A High-Repetition-Rate Hard X-ray Laser

Proposed Energy Upgrade for LCLS-II (LCLS-II-HE)

The LCLS-II project at SLAC is now underway, underpinned by compelling new science opportunities compiled by the user community [1]. When it becomes operational in 2020, LCLS-II will be the first XFEL to be based on continuous-wave superconducting accelerator technology (CW-SCRF) that is tailored specifically for X-ray science needs. With a CW-SCRF linac energy of 4 GeV, and two tunable-gap undulators (SXU, HXU), LCLS-II will generate soft X-ray pulses from 0.25 to 5 keV (2.5 Å) at repetition rates up to 1 MHz [2, 3] as shown in Fig. 1. At the same time, the existing Cu-linac and new tunable-gap hard X-ray undulator will provide photon energies up to 25 keV at 120 Hz.

Looking to the future, there is a compelling opportunity to upgrade the energy of LCLS-II (LCLS-II-HE), taking advantage of infrastructure already being installed as part of the ongoing LCLS-II construction project. LCLS-II is based on new accelerator cryomodules to be installed in the first 750 m of the 3 km SLAC linac tunnel. By adding additional cryomodules in the final 250 m of the refurbished tunnel, the electron beam energy can be doubled to 8 GeV and thus increase the spectral reach of the hard X-ray undulator (HXU) to more than 12 keV. Anticipated improvements in electron beam emittance will extend the energy reach to 20 keV as illustrated in Fig. 1. This will enable the study of atomic-scale dynamics with the penetrating power and pulse structure needed for *in situ* and *operando* time-resolved studies of real-world materials, functioning assemblies, and biological systems.

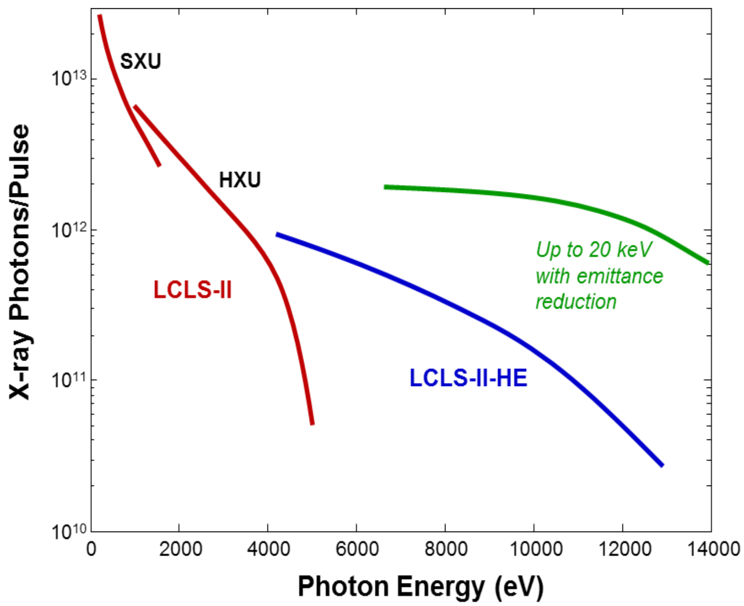

Figure 1. Calculated photons per pulse for high-repetition-rate operation from LCLS-II soft X-ray (SXU) and hard X-ray undulator (HXU) at 4 GeV, and proposed LCLS-II-HE (8 GeV). Projected high-energy performance is bounded by the blue and green lines, dependent on electron beam emittance (with the resultant highest photon energy being between 12.8 and 20 keV). Note that ph/pulse is constant with repetition rate up to ~300 kHz, and scales inversely with repetition rate above ~300 kHz.

LCLS-II-HE will:

- Deliver two to three orders of magnitude increase in average spectral brightness beyond any proposed or envisioned diffraction-limited storage ring (DLSR).
- Provide temporal coherence for high-resolution spectroscopy near the Fourier transform limit with more than 300-fold increase in average spectral flux (ph/s/meV) beyond any proposed or envisioned DLSR.
- Generate ultrafast hard X-ray pulses in a uniform (or programmable) time structure at a repetition rate of up to 1 MHz – a qualitative advance beyond the burst-mode nature of the European-XFEL, and a 100,000-fold improvement in temporal resolution compared to storage ring sources.

The performance of LCLS-II-HE in comparison to other X-ray sources is shown in Figs. 2 and 3.

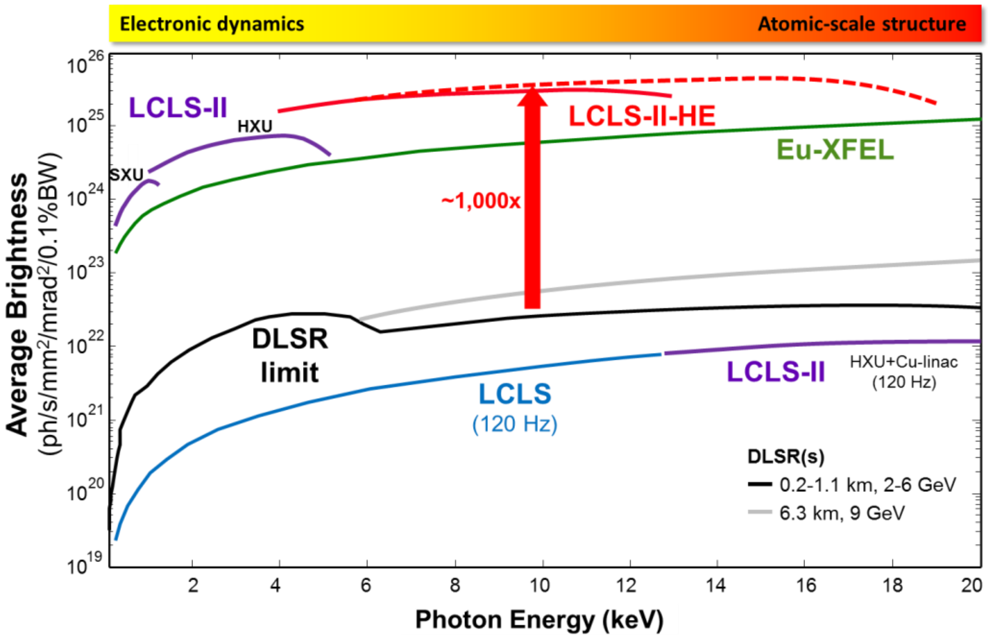

Figure 2. Average spectral brightness of current, planned, and potential future X-ray science facilities including diffraction-limited storage rings (DLSRs) [4] and the European XFEL. LCLS-II-HE provides ~1,000-fold increase in average brightness in the fundamental to >12.8 keV. All XFEL curves assume SASE operation. Self-seeding will increase the average brightness of XFELs by an additional factor of 20 to 50, and operation at the 3rd harmonic will push the useful spectral range beyond 30 keV [4].

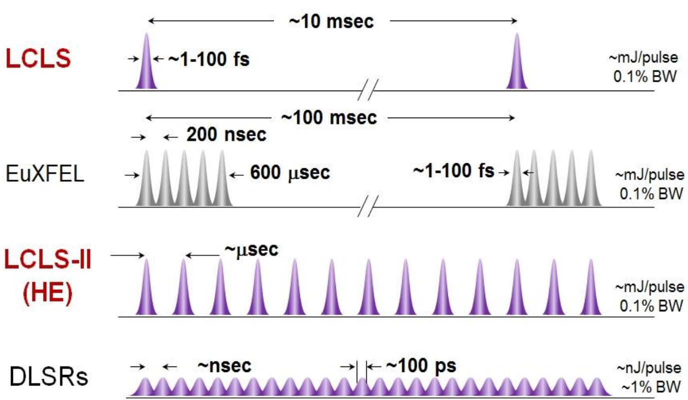

Figure 3. Pulse structure from LCLS warm Cu-linac at 120 Hz, burst-mode structure from the pulsed SCRF linac of the European XFEL at 5 MHz/10Hz, and the uniform (programmable) bunch structure from the CW-SCRF linac of LCLS-II-HE.

Detailed modeling of LCLS-II-HE performance is presently in progress. Current source tables for LCLS (at moderate bunch charge and peak current) provide a rough guide to the expected beam characteristics (e.g. source point and divergence) for LCLS-II-HE and are available at the following link:

https://portal.slac.stanford.edu/sites/lcls_public/Lists/machine_faq/FAQ.aspx

References

1. New Science Opportunities enabled by LCLS-II X-ray Lasers, SLAC-R-1053 (2015) https://portal.slac.stanford.edu/sites/lcls_public/Documents/LCLS-IIScienceOpportunities_final.pdf
2. "LCLS-II Conceptual Design Report (2014)," https://portal.slac.stanford.edu/sites/ad_public/people/galayda/Shared_Documents/LCLS-II%20Conceeptual%20Design%20Report.pdf.
3. "LCLS-II website," https://portal.slac.stanford.edu/sites/lcls_public/lcls_ii/Pages/default.aspx.
4. DLSR contributions from M. Borland (APS) and C. Steier (ALS)

LCLS-II-HE Preliminary Photon Parameters Based on CD0 Simulations

Calculated using electron bunch charge of 20 pC (100 pC)

Fundamental Energy	8 keV	13 keV	Units
General			
FW Pulse Duration	30 (105)	30 (102)	fs
Shot-Shot FWHM Timing jitter	50	50	fs
Total energy/pulse	235 (625)	108 (57)	μJ
Source point relative to end of undulator	25 (19)	24 (21)	m
First Harmonic			
Photons/FEL pulse	18 (49)	5 (2.8)	10^{10} photons
Relative FWHM Bandwidth	0.05 (0.09)	0.06 (0.1)	%
Maximum FWHM pulse energy jitter	12 (8)	11 (8)	%
FWHM wavelength jitter	0.05	0.05	%
FWHM Source Size	36 (37)	26 (22)	μm
FWHM Source Divergence	2.4 (2.0)	1.8 (1.8)	μrad
Third Harmonic			
Photons/FEL pulse	0.15 (0.29)	0.016 (0.005)	10^{10} photons
Relative FWHM Bandwidth	0.05 (0.09)	0.06 (0.1)	%
Maximum FWHM pulse energy jitter	>12 (>8)	>11 (>8)	%
FWHM wavelength jitter	0.05	0.05	%
FWHM Source Size	<36 (<37)	<26 (<22)	μm
FWHM Source Divergence	<2.4 (<2.0)	<1.8 (<1.8)	μrad

Nominal Instrument Location (meters from end of undulator)

TXI	140
XPP	150
XCS/IXS	400
MFX	415
CXI	425
MEC	440