THE FIRST ANGSTROM X-RAY FREE-ELECTRON LASER*

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Abstract

The Linac Coherent Light Source produced its first x-ray laser beam on 10 April 2009. Today it is routinely producing x-ray pulses with energy >2 mJ across the operating range from 820-8,200 eV. The facility has begun operating for atomic/molecular/optical science experiments. Performance of the facility in its first user run (1 October - 21 December) and current machine development activities will be presented. Early results from the preparations for the start of the second user run is also reported.

INTRODUCTION

The Linac Coherent Light Source (LCLS) [1] is the world's first x-ray free-electron laser to operate in the photon energy range 820-8,200 eV. It employs an electron beam produced by a 1 km section of the linear accelerator at SLAC National Accelerator Laboratory (SLAC). This beam is sent to a system of undulators designed and built by Argonne National Laboratory. The undulators have a fixed gap, so the electron beam energy is varied over a range 4.3-13.6 GeV to vary the energy of the x-ray photons. This x-ray beam is collimated, characterized and attenuated by an x-ray transport, optics and diagnostics (XTOD) system provided by Lawrence Livermore National Laboratory. The diagnostics suite includes grazing-incidence mirrors that deflect the x-ray beam onto one of three paths to x-ray experiment stations. Presently, two stations for "soft" (<2 keV) x-ray research are operational. A "hard" x-ray station will begin commissioning in July 2010.

The idea of converting the SLAC linac to a free-electron laser first gained attention in 1992 [2]; a concept for a complete x-ray research facility was produced in 1998 [3], to support SLAC's proposal to build such a facility. From 1999 to 2002, the US Department of Energy provided funds for early-stage research and development. Several institutions (UCLA, Argonne National Lab, Brookhaven National Lab, Los Alamos National Lab, and Lawrence Livermore National Lab) collaborated with SLAC in a coordinated effort to test the key components of the LCLS concept: electron gun performance, x-ray optics, undulator characteristics, and beam physics of free-electron lasers). Engineering design began in 2002, and purchases of components for the injector and undulator magnets began in 2005. Major facility construction began in 2006, and was completed in 2008. Electrons from the injector were first observed in 2007 [4]. Commissioning of the LCLS linac was completed by March 2008 [5]. By December 2008 the entire electron beam path was commissioned prior to installation of any undulators. For the first attempt to produce an x-ray laser beam, 20 undulators were installed and, after beam-based alignment of the undulator transport line, these undulators were placed on the beam path one at a time. With the electron beam energy set to 13.6 GeV, exponential gain was observed immediately at 8 keV, and the x-ray beam was amplified to near-saturation as more undulators were placed on the beam path [6]. FEL commissioning continued through the summer of 2009. A stable beam of ~80 femtosecond (fs) pulses was provided to support commissioning of the Atomic/Molecular Optical (AMO) science station. In the first LCLS user run (October-December 2009), eleven experiments were carried out successfully. Approximately 200 TB of data were collected in this run, and the results are being prepared for publication. The second experiment run began on 6 May 2010. In this run, the maximum repetition rate of the linac has been raised from 30 Hz to 60 Hz, and the allocation of beam time to each experiment has been reduced from 120 hours to 60 hours.

GUN AND INJECTOR

Since commissioning began in April 2007, the LCLS RF photocathode gun has performed reliably. The cathode was changed once, in August 2007, in response to a rapid degradation of quantum efficiency [7]. It is believed that the degradation was related to the presence of a waveguide vacuum leak, too small to trigger a vacuum interlock. Since the cathode change, quantum efficiency has been about $3\text{-}4\times10^{-5}$. Degradation of quantum efficiency is seen to be rather slow over many months [8]; laser fluence is increased to compensate. It has proven to be straightforward to re-steer the laser to a new spot on the cathode where quantum efficiency is not degraded. The electron beam position can then be steered onto the linac axis with restored emittance and quantum efficiency. LCLS has been operated through 2009 and 2010 with the cathode installed in July 2008.

Generally, the gun is required to produce either 250 pC from a 1.2 mm diameter laser-illuminated spot in a 6 psec pulse, or 20 pC from a 0.6mm spot in a 3 psec pulse. Typical normalized slice emittances for these two operating modes, measured at the end of the injector linac (135 MeV), have been <~0.4 mm-mrad and ~0.16 mm-mrad [9], respectively.

The laser heater [10] is used routinely to improve the gain length, particularly for 8 keV operation. When optimized, it generally reduces the gain length by 1 meter for 8 keV operation.

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LINAC

The linac and transport line to the undulator system have been operated over an extended energy range in order to expand spectral reach of the FEL. The lowest energy deemed practical for operation is 3.0 GeV. The linac has supported FEL operation over the energy range 3.5 – 15 GeV. The 3.5 GeV operating point will be used in the second experiment run, to permit excitation of K-shell electrons from oxygen. Operation at this energy will be implemented by decelerating the electron beam from 4.3 GeV to 3.5 GeV downstream of the second bunch compressor. Lasing has been achieved at 10 keV using a 15 GeV beam from the linac. A gain length of 4.2m was observed at this energy.

UNDULATOR SYSTEM

The undulator system [11, 12, 13, 14] has met its design goals and has functioned reliably in operations. Some of the most important design considerations and concerns can now be evaluated from the perspective of experience. Radiation damage was a serious concern during the design phase. It is now known that the undulators take a weekly dose of only 100 mR from bremsstrahlung or losses of the electron beam. This can be directly measured with the undulators moved away from the electron beam path. When the undulators are placed on the beam path, high doses (~900 mR/week) are measured with thermo luminescence detectors. It is conjectured that this dose is from energetic spontaneous synchrotron radiation; however, these "hard" x-rays do not affect the undulators' field quality, as has been verified by removal and re-measurement of several undulators. Interlocks [15, 16] are in place to interrupt the electron beam if radiation is detected or if the beam strays more than 1 mm from the center of the resonant cavity beam position monitors. Three types of radiation detectors have been employed: Cerenkov detectors of the type used in PEP-II, a fiber optic scintillator placed in the undulator gap, and fused silica Cerenknov detectors [17] that fit around the small aperture vacuum chamber. These detectors will be modified by the addition of shielding to make them insensitive to the spontaneous synchrotron radiation from the undulators. Pre-emptive radiation protection is provided by an interlock that interrupts the electron beam if it deviates from its prescribed trajectory through the undulators by more than 1mm.

Temperature in the undulator tunnel was a serious concern during LCLS design. It is now seen [18] that temperature stability is excellent, <0.025^{o}C rms over 24 hours during operation. Larger temperature variations are observed during maintenance periods, but an acceptable temperature is quickly re-established when operations conditions are restored. There is a linear temperature gradient from the beginning to the end of the tunnel, increasing about 0.8^{o}C from the cool air input duct to the exhaust.

The mechanical stability of the undulator system has been very good. At approximately 2-week intervals, the undulator is aligned by means of "dispersion-free steering" (i.e. beam-based alignment). In this process, the electron beam energy is increased from 4.3 GeV to13.6 GeV, in four steps. No change is made to any magnet setting in the undulator beam path. Positions of the undulators and quadrupoles are adjusted so that the energy scan produces no more than 10 micron motions of the electron beam. The resonant-cavity RF beam position monitors [19] are sensitive to beam motions less than 0.5 microns and the cam movers beneath the undulator girders can be reliably adjusted in 0.2 micron steps.

A hydrostatic level system and a stretched-wire alignment system [20] are mounted on the undulator girders. These systems are under study as a possible alternative for realignment, so as to reduce the frequency of beam-based alignment. The stretched-wire system looks very promising in this regard. The water level system has excellent sensitivity; however, it displays an inconveniently long transient response to commanded motions. Other anomalies in response are still under investigation.

Since saturation of SASE at 8 keV can be achieved with only 23 undulators, LCLS is modifying 10 standard undulators to have larger (but still fixed) gaps, so that they produce 16 keV radiation. They will be re-installed to make a "2nd – harmonic afterburner", expected to produce ~10^{11} photons per pulse at 16 keV using the electron beam that has been bunched by SASE in the first part of the undulator channel.

FRONT END ENCLOSURE

Downstream of the undulator beam dump and its shielding, a separate enclosure houses the transport, optics and diagnostics devices designed to control and characterize the x-ray beam. Controllable attenuation of the x-ray beam over a range of >10^4 is provided by a combination of 9 beryllium absorbers of varying thickness, and a nitrogen gas channel with dynamically controlled pressure [21]. The beryllium absorbers produce some distortion of the x-ray wavefront, perhaps the result of impurities in the material used. A replacement for the present solid absorbers is being sought. Options under consideration are better purity beryllium and silicon, which is capable of attenuating the hard x-ray beam without damage.

Fluorescence is produced in the gas attenuator by nitrogen atoms re-capturing electrons after ionization by the x-ray beam. The intensity of this fluorescence is observed with photomultipliers, providing a very useful, practically non-invasive measurement of x-ray intensity on a pulse-by-pulse basis. After calibration for different energy photons and different intensities against direct and indirect measurements of the energy in each x-ray pulse, the gas detectors provide intensity data with a precision of 1-2%.

The "K-monochromator [22]" is set to a fixed photon energy of 8.2 keV. It has been used to observe the first, third and fifth harmonics of radiation from single undulators as well as the FEL radiation after attenuation. The device has been used to determine the K-parameter of a single undulator with reproducibility of δK/K of $4x10^{-4}$ RMS. Extended to observation of the spectrum of multiple undulators, it is likely that the precision of this measurement can be further improved.

A cryogenically cooled thermistor [23] has been used to measure the total x-ray energy deposited on a pulse-by-pulse basis. The device is calibrated in-situ by a laser. This means of measurement was used to cross-check the total energy in the FEL pulse determined by energy loss of the electrons. This latter measurement cannot be done on a shot-by-shot basis; energy averaged over many shots was used as the basis of comparison. The agreement was within 9%. Recently, an automated version the electron energy loss has been employed routinely.

Downstream of these diagnostics, a set of mirrors [24, 25, 26] deflect the x-ray beam to the experiment hutches. All mirrors are silicon blocks coated with either boron carbide for the deflection of x-rays < 2 keV or silicon carbide for harder x-rays. The soft x-ray mirrors have been in use since June 2010. Evidence of accumulation of carbon compounds has been seen on that part of the surface of these mirrors exposed to the x-ray beam; however there is no evidence that the x-rays do mechanical damage to the mirrors. Since LCLS uses collimating apertures made from boron carbide, the ability of this material to withstand the x-ray beam is particularly important to LCLS operations. Tests of mechanical damage have been conducted, indicating the damage threshold for 830 eV photons is approximately 2.8 J/cm^2 (+/- 40%) at normal incidence.

X-RAY EXPERIMENT STATIONS

The LCLS Project included one x-ray experiment station (i.e. "instrument") designed for atomic/molecular/optical physics research. This instrument first received x-rays in August 2009 and was prepared for its first experiment by mid-September. The instrument can focus the incoming LCLS beam to a micron spot, where gas or solid targets may be placed. It can accept pulses of laser light from a source synchronized to the LCLS x-ray beam. An array of time-of-flight spectrometers is used to observe the energies of ejected electrons and the energies and charge states of ions. The instrument has been used to create and observe short-lived ionization states of atoms and molecules, such as neon atoms with no electrons in the s shell, and to study the shifting of inner-shell energy levels in nitrogen as a result of exposure to an intense laser beam. Synchronization of a laser with the x-ray has been achieved using an actively stabilized fiber-optic link from the gun laser to the experiment halls. Tests of the link indicate that 6 fs stability [27] has been achieved. S-band resonant cavity monitors installed downstream of the undulators are linked by this fiber to the pump laser used for AMO experiments. The jitter and drift of the x-ray beam with respect to the pump laser is of the order of 120 fs rms in a bandwidth of 1 kHz; however, most of this noise is attributed to phase lock loop internal to the Ti-sapphire laser [28]. It is believed that the laser-to-x-ray jitter can be reduced to 50 fs RMS with improvement in the laser phase locking. By comparison of timing signals from two cavities, it is estimated that this technique contributes only 12 fs of noise to the measurement of bunch time-of-arrival for a bunch charge is 250 pC. At 20 pC, the intrinsic noise is 20 fs [29].

Over the next few months, a second soft x-ray instrument will be commissioned. It will provide a focused and monochromatic x-ray beam to user-supplied sample environments. Three more instruments [30], designed for experiments with "hard" x-rays (2-24 keV), will be commissioned over the next two years. The first will ready for first user experiments in October. The next two instruments will be commissioned in 2011(a station for imaging nanoparticles and complex molecules) and 2012(x-ray correlation spectroscopy). A high energy-density science [31] station will receive first light in 2012.

OPERATION

During the first user run (October-December 2009), 1,295 hours of experiment operation were scheduled. Less than 3% of this time was lost to equipment problems. About 4% of this time was devoted to changing FEL operating parameters (changes in photon energy or electron bunch length) at the request of the x-ray experimenters. About 16% of scheduled operating time was devoted to adjustments or maintenance of the experiment station with the x-ray shutter closed. Eleven experiments were scheduled, each receiving x-rays for approximately 120 hours. Generally the operating hours were contiguous, interrupted only by scheduled maintenance days. The second user run began on 6 May 2010, and will continue through 13 September. Twenty-one experiments are scheduled to receive x-rays for 60 hours each. Delivery of x-rays will alternate between two experiment stations, switched every twelve hours.

It is hoped that scheduling 12-hour blocks of time will provide better efficiency in exploiting the x-ray beam, since instrument maintenance and repair can take place while another experiment is using the beam.

PERFORMANCE

Operating parameters such as electron bunch length and photon energy are changed at users' request. Presently two experiment stations are available for use of soft x-rays. The FEL can be tuned from 540 to 2,000 eV for these stations. Changes in photon energy over this range require 5-30 minutes. Increases in photon energy can be made quickly, while downward changes require more time since the magnet currents must be cycled around a "hysteresis loop". Energy per pulse (for 70-80 fs duration) was routinely >2 mJ for all wavelengths during 2009. Shot-to-shot stability of the energy has been 6% RMS. Presently, operation with 2-3 mJ is routine. The maximum energy per pulse seen to date is 4.5 mJ. Bunch length is changed in a very short time by adjusting RF system phases upstream of the bunch compressors. Generally the charge per bunch is not reduced to produce shorter bunches. Adjustments

Table 1: Comparison of "design" (shown for 8,000 eV only) to measured performance of LCLS for "hard" (8,000 eV) and "soft (800-2,000 eV) photons.

parameter	design	hard	soft	unit
electrons				
charge per bunch	1	0.25	0.25	nC
single bunch rep. rate	120	60	60	Hz
final linac e^- energy	13.6	13.6	3.3-6.7	GeV
slice† emittance (inj.)	1.2	0.4	0.4	μm
final *proj.*† emittance	1.5	0.5-1.2	0.5-1.6	μm
final peak current	3.4	2.5-4.0	0.5-4.0	kA
timing stability (rms)	120	50	50	fs
peak current stability (rms)	12	8-12	5-10	%
x-rays				
FEL gain length	4.4	3.5	~1.5	m
radiation wavelength	1.5	1.5 (1.2)	6-22	Å
photons per pulse	2.0	1.0-2.3	10-20	10^{12}
energy in x-ray pulse	1.5	1.5-3.5	1-4.5	mJ
peak x-ray power	10	15-40	5-40	GW
pulse length (fwhm)	200	60-100	60-500	fs
bandwidth (fwhm)	0.1	0.2-0.5	0.2-1.0	%
peak brightness (est.)	8	20	0.3	10^{32} *
wavelength stability (rms)	0.2	0.1	0.2	%
power stability (rms)	20	5-12	3-10	%

† "*slice*" refers to femtosecond-scale time slices and "*proj.*" to the full time-projected (*i.e.*, integrated) emittance of the bunch.
* Brightness is photons per phase space volume, or photons/sec/mm²/mrad² per 0.1% spectral bandwidth.

over the range 60-500 fs FWHM are accomplished in one minute by adjustment of RF phase and hence the energy "chirp" in the electron beam. As bunch length is reduced, the energy per pulse is also reduced, though peak power is increased. Lasing at 8 keV requires a high-current bunch; with 0.25 nC, bunch length can be varied over 60-100 fs. There has been considerable demand for a special operating mode in which a bunch charge of 20 pC is compressed to less than an estimated 10 fs. This is an estimate because the available electron diagnostics cannot resolve such short bunch lengths. The 20 pC operating mode can take ~2 hours to establish. Typically, 0.2 mJ x-ray pulses can be provided to users in this mode.

USER ACCESS, FUTURE PLANS

LCLS has made three calls for proposals. The first call attracted 28 proposals, of which 11 were accepted and scheduled for beam time September-December 2009. For the May-September 2010 run, 62 proposals were received and 23 have been accepted. Two instrument stations will be operated during this run. For the September-December 2010 run, 107 proposals have been submitted. Of this total, 59 proposals are for the new X-ray pump/probe (XPP) instrument, which will begin commissioning in July 2010. XPP is the first instrument to use the "hard" x-ray (2-8 keV) end of the LCLS operating spectrum. It is likely that about 25 proposals will be approved and scheduled. During this run, the LCLS linac repetition rate will be increased to 120 Hz. Presently the repetition rate is limited to 60 Hz; however the linac often runs at 10Hz, 30Hz or singe-shot, to suit the needs of the experiment at hand. During the September-December run, the second-harmonic afterburner will be tested and perhaps used for experiments.

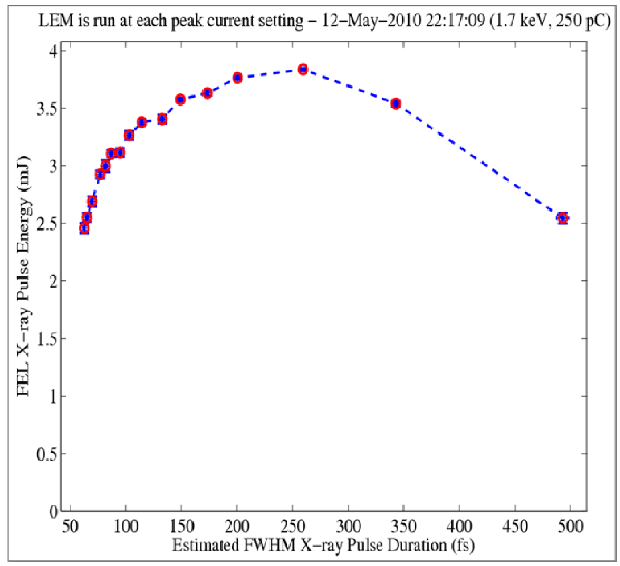

Figure 1: LCLS energy per pulse vs. electron bunch length, for 0.25 nC charge. Photon energy=1.7 keV

For the next few years, it is expected that LCLS will run about 4,000 hours/year for proposed experiments. Because of the very high demand for LCLS user beam time, LCLS is working toward methods for sharing the x-ray beam among the growing number of stations. Many of the "hard" x-ray experiments could take data simultaneously if the x-ray beam could be split with specialized optics. Generally, "soft" x-ray experiments demand a specific photon energy; it will be difficult or impractical schedule two soft x-ray experiments that require the same FEL configuration. For this reason, conceptual design of a second LCLS undulator source has begun. This second source will cover the wavelength range 200- 6,000 eV, and will be configured to run simultaneously with the existing LCLS x-ray source.

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