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TECHNICAL CHALLENGES IN THE LINAC COHERENT LIGHT SOURCE, COMMISSIONING AND UPGRADES*

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Abstract

Five months after first lasing in April 2009, the Linac Coherent Light Source (LCLS) began its first round of x-ray experiments. The facility rapidly attained and surpassed its design goals in terms of spectral tuning range, peak power, energy per pulse and pulse duration. There is an ongoing effort to further expand capabilities while supporting a heavily subscribed user program. The facility continues to work toward new capabilities such as multiple-pulse operation, pulse durations in the femtosecond range, and production of >16 keV photons by means of a second-harmonic "afterburner" undulator. Future upgrades will include self-seeding and polarization control. The facility is already planning to construct a major expansion, with two new undulator sources and space for four new experiment stations.

LCLS TRANSITION TO OPERATIONS

LCLS is well on its way to realizing all the scientific capabilities envisioned in *LCLS – the First Experiments*, which described six broad areas of opportunity for research with an x-ray laser. The facility achieved its design goals in the first weeks of operation and develops new capabilities on an almost weekly basis. Essentially all the experiment techniques envisioned for LCLS-I are being tested and proven in early operation. The full suite of six experiment stations will be implemented by 2012, twenty years after the facility was conceived.

The principal performance goals of LCLS-I were to produce

- X-ray pulses of 230 fs duration or shorter,
- Photon energies ranging from 800 eV to 8,000 eV,
- 10^{12} photons per pulse at 8 keV.

These goals were achieved or exceeded promptly at the outset of commissioning, in April- May 2009. A rapid and productive research program commenced with a 1,300 hour operation run, October-December 2009, during which 152 experimenters participated in 10 experiments. Productivity has continued to increase; In FY2010, 359 experimenters participated in LCLS experiments. Demand for access to LCLS continues to grow. However LCLS productivity is already limited by capacity; one in four proposals is approved.

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EXTENDED LCLS CAPABILITIES

Rapid progress in accelerator research and accelerator commissioning has made it possible to expand LCLS capabilities well beyond LCLS-I goals. The energy produced in a single x-ray pulse has also exceeded project goals, reaching 4 mJ. The operating range of photon energies, originally specified at 800-8,000 eV, has been expanded to 480-10,000 eV, limited by the electron beam energy and the fixed period and magnetic field in the undulator; it is now known that the electron beam quality is high enough to achieve lasing at 16-20 keV.

Perhaps the most important measure by which LCLS-I has exceeded its design goals is in the duration of the x-ray pulse. The LCLS routinely operates with 80 femtosecond (fs) pulses, a duration at which it readily produces 2 mJ/pulse. Pulse duration can be readily adjusted from 4 fs to 500 fs in response to user needs. Such changes can be achieved in a matter of minutes in most cases. Generally, peak power remains constant or is increased somewhat as the pulse duration is reduced.

The ability to change pulse length has proven to be extremely important to LCLS experimenters. Control of pulse duration has made it possible to create and study double-core hole states in atoms, and to observe "bleaching" or increased transparency to x-rays resultant from depletion of inner-shell electrons. By varying pulse duration, it has been possible to confirm the feasibility of obtaining single-shot images of single virus particles even though these particles are immediately destroyed by LCLS x-rays. It has already been shown that it is possible to reconstruct, with 0.9 nm resolution, the structure of the photosystem-I protein from diffraction patterns of nanocrystals exposed to the LCLS beam. Data collection at several pulse durations is now a routine part of most LCLS experiments.

LCLS OPERATIONS-CAPACITY, GROWTH AND LIMITS

The LCLS-I project constructed three experiment stations in each of two experiment halls. One instrument, Atomic, Molecular and Optical Science (AMO), part of the LCLS project scope, is housed in the first station. A second instrument for soft x-ray research has been donated by a consortium, and has been operational since May 2010. Three more instruments are being constructed for research with hard x-rays as part of the LCLS Ultrafast Scientific Instruments (LUSI) equipment project. The first of the LUSI instruments began research in July 2010, and

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the remaining LUSI instruments will be commissioned in 2011-2012. A sixth instrument for the production and study of Matter in Extreme Conditions (MEC) will also begin its research program in 2012, at which time the LCLS experiment stations will be fully occupied.

Table 1: Typical LCLS x-ray beam characteristics

X-RayTuning Range	480 - 10,000	eV
Peak Power	up to 40	GW
Bandwidth, 8,000 eV	0.2 typical	% FWHM
Bandwidth, 800 eV	0.5 typical	% FWHM
X-Ray pulse duration	50-500	x 10^{-15} sec
Beam size at waist, 800 eV	20, typical	μm, RMS
Beam divergence, 800 eV	20, typical	μrad, FWHM
Beam size at waist, 8,000 eV	15, typical	μm, RMS
Beam divergence, 8,000 eV	3, typical	μrad FWHM
Energy/Pulse	> 2 typical, 4.5 max	mJ
Energy Jitter/Pulse	5 typical	%
Pulse Repetition Rate	120	Hz

Since LCLS-I constructed a single undulator source with fixed magnetic field, the energy of the linac must be changed to change the wavelength of the x-rays. An energy change can be accomplished in a fraction of an hour, at the request of the experimenter receiving the beam. The facility has settled into a routine in which x-rays steered to one instrument for 12 hours, and then re-tuned to support the program at another instrument for 12 hours. This has proven to be an efficient scheduling routine. In the next few years of operations, the LCLS Facility will be operated at least 4,000 hours per year for experiments. So far, the operation of the FEL has been quite reliable. Overall, about 3.3% of scheduled beam time has been lost to technical faults. An additional 1.9% of scheduled time has been consumed by readjustment of photon energy or pulse duration at the request of the experiments [1, 2].

Many experiments require the precise synchronization of the LCLS x-ray pulse with a laser used in the experiment. Pump laser-FEL synchronization of 120 femtoseconds has been achieved using a stabilized fiber optic trigger distribution system, combined with a diagnostic system for measuring the time of arrival of the electron bunch at a point downstream of the undulator [3,4].

LESSONS LEARNED IN EARLY OPERATION

Early experiments give strong evidence that LCLS can be used effectively for imaging nanoscale objects and solving protein structures5. However productivity and scientific impact will be limited by the limited access to the LCLS beam.

Not surprisingly, requests for changes in wavelength are common. In addition, however, LCLS operations experience has already shown a surprisingly high demand changes in x-ray pulse duration. It is common practice to change pulse durations once or twice a day. Changing pulse duration requires a straightforward readjustment of the electron source, which can be accomplished in 10-60 minutes.

Demand for access continues to build, and LCLS is working to develop optics that will split each x-ray pulse into two beams for true simultaneous operation of two or more instruments. It is reasonable to expect this will increase the productivity of the facility, perhaps by a factor of 2 or more, during hard x-ray operations. For soft x-ray operations however, scheduling experiments that are compatible for simultaneous running will be more difficult. Assuming a 50/50 split of operating hours between experiments that require dedicated operation of the FEL and experiments that can optically split or share the beam, it would be possible to complete 100 experiments per year; however it is too early in the hard x-ray research program to reliably predict throughput in split-beam operation; annual capacity could exceed this amount.

PRIORITIES AND PROGRESS TWARD EXPANSION OF CAPABILITY

The capabilities of LCLS-I continue to expand at a rapid pace. In the next few months and years, it will be possible to:

Extend the photon energy range to 16 keV: Since the LCLS electron beam is considerably brighter than had been assumed in designing the undulator system, only 28 of the installed 33 undulators are required to reach maximum power for 8-9 keV x-rays. Therefore it has been possible to produce considerable x-ray power (~0.1 mJ/pulse) at 16-18 keV by means of a simple modification of the “extra” five undulators [6]. This extended spectral range is already being tested in the x-ray pump/probe instrument.

Produce pulses with duration approaching 1 fs: Two techniques for producing very short (~1fs) x-ray pulses were proposed during the design of LCLS [7,8], and both have yielded very good results during accelerator studies and in x-ray experiments. Operation with low (20 picocoulomb) charge, it has been possible to produce electron bunches shorter than 10 fs with pulse energies of ~0.14 mJ. This configuration is used in routine operations at the request of x-ray experimenters. Using new techniques for measuring the electron bunch length [9], it may be possible to achieve 1 fs rms resolution. Direct measurement of the x-ray pulse length is perhaps even more important. Ongoing studies of the x-ray spectrum and development of accurate x-ray timing diagnostics will hopefully enable better understanding of the time structure of the x-ray pulse.

Produce short, hard x-ray pulses with full temporal coherence; A very attractive scheme for self-seeding short hard x-ray pulses [10] has been proposed, and will be tested in the LCLS. The scheme can be implemented without significant impact on other operating modes. Preparatory tests of compatibility with normal operations have begun, and first tests of seeding in LCLS will take place in 2012.

Provide polarization control: This is an active area of theoretical and numerical FEL studies (see Ref. [11] and references therein). In addition, an APPLE undulator has been borrowed from SSRL for studies of magnetic field quality and reproducibility. The feasibility of using this magnet in LCLS is presently under study.

Provide a synchronized source of high-field pulsed THz radiation: It is possible to pass the electron beam through a thin conducting foil, causing extremely high currents to flow the few femtoseconds during which the electrons pass. The acceleration of the electrons in the foil results in the emission of Coherent Transition Radiation (CTR). With a bunch length of 10-100 fs, one can expect CTR in the frequency range 10-100 THz; however it is more useful to think of the CTR as an electromagnetic pulse with time structure similar to the derivative of the beam current. As explained elsewhere, there is an exciting opportunity to use THz radiation to produce excitations in molecules adsorbed on catalysts, enabling study of the dynamics of catalyzed chemical reactions. SLAC researchers are presently investigating the feasibility of producing THz pulse with electric fields in the range 0.1-1 volt per Ångstrom [12]. If successful, these pulses can be transported to the Near Experiment Hall hutches for THz pump/x-ray probe investigations.

Provide two x-ray FEL pulses (using two electron bunches), separated by a few nanoseconds, has been demonstrated. This is an enabling step toward novel techniques for pump/probe experiments with LCLS or simultaneous 120 Hz operation of multiple undulators using a single injector.

EXPANSION OPTIONS ANTICIPATED IN THE LCLS-I PROJECT

The LCLS-I project gave due consideration to future needs for facility expansion. Two options or stages for expansion were envisioned and integrated into the design:

- construction of an undulator system in the existing tunnel and
- construction of new tunnel and experiment hall facilities.

The LCLS-I was designed to accommodate a second undulator in its existing tunnel. The beam transport hall, undulator hall, beam dump area, and surface support buildings were sized to support the installation of a second undulator. Therefore the October 2009 proposals for LCLS-II could be carried out as a Major Item of Equipment project; no significant civil construction would be required.

To facilitate the addition of new tunnels for undulators, the upstream end of the electron Beam Transport Hall (BTH) was designed with a flare-out section to permit the addition of up to four more undulator tunnels and associated experiment halls. A concept for electron beam transport lines was developed, confirming that fan-out bends of +/- 2 degrees and +/- 4 degrees could deliver low-emittance electron beams to four or more undulator sources. The critical characteristics of the electron beam in the 2-degree lines should be virtually identical to those achieved in the LCLS today. Only minimal beam degradation is expected in the 4-degree bends. Experience with LCLS has confirmed the reliability of the computer models used to predict the characteristics of the electron beam at the output of these bends. Based on measured performance and tested predictive capability of the computer models of the FEL, it is safe to say that the LCLS facility could be expanded to house two undulator sources in each newly constructed tunnel.

LCLS-II PROJECT

Today and, perhaps, for a few months to come, the LCLS is the world's only "hard" x-ray free-electron laser user facility. Its 14 GeV electron source and single fixed-gap undulator can provide intense x-ray pulses to one of four experiment stations in operation today. By 2012, all six stations will be operational. While there is room in the existing undulator hall to add another x-ray source, there is no room for new instruments. In order to remain at the forefront of ultrafast x-ray science, the LCLS facility must be expanded to accommodate more x-ray sources and instruments.

The LCLS-II Project concept has been developed to provide the new facilities and capacity for expansion required to position SLAC as one of the world's preeminent free-electron laser research centers. With two new, independently controllable x-ray sources in a new undulator hall, it will be possible to simultaneously provide tunable soft and hard x-ray beams, one optimized for 250-2,000 eV photons and the other optimized for 2,000-13,000 eV. Figure 1 shows the photon energy ranges of the HXR and SXR undulators. With a dedicated injector, these two new sources will operate completely independent of the existing LCLS x-ray source, so that existing and new sources may be optimized to meet the specific needs of each experiment. This is a major step beyond present capabilities of LCLS, which can only provide a single x-ray beam optimized for one experiment at a time. At the completion of this project, the LCLS facility will be positioned to implement further upgrades necessary to keep its place at the forefront of the field it has pioneered: ultrafast x-ray research.

The LCLS-II Project will create room for expansion to keep pace with the explosive growth of research opportunities and user demand that has already begun even before existing LCLS facilities reach full capacity in 2012. SLAC will be positioned to continue its leadership as the world's most powerful and capable x-ray laser facility into the next two decades. The LCLS-II Project will add two new undulator sources and space for four new instruments to the existing facility. At the completion of the LCLS-II project, the expanded LCLS facility will accommodate a total of four undulator sources and ten experiment stations.

This expansion of the LCLS facility will build upon the proven performance characteristics of the LCLS, enabling groundbreaking research in a wide range of scientific disciplines. LCLS-II will create unbounded opportunity for research into atomic-level dynamics of processes that are fundamentally important to materials science, chemistry and the life sciences. The LCLS-II conceptual design provides greatly enhanced capacity and capability for the LCLS facility.

The Linac Coherent Light Source II (LCLS-II) Project conceptual design will provide the following facility enhancements (see Figure 2):

- A hard x-ray undulator source (2-13 keV).
- A soft x-ray undulator source (250-2,000 eV).
- A dedicated, independent electron source for these new undulators, using sectors 10-20 of the SLAC linac.
- Modifications to existing SLAC facilities for the injector and a new shielded enclosure for the two new undulator sources, beam dumps and x-ray front ends.
- A new experiment hall capable of accommodating four experiment stations.
- Relocation of the two soft x-ray instruments in the existing Near Experiment Hall to the new experiment hall (Experiment Hall-II).

The undulator sources will produce spatially coherent plane-polarized x-rays by self-amplified spontaneous emission (SASE). They will be designed to be compatible with future upgrades to include full temporal coherence and polarization control.

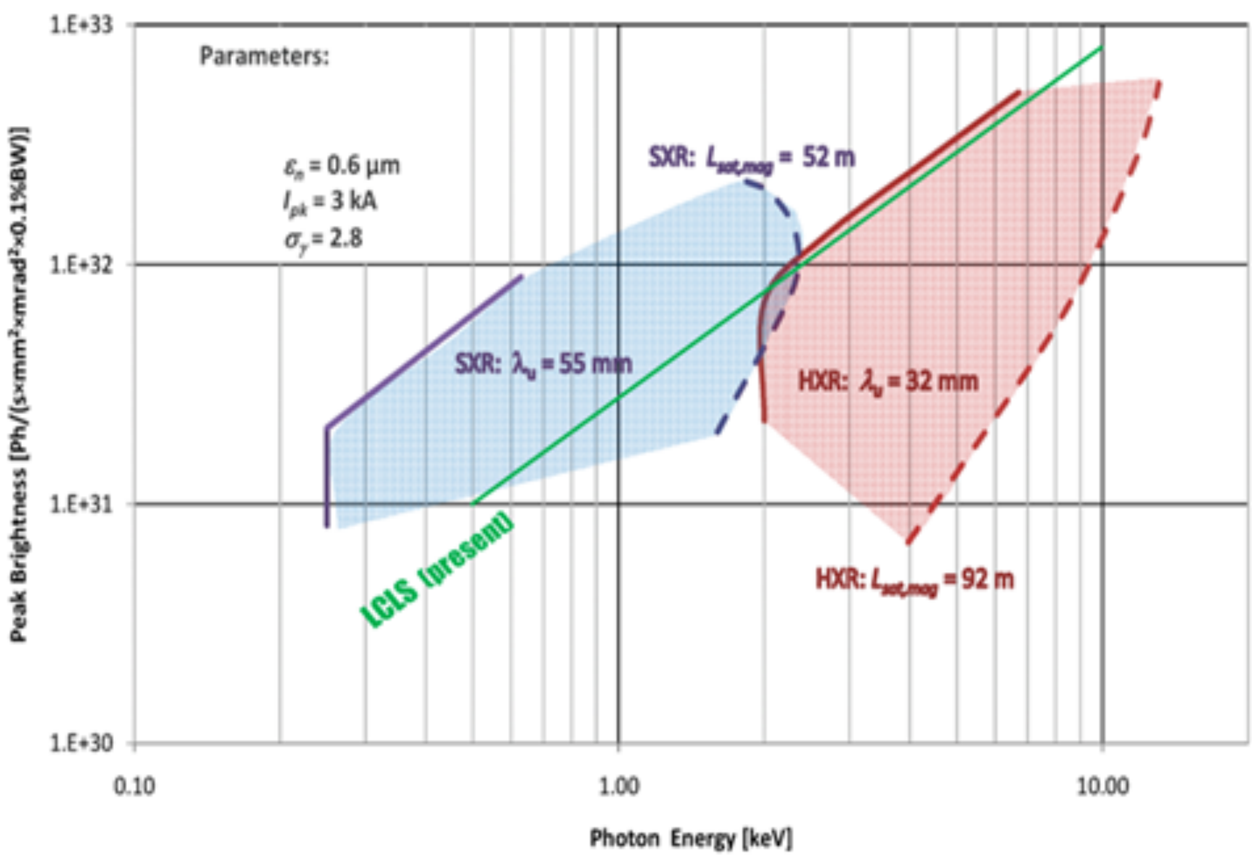

Figure 1: Brightness at saturation versus photon energy for the two new undulator sources proposed in the LCLS-II Project. The blue field indicates the brightness of the soft x-ray (SXR) undulator source and the red field indicates the hard x-ray brightness range. The existing LCLS undulator brightness is indicated by a green line. The new undulators a field in the brightness plot because a range of combinations of undulator gap and electron beam energy can be used to produce a given photon energy. For a given photon energy, the highest brightness is achieved with the highest electron energy and highest undulator magnetic field.span

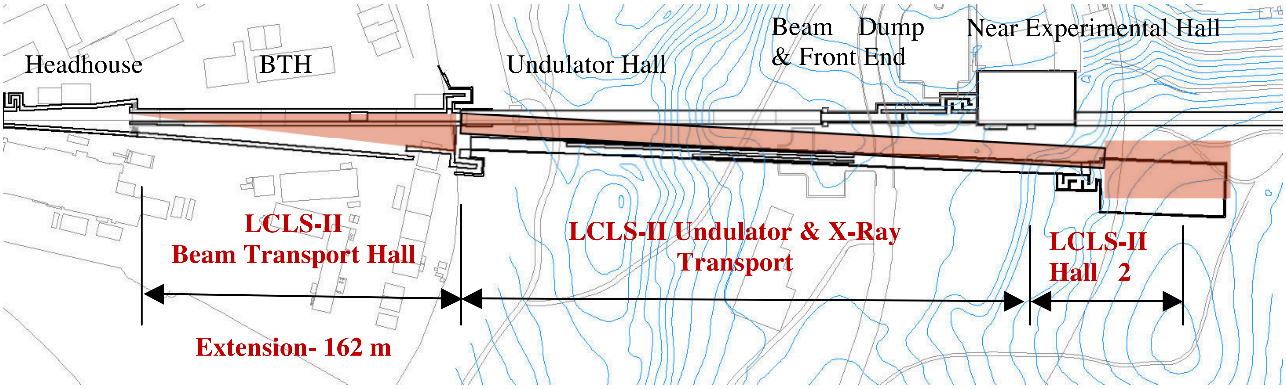

Figure 2: Layout of the expansion of the LCLS facility as proposed for the LCLS-II Project. New construction is tinted red and labelled with red text. Black text and features in the illustration indicate LCLS facilities already in operation. The LCLS-II Beam Transport Hall is attached to the existing facility at the "headhouse".

Much of the new technical systems and facilities will be virtually identical to those constructed in the original LCLS Project (LCLS-I). The LCLS-II Project will build on experience and lessons learned during LCLS-I construction, commissioning and operation so as to reduce cost, schedule and technical risk.

The LCLS-II Project will enable expansion of LCLS to keep pace with the explosive growth of research opportunities and user demand which will saturate the existing facility by 2012.

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REFERENCES

[1] J.A. Rzepiela, H. Loos, R. Akre, A. Brachmann, F.-J. Decker, Y.T. Ding, P. Emma, A.S. Fisher, J.C. Frisch, A. Gilevich, P. Hering, Z. Huang, R.H. Iverson, N. Lipkowitz, H.-D. Nuhn, D.F. Ratner, T.J. Smith, J.L. Turner, J.J.Welch, W.E. White, J.Wu, G. Yocky, "Tuning of the LCLS Linac for User Operation", these proceedings, THP184.

[2] N. Lipkowitz, "Improved Energy Changes at the Linac Coherent Light Source", these proceedings, WEOBS4.

[3] John Byrd, "Synchronization of X-Rays and Lasers For Pump-Probe Experiments at Ultrafast Light Sources", these proceedings, WEOBS2.

[4] A. Brachman, et al., "Femtosecond Operation of the LCLS for User Experiments", Proceedings of IPAC 2010, Kyoto, Japan, pp. 2287-2289, TUPE066.

[5] H. N. Chapman, et al., "Femtosecond x-ray protein Nanocrystallography", Nature 470, pp. 73-78 (2011)

[6] H. D. Nuhn, et al., "Characterization of Second Harmonic Afterburner Radiation at the LCLS", Proceedings of FEL2010, Malmö, Sweden, THOC12, pp. 690-695, 2010.

[7] P. Emma, K. Bane, M. Cornacchia, Z. Huang, H. Schlarb, G. Stupakov, and D. Walz, "Femtosecond and Subfemtosecond X-Ray Pulses from a Self-Amplified-Spontaneous-Emission-Based-Free-Electron Laser", Phys. Rev. Lett. **92**, 074801(4) (2004).

[8] Y. Ding et. al. "Measurements and Simulations of Ultra-low Emittance and Ultra-short Electron Beams in the Linac Coherent Light Source", Phys. Rev. Lett. **102**, 254801, (2009).

[9] Z. Huang, A. Baker, C. Behrens, M. Boyes, J. Craft, F.-J. Decker, Y.T. Ding, P. Emma, J. Frisch, R.H. Iverson, J.J. Lipari, H. Loos, D.R.Walz, "Ultrashort LCLS Bunch Length Measurement Using the SLAC A-line Spectrometer", These proceedings, THP183.

[10] Gianluca Geloni, "Cost-effective way to enhance the capabilities of the LCLS baseline," DESY 10-133, http://arxiv.org/abs/1008.3036v1, August 2010,

[11] H. Geng, Y. Ding, Z. Huang, Nuclear Instruments and Methods in Physics Research A **622** 276 (2010).

[12] A. Fisher, private communications.