LCLS OPERATIONAL EXPERIENCE AND LCLS-II DESIGN*

Tor O. Raubenheimer#, for the LCLS/LCLS-II Team, SLAC, Menlo Park, U.S.A.

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 has 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 fs-scale pulses, self-seeding, synchronized THz for pump-probe, and multiple-bunch operation. Future upgrades will include polarization control as well as hard and soft x-ray self-seeded operation. The facility is already starting to construct a major expansion, with two new undulator sources and space for four new experiment stations referred to as the LCLC-II.

LCLS FACILITY

The Linac Coherent Light Source Facility (LCLS) at SLAC National Accelerator Laboratory is based on the last third of the SLAC linac where a high brightness beam is generated in an off-axis injector and then accelerated to ~14 GeV [1,2]. The concept for the facility was laid out in 1992 at the Workshop on 4th Generation Light Sources at SLAC [3]. Now, the LCLS is well on its way to realizing all the scientific capabilities envisioned in *LCLS – the First Experiments* [4], which described six broad areas of opportunity for research with an x-ray laser.

The facility achieved its design goals during the first weeks of operation [5] and is developing new capabilities on an almost weekly basis. Essentially all the experiment techniques envisioned for LCLS are being tested and proven in operation and the full suite of three experimental stations in each of two experiment halls have been commissioned as indicated in Table 1.

Table 1: LCLS Experimental Stations

Experimental Station	Start of User Operations
Atomic, Molecular & Optical Science (AMO)	October, 2009
Soft X-ray Materials Science (SXR)	June, 2010
X-ray Pump-Probe (XPP)	October, 2010
Coherent X-ray Imaging (CXI)	February, 2011
X-ray Correlation Spectroscopy (XCS)	November, 2011
Matter in Extreme Conditions (MEC)	April, 2012

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# tor@slac.stanford.edu

The principal performance goals of LCLS-I were to produce:

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

As noted, these goals were achieved or exceeded promptly at the outset of commissioning, in April- May 2009; a list of the present operating parameters can be found in Table 2. A rapid and productive research program commenced with a 1,300 hour operation run, October-December 2009, during which 152 experimenters participated in 11 experiments. Productivity has continued to increase; in FY2010, 359 experimenters participated in LCLS experiments. Demand for access to LCLS continues to grow as illustrated in Fig. 1 where the proposals for each the experimental stations is is plotted versus run number; each run is roughly 5 months in duration. However, as shown in Fig. 1, the LCLS productivity is already limited by capacity; only one in four proposals receive beam time.

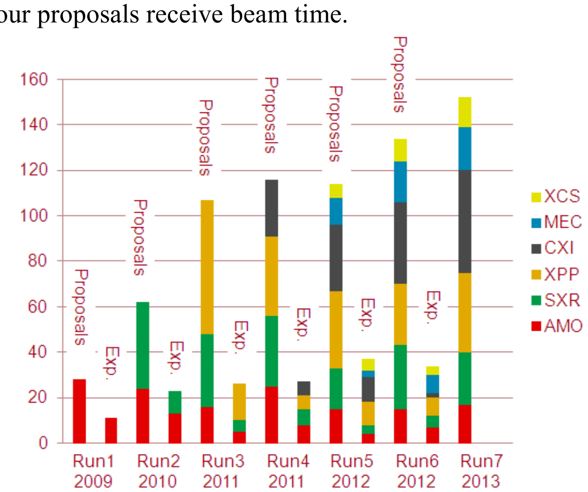

Figure 1: LCLS proposals and experiments receiving beam time by experimental station and run number.

OPERATIONAL EXPERIENCE EXTENDED LCLS CAPABILITIES

Rapid progress in accelerator research and accelerator commissioning has made it possible to expand LCLS capabilities well beyond the LCLS the goals listed in the previous section. The energy produced in a single x-ray pulse has reached 6 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. The pulse duration can be varied between a few femtosecond (fs) and 500 fs with soft x-rays and a few fs to ~100 fs for hard x-rays.

Table 2: Typical LCLS X-ray Beam Characteristics

X-RayTuning Range	480 - 10,000	eV
Peak Power	up to 70	GW
Bandwidth, 8,000 eV	0.2 typical; <0.01 seeded	% FWHM
Bandwidth, 800 eV	0.5 typical	% FWHM
X-Ray pulse duration	~3-500	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, 6 max	mJ
Energy Jitter/Pulse	5 typical	%
Pulse Repetition Rate	120	Hz

Perhaps the most important measure by which LCLS has exceeded its design goals is in it's flexibility. The x-ray pulse length and pulse energy and the beam and photon energy can all be rapidly varied; typical x-ray parameters are listed in Table 2. For example, the LCLS routinely operates with 80 fs pulses, a duration at which it readily produces 2 mJ/pulse. But the pulse duration can be readily adjusted from a few 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. This ability to change pulse length has proven to be extremely important and data collection at several pulse durations is now a routine part of most LCLS experiments.

Similarly, many experimenters will want to scan many x-ray photon energies during their shifts. With the fixed gap undulator in the LCLS, this requires adjusting the beam energy. The photon energy can be varied between 480 to 10,000 eV. Making small changes of a few % can be done in minutes while making larger changes can take as long as an hour.

This performance is due to an injector that significantly exceeds the design performance [6], a linac and bunch compression system that is extremely well understood [7], extensive feedback and control systems that allow varying across a broad range of parameters with minimal impact to the expected performance [8], and a long highly precise undulator and beam-based alignment system [9].

Finally, another critical performance metric is the x-ray availability for user experiments. The LCLS runs delivering x-rays over a 5-day block of time (typically two experiments) followed by two days for scheduled maintenance or machine development, The facility has been running extremely well, with better than 93% availability of x-rays for the users [10] as illustrated in Figure 2.

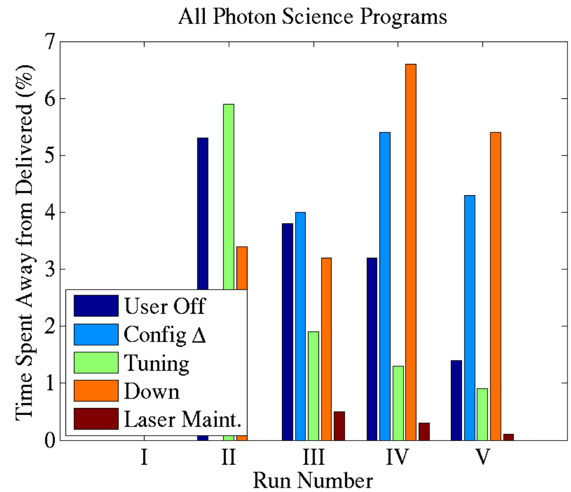

Figure 2: LCLS availability from May 2010 through May 2012; note that User Off and Configuration Δ are counted as available time to users while Tuning, Down and Maint. Are counted as unavailable time (Ref. [10]).

LCLS R&D PROGRAM [11]

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

Produce pulses with duration approaching 1 fs: Two techniques for producing very short (~1 fs) x-ray pulses were proposed during the design of LCLS [12,13], 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 [14,15], it may be possible to achieve 1 fs rms resolution. Direct measurement of the x-ray pulse length is perhaps even more important. A new X-band deflecting cavity is being installed after the undulator and it should provide fs-scale resolution of both the electron beam and the x-ray pulse [15]. 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 [16,17] was proposed and has been demonstrated in the LCLS producing a bandwidth roughly 50 times smaller than SASE [18,19]. The scheme can be implemented without significant impact on other operating modes. Compatibility with normal operations has been established and seeded beams will be offered to users starting in the Fall of 2012 [20]. A soft x-ray self-seeding experiment is being design for the LCLS and will be tested in roughly two years.

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Produce terawatt-level peak powers; When generating temporally coherent x-ray pulses, it is also possible to heavily taper the undulator to extract very high peak powers. Simulation studies appear to support the generation of terawatt-level peak powers with tapers on the order of 10% [21]. Studies are being performed on the LCLS to verify the physics of heavy tapering.

Provide polarization control: LCLS is presently developing options for polarization control. In specific, the DELTA undulator [22] is a novel compact design with a fixed gap that would fit with the LCLS undulator system. Both the polarization and the K are fully adjustable. SLAC is building a 3.2-m prototype to be installed and tested at the end of the LCLS undulator [23].

Provide a synchronized source of high-field pulsed THz radiation: Passing the electron beam through a thin conducting foil will generate Optical Transition Radiation (OTR). With a bunch length of 10-100 fs, one can expect OTR in the frequency range 10-100 THz; however it is more useful to think of the OTR as an electromagnetic pulse with time structure similar to the derivative of the beam current. SLAC researchers are presently investigating the feasibility of producing OTR pulse with electric fields in the range 0.1-1 volt per Ångstrom. If successful, these pulses might 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 [24]. 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.

LCLS-II PROJECT [25]

The LCLS-II Project (LCLS-II) will provide a major enhancement of the LCLS. LCLS-II will enable operation and optimization of the electron beam for its two new undulator sources with complete independence from operation of the existing LCLS undulator x-ray source and experiment stations. LCLS-II will also construct the essential infrastructure necessary to enable LCLS to continue growth in both capacity (up to four x-ray sources and ten experiment stations) and capability (a range of photon energies from 250 eV to >20 keV, a 100x-1,000x increase in brightness and >10X increase in peak power). The design of LCLS-II draws heavily on experience from construction and operation of LCLS. In addition, key design features of LCLS-II have been chosen to support new capabilities presently under development at LCLS.

The LCLS-II will take advantage of existing SLAC infrastructure and accelerator facilities, most notably the second kilometer of the 3-km SLAC linac. The addition of this second electron source will greatly enhance LCLS operations flexibility. Experience has already shown a surprisingly high demand for changes in x-ray pulse duration. It is common practice to change pulse durations once or twice a day. With two completely independent sources of electrons, the new undulator sources for LCLS-II can be optimized without compromising the needs of experiments using the LCLS undulator. LCLS-II also re-uses the off-axis vault at Sector 10 to house the injector linac, and the beam transport facilities originally built to inject electrons into the PEP-II ring. This transport line passes through Sectors 20-30 of the SLAC linac, which provides electrons to LCLS. The operating range of the hard and soft x-ray undulators is illustrated in Figure 2 while Figure 3 is a schematic of the LCLS-II layout and associated electron beam diagnostics. Finally, Figure 4 shows the planned civil construction and the location of the new Undulator and Experimental Halls.

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:

- 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 at least four experiment stations.

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.

Much of the new technical systems and facilities will be virtually identical to those constructed in the original LCLS Project (LCLS-I) and the LCLS Ultrafast Scientific Instruments equipment project (LUSI). 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.

There are, however, important differences between the LCLS-II design and LCLS:

- The LCLS-II undulators are variable-gap devices that are being produced at LBNL and are similar in design to those planned for the European XFEL or in common use at many storage ring light sources

- The LCLS-II undulator hall is 302-m in length, 132-m longer than in LCLS. This will provide sufficient length to achieve SASE performance goals at 13 keV, and additional length for undulators and other hardware necessary to achieve 1 TW power levels at 13 keV.
- LCLS-II has one experiment hall, whereas LCLS-I constructed two halls
- The LCLS-II experiment hall is 80-m in length, an increase of 10-m compared to LCLS

The LCLS-II undulator hall will provide ample space for future upgrades such as self-seeding systems, polarization-control "afterburner" undulators and generation of multi-color x-ray pulses. The tunnel can also accommodate a large number of post-saturation tapering undulators to produce x-ray pulses with extreme peak powers (approaching one terawatt).

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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.

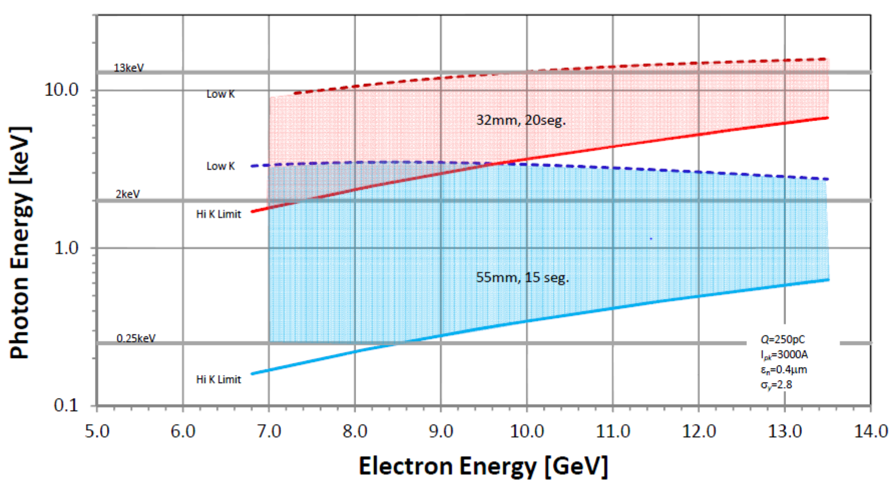

Figure 2: Photon energy versus electron beam energy at saturation for the two new undulator sources proposed in the LCLS-II Project. The blue field indicates the range of the soft x-ray (SXR) undulator source and the red field indicates the hard x-ray operating range range. The lower range on the curves is set by the largest *K* available for each undulator while the upper bounds on the curves is set by the installed length of undulator which is initially planned to be 66-meters in the SXR and 88-meters in the HXR; the upper bounds increase with the installation of additional undulator segments which can be accommodated in the long Undulator Hall which is roughly 300-meters in length.

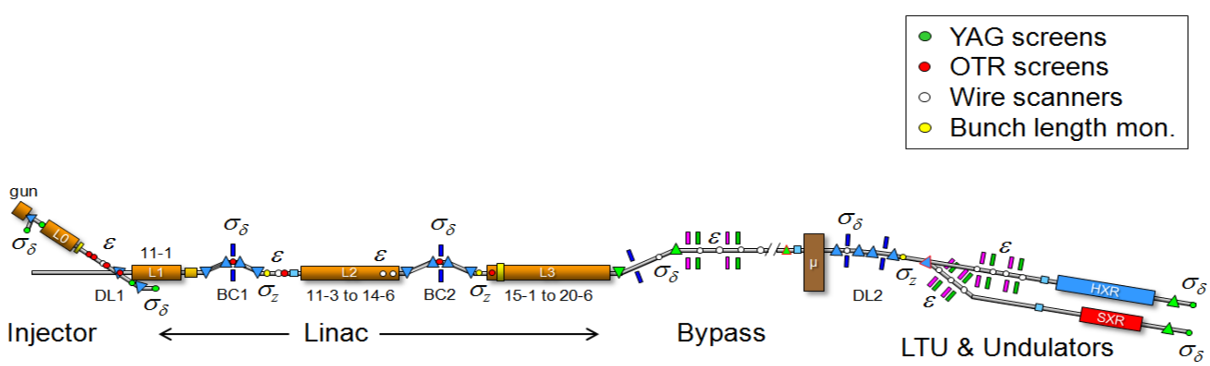

Figure 3: Schematic of the LCLS-II design illustrating the Injector, Linac and bunch compressors, the 1.2 km long bypass around LCLS-I and the Linac-to-Undulator (LTU) and undulators. The primary beam diagnostics are shown for each section.

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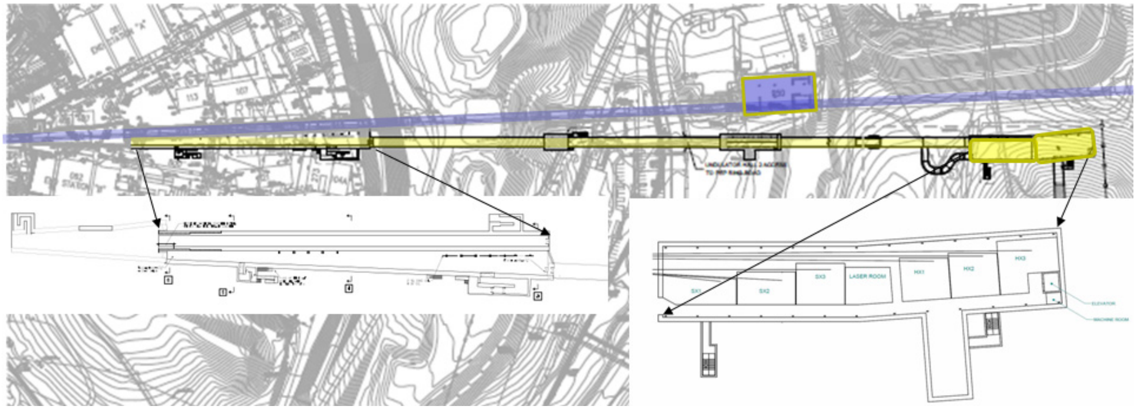

Figure 4: Layout of LCLS-I and LCLS-II. Items tinted blue are existing LCLS facilities. Items tinted yellow are new LCLS-II facilities. Blow-ups of the Beam Transport Hall extension and the new Experiment Hall are shown below the site layout. The LCLS-II Beam Transport Hall is attached to the existing facility at the "headhouse". The long Undulator Hall, roughly 300-meters in length, will be used to support a number of possible upgrades including self-seeding, multi-color generation, polarization control and the generation of terawatt-scale peak x-ray powers.

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REFERENCES

[1] J. Arthur, *et al.*, *Linac Coherent Light Source (LCLS) conceptual design report*, SLAC-R-593, SLAC (2002).

[2] P. Emma, *et al.*, "*First lasing and operation of an ångstrom-wavelength free-electron laser,"* Nature Photon. **4**, 641 (2010).

[3] C. Pellegrini, "*A 4 to 0.1-nm FEL based on the SLAC Linac,"* Proc. of the Fourth generation light sources, Feb. 1992, Stanford, CA (1992).

[4] Shenoy, Stöhr, *ed.,* "LCLS: The first Experiments," SLAC-R-0611, Stanford, September 2000 (2003).

[5] P. Emma, "*First Lasing of the LCLS X-ray FEL AT 1.5 Å*," Proc. of PAC2009, May 2009, Vancouver, BC (2009).

[6] R. Akre *et al.*,"*Commissioning the Linac Coherent Light Source Injector*", Phys. Rev. STAB, **11**, 030703 (2008).

[7] F.J. Decker, *et al.*, "*Improving the beam stability in the LCLS Linac*," Proc. of PAC2009, May 2009, Vancouver, BC (2009).

[8] H. Loos, *et al.*, "*Operational Performance of LCLS Beam Instrumentation,"* 14th Beam Instrumentation Workshop (BIW10), Sept. 2010, Santa Fe, NM (2010).

[9] H.D. Nuhn, "*LCLS Undulator Commissioning, Alignment, and Performance,"* 31st Free Electron Laser Conf., Aug 2009. Liverpool, United Kingdom (2009).

[10] B. Allen, "*LCLS Availability*," Workshop on Accelerator Operations, Aug 2012, SLAC, California (2012).

[11] Z. Huang, "*Some R&D Towards Brighter X-ray FEL's*," Proc. of Future Light Sources, March 2012, Jefferson Lab., Virginia (2012).

[12] P. Emma, *et al.*, "*Femtosecond and Subfemtosecond X-Ray Pulses from a Self-Amplified-Spontaneous-Emission-Based-Free-Electron Laser"*, Phys. Rev. Lett. **92**, 074801(4) (2004).

[13] 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).

[14] Z. Huang, *et al.*, "*Ultrashort LCLS Bunch Length Measurement Using the SLAC A-line Spectrometer"*, Proc. PAC2011, March 2011, BNL, New York, p. 2459 (2011).

[15] Y. Ding, *et al.*, "*Femtosecond x-ray pulse temporal characterization in free-electron lasers using a transverse deflector,"* Phys. Rev. STAB, **14,** 120701 (2011).

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

[17] G. Geloni, V. Kocharyan, E. Saldin, "*A novel self-seeding scheme for hard X-ray FELs*," J. Mod. Opt. **58**, 1391 (2011).

[18] J. Amman, *et al.*, "*Demonstration of self-seeding in a hard-X-ray free-electron laser*," Nature Photonics, DOI: 10.1038/NPHOTON.2012.180 (2012).

[19] R. Lindberg, *et. al.*, "Hard X-ray Self-Seeding at the LCLS," proceedings of FEL'12, Aug. 2012, Nara, Japan (2012).

[20] J. Welch, et al., "*Comparison of Hard X-Ray Self-Seeding with SASE after a Monochromator at LCLS*," Proc. of FEL'12, Aug. 2012, Nara, Japan (2012).

[21] W. Fawley, *et al.*, "*Toward TW-level LCLS Radiation Pulses*," proc. FEL'11, Aug. 2011, Shanghai, China (2011).

[22] A. Temnykh, "Delta undulator for Cornell energy recovery linac," Phys. Rev. STAB **11**, 120702 (2008).

[23] H.D. Nuhn, "*Delta Undulator R&D Project at SLAC*," Proc. of Future Light Sources, March 2012 Jefferson Lab., Virginia (2012).

[24] F.J. Decker, *et al.*, "*A demonstration of multi-bunch operation in the LCLS*," Proc. of FEL2010, Aug. 2010, Malmö, Sweden (2010).

[25] J. Galayda, *ed.,* LCLS-II Conceptual Design Report, https://slacportal.slac.stanford.edu/sites/lcls_public/lcls_ii/Published_Documents/CDR%20Index.pdf.