber has been polished to reduce wake fields. The desired interior finish was achieved by pumping abrasive paste through the extrusions. After polishing, the extrusions were machined to an overall height of 6mm to allow adequate (albeit tight) clearance between chamber and undulator poles.

The entire girder assembly is mounted on a set of cam movers that can adjust the vertical and horizontal positions of each end of the girder with less than 7 micron resolution[15]. The necessary trajectory straightness can be achieved by beam-based alignment techniques. Based on observation of the change in RFBPM readings resultant from changing the energy of the electron beam, the orbit through the undulator system can be corrected to the desired precision by displacement of the quadrupole magnets. This will guarantee that the one end of the undulator (the end adjacent to the quadrupole) is aligned to sufficient accuracy (80 microns vertically and 160 microns horizontally). The other end of the undulator will be aligned to the electron beam by scanning the girder position while observing radiation signals from a thin carbon filament (a “beam finder wire”) built into the undulator vacuum chamber[16]. The carbon filament will be scanned across the beam profile by displacing the girder, thus positioning both ends of the undulator well within its 80 micron vertical tolerance.

The beam-based alignment process is expected to be somewhat time-consuming, and will likely be repeated every 1-2 weeks. A wire position monitor system and a hydrostatic level sensor[17] will be employed to maintain alignment of the undulator system on a day-to-day basis.

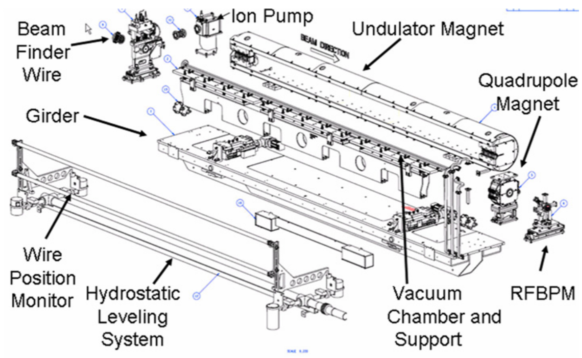

Figure 4: Undulator girder assembly. The cam movers and pedestals that support the girder are not shown.

The Undulator[18] rests on a motorized horizontal translation stage affixed to the girder. This stage allows the undulator to be moved 8 cm away from the beam path. In this retracted position the undulator may be removed from the girder without disturbing the other components on the girder. Though the undulator poles are held rigidly in a titanium "strongback" support, the vertical gap and hence the K parameter of the undulator can be varied about 0.25% through adjustment of the horizontal translation stage. Since achievement of the desired FEL performance at 0.15 nm requires control of the K parameter to a precision of 0.015%, the ability to adjust K remotely is crucial.

X-RAY DIAGNOSTICS

Systems for control, steering and study of the x-ray beam have been designed and constructed at Lawrence Livermore National Laboratory. In the fall of 2008 these very important systems will be installed in a shielded enclosure, shown schematically in figure 5, upstream of the experiment stations.

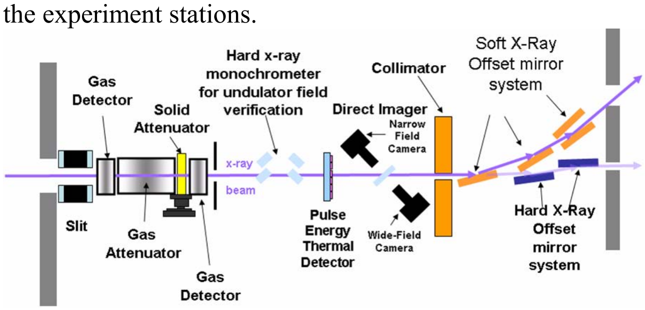

Figure 5: X-ray diagnostic devices at the output of the free-electron laser.

Boron carbide-faced tungsten heavy alloy slits will be employed to collimate the x-ray beam, thus eliminating much of the spontaneous radiation. The slits can withstand an occasional hit by the SASE beam.

The SASE beam intensity will be controlled using an attenuator system. Soft x-rays (to 2,000 eV) may be attenuated about 1,000X by varying the pressure (up to 20 Torr) of nitrogen gas in a differentially pumped volume, connected to the accelerator through 3mm apertures. A turbopump system quickly adjusts the attenuation while maintaining good vacuum in the accelerator and experiments. For hard x-rays, a series of beryllium blocks inserted in the beam will provided stepwise adjustable attenuation up to 1,000.

Fluorescence from a separate volume of pressure-controlled nitrogen will provide a non- or minimally-invasive measurement of the FEL intensity. Spontaneous radiation will contribute only 1% to the fluorescence signal from the FEL beam at full power[19].

A four-bounce silicon monochromator will be used to measure the angle-integrated spectrum of each undulator so as to verify that each is correctly set to achieve SASE[20].

YAG::Ce scintillators in three thicknesses (5 micron for soft x-ray FEL radiation, 50 microns for hard x-ray FEL radiation, and 1mm for spontaneous radiation) will be inserted in the x-ray beam for profile measurement, to provide beam profile information during initial commissioning and operation. The "wide field camera" in figure 5 will cover a 60mm field with 110 micron resolution while the "narrow field camera will cover 10mm field with 20 micron resolution. With judicious use of attenuation, the scintillators can provide accurate information at full FEL intensity as well as sensitivity sufficient to observe the spontaneous radiation on a shot-by-shot basis.

The pulse energy thermal detector will measure the heat deposition in a silicon absorber. The heat of the FEL pulse will be detected with a "colossal magnetoresistor" affixed to the absorber. Tests of the detector have demonstrated its ability to detect a single-shot deposition from 0.1-2 millijoules. A pulse-averaging detector is also being developed.

EXPERIMENT STATIONS

The LCLS has provision for six experiment stations. The first station, designed for research in atomic/molecular/optical (AMO) science, will begin operation in July 2009. Experiments with the AMO instrument will generally require 800-2,000 eV x-rays. The instrument will bring the FEL beam to a focus on a gaseous sample surrounded by time-of-flight spectrometers for ions and electrons, in addition to x-ray fluorescence spectrometers. Three more instruments are under construction as part of the LCLS Ultrafast Scientific Instruments (LUSI) project[21].

CONCLUSION

The Linac Coherent Light Source project is on schedule to provide x-ray beams to its first experiment station in the summer of 2009. All undulator systems have been manufactured and are being prepared for installation. The SLAC linac has demonstrated stable operation with an electron beam of quality sufficient for the FEL to reach saturation at 0.15 nm.

ACKNOWLEDGEMENTS

I am grateful to Paul Emma and Heinz-Dieter Nuhn for providing graphics and presentation materials for this report. I am especially grateful to Paul and his commissioning team for the excellent work they have done commissioning the LCLS accelerators since April 2007. On a daily basis I am aware of my good fortune to be working in this project with outstanding engineers and scientists, led by Geoffrey Pile at ANL and by Richard Bionta at LLNL. Finally I am grateful to the excellent LCLS Project team at SLAC. I cannot mention them all; but I feel some obligation to mention several individuals who are condemned to deal with me directly on a daily basis: Jess Albino, John Arthur, Mark Reichanadter, David Saenz, David C. Schultz and Tom Fornek.

REFERENCES

[1] J. Arthur, et al., *Linac Coherent Light Source (LCLS) Conceptual Design Report*, SLAC-R-593, April 2002;

[2] John N. Galayda, "Linac Coherent Light Source - Status and Prospects", SLAC-PUB-11560, Nov 9, 2005. 11pp. SPIE Conference on Optics and Photonics 2005, San Diego, California, 31 Jul - 4 Aug 2005.

[3] G. K. Shenoy and J. Stohr, editors, *LCLS : The First Experiments*, SLAC-R-611, September 2000;

[4] D. H. Dowell, et al., "Results of the SLAC LCLS Gun High-Power RF Tests", SLAC-PUB-12946 2007; also PAC07-TUPMS047PAC'07 Albuquerque, 2007, pp 1296. http://www.jacow.org/

[5] D.T Palmer et al., "Microwave measurements of the BNL / SLAC / UCLA 1.6 Cell Photocathode RF Gun", SLAC-PUB-95-6799; also in *PAC'95*, Dallas, Texas, pg 982 (2005); http://www.jacow.org/

[6] L.D. Bentson, P. Bolton, R. Carr, D. Dowell, P. Emma, S. Gilevich, Z. Huang, J.J. Welch, J. Wu, "Inverse Free Electron Laser Heater for the LCLS", SLAC-PUB-11186, Jul 2004; EPAC 2004, Lucerne, Switzerland, 5-9 Jul 2004; http://www.jacow.org/

[7] D.H. Dowell et al., "LCLS Injector Drive Laser", SLAC-PUB-12948, 2007; also in PAC'07, Albuquerque, 2007; http://www.jacow.org/

[8] R. Akre et al., "Commissioning the LCLS Injector", SLAC-PUB-13014, Nov 28, 2007. 18pp. Published in Phys.Rev.ST Accel.Beams 11:030703,2008.

[9] R. Akre, et al., "LCLS LLRF Upgrades to the SLAC Linac", SLAC-PUB-12843, PAC'07, Albuquerque, New Mexico (2007) http://www.jacow.org/

[10] M. Zelazny, et al., "Electron Bunch Length Measurement for LCLS at SLAC", SLAC-PUB-12816, (2007); also ICALEPCS 2007), Knoxville, Tennessee (2007); http://www.jacow.org/

[11] R.M. Lill, L.H. Morrison, W.E. Norum, N. Sereno, G.J. Waldschmidt, D.R. Walters, S. Smith, T. Straumann, "Design and Performance of the LCLS Cavity BPM System", SLAC-PUB-13067, Jun 2007. Also PAC'07, Albuquerque, pp 4366 (2007); http://www.jacow.org/

[12] W.M. Fawley, K.L.F. Bane, P. Emma, Z. Huang, H.-D. Nuhn, G. Stupakov, S. Reiche, "LCLS X-Ray FEL Output Performance in the Presence of Highly Time-Dependent Undulator Wakefields", SLAC-PUB-11504, FEL'05, THPP027, Stanford, California, (2005); http://www.jacow.org/

[13] K.L.F. Bane, G. Stupakov "Reflectivity Measurements for Copper and Aluminum in the Far Infrared and the Resistive Wall Impedance in the LCLS Undulator", SLAC-PUB-11924, Jun 27, 2006. also in EPAC'06, Edinburgh, Scotland; http://www.jacow.org/

[14] S. Reiche, K.L.F. Bane, P. Emma, Z. Huang, H.D. Nuhn, G.V. Stupakov, W.M. Fawley, "Optimization of the LCLS X-ray FEL output performance in the presence of strong undulator wakefields", SLAC-PUB-11773; also PAC-2005-RPPT035, PAC'05, Knoxville, Tennessee (2005); http://www.jacow.org/

[15] E. Trakhtenberg, J.T. Collins, P.K. Den Hartog, M. White, "Design of a Precision Positioning System for the Undulators of the Linac Coherent Light Source", PAC '05, Knoxville, Tennessee, pp 4099 (2005); http://www.jacow.org/

[16] J.L. Bailey, D. Capatina, J.W. Morgan, H.D. Nuhn "An Instrument Design for the Accurate Determination of the Electron Beam Location in the Linac Coherent Light Source Undulator", SLAC-PUB-13068, also PAC07, PMN102, Albuquerque, New Mexico, p. 324 (2007); http://www.jacow.org/

[17] H.-D. Nuhn, P.J. Emma, G.L. Gassner, C.M. LeCocq, F. Peters, R.E. Ruland, "Electron Beam Alignment Strategy in the LCLS Undulators", SLAC-PUB-12098 (August 2006); also FEL'06, Berlin, (2006); http://www.jacow.org/

[18] Emil Trakhtenberg et al. "LCLS Undulator Production. (PAC 07), Albuquerque, 25-29 Jun 2007, PAC07-TUPMN100, Jun 2007. pp 1148; http://www.jacow.org/

[19] S. P. Hau–Riege, R. M. Bionta, D. D. Ryutov, and J. Krzywinski, " Measurement of X-Ray Free-Electron-Laser Pulse Energies by Photoluminescence in Nitrogen Gas", J. Appl. Phys. 103, 053306 (2008); DOI:10.1063/1.2844478, 11 March 2008

[20] J.J. Welch, J. Arthur, P. Emma, J.B. Hastings, Z. Huang, H.D. Nuhn, P. Stefan, R.M. Bionta, R.J. Dejus, B.X. Yang , "Precision measurement of the undulator K parameter using spontaneous radiation", SLAC-PUB-12450, Aug 2006, also FEL'06, Berlin, Germany, (2006) ; http://www.jacow.org/

[21] J. Arthur et al., "LCLS Ultrafast Science Instruments: Conceptual Design Report", SLAC-R-852, 10/2007.