Projected Run 25 LCLS FEL Parameters – Update December 19, 2024

LCLS FEL parameters with hard and soft x-ray undulators (HXU and SXU) driven by the normal conducting and superconducting (NC and SC) linacs. NC linac values are based on Run 20-24 performance. Projected SC linac figures were largely demonstrated at 50-80 pC in Run 24 and are transitioned to stable operation. Many parameters vary according to the energy, pulse length and bandwidth. Stability values below are taken over a few minutes.

The following table shows values at fixed photon energies FEL systems can generate. For important detail on nominal pulse energy versus photon energy (other parameters fixed), see the figures in the following section.

Values are capability from the FEL source and do not reflect effects specific to beamlines (e.g., transport efficiency/capability/operational beam rate). Please refer to Points of Contact and information for the relevant beamline for further details.

(See table on next page)

§Brightness units are photons/sec/mm^2/mrad^2/0.1%-BW

*Calculated assuming nominal pulse duration and undulator strength, and depends on other electron beam parameters

** Highest achievable beam rate will depend on accelerator protection considerations and beamline acceptance

*** **Projected** SC linac parameters depend on optimization of performance (see next sections & Page 3)

Photon Beam Parameters	Symbol	NC linac HXU x-rays		NC linac SXU x-rays		SC linac SXU x-rays (Projected***)			Unit
		$\hbar\omega_{max}$	$\hbar\omega_{min}$	$\hbar\omega_{max}$	$\hbar\omega_{min}$	$\hbar\omega_{max}$	$\hbar\omega_{nominal}$	$\hbar\omega_{min}$	
Photon Energy	$\hbar\omega$	**25000**	**1000**	**5000**	**200**	**1300**	**800**	**200**	**eV**
Fundamental wavelength	λ_r	0.5	12.4	2.5	62.0	9.5	15.5	62.0	Å
Final linac e- energy	γmc^2	16.5	3.5	10.0	3.5	3.5 - 4.0			GeV
FEL 3-D gain length	L_G	4.0	1.0	2.5	1.0	TBD			m
Peak power	P	20	80	50	30	2.5	4.7	12.5	GW
Pulse duration range (FWHM)		10 – 50		10 – 250		20 – 40			fs
Nominal pulse duration (FWHM)	$\Delta\tau_f$	30		50		20	30	40	fs
Max Pulse Energy*	U	0.6	2.0	2.5	1.5	0.05	0.14	0.5	mJ
Photons per pulse*	$N\gamma$	0.15	14	3.1	47	0.2	1.1	15.6	10^{12}
Peak brightness*	$B_{pk,\,SASE}$	7800	425	2250	19	16.7	16.0	2.7	10^{30} §
Average brightness*	$\langle B \rangle$	280 @ 120 Hz	16 @ 120 Hz	138 @ 120 Hz	1.5 @ 120 Hz	114 @ 33 kHz	161 @ 33 kHz	37.5 @ 33 kHz	10^{20} §
SASE bandwidth (FWHM)	$\Delta\omega/\omega$	30	2	10	2	4	3	3	eV
Photon source size (rms)	σ_s	8	20	16	46	TBD			µm
Photon far field divergence (FWHM)	$\Theta_{FWHM,x,\infty}$	1	12	3	25	TBD			µrad
Max. Beam Rate	ϕ_{FEL}	120		120		1,000 – 40,000**			Hz
Avg. x-ray beam power	P_x	0.07	0.24	0.30	0.18	1.7 @ 33 kHz	4.6 @ 33 kHz	16 @ 33 kHz	W
Linear Polarization (100%)	$\langle P \rangle$	Vertical		Horizontal		Horizontal			
Electron Beam Parameters									
Nominal Bunch Charge	Q	180		180		70			pC
Total Energy Spread	$\sigma E/E$	1		1		0.3			10^{-3}
Emittance (Undulator)	$\gamma\varepsilon^{u}_{x,y}$	0.5-1.6		0.5-1.6		0.5	1.0-0.5	1.0	µm
Undul. bunch length (rms)	σ_{zf}	16 – 3		16 – 5		2.5-6			µm
Final peak current	I_{pk}	1.0 – 5.0		1.0 – 3.0		0.5-2.0			kA
Proj. Emittance (injector)	$\gamma\varepsilon_{x,y}$	0.45		0.45		0.5-1.0			µm
Slice Emittance (injector)	$\gamma\varepsilon^{s}_{x,y}$	0.37		0.37		0.3-1.0			µm
Inject. bunch length (rms)	σ_{z0}	550		550		< 1,000			µm
Max. Single Bunch Rep. Rate	F	120		120		1,000 – 40,000**			Hz
e- energy stability (rms)	$\Delta E/E$	0.02		0.07		0.01			%
e- x,y stability (rms)	x/σ_x	15,10		25,20		25,20			%
e- timing stability (rms)	Δt	50-100		50-100		20			fs
Peak current stability (rms)	$\Delta I/I$	10		6		4			%
Charge Stability (rms)	$\Delta Q/Q$	2.5		2.5		2.5			%
FEL pulse energy stability	$\Delta N/N$	< 10		< 10		< 10			%

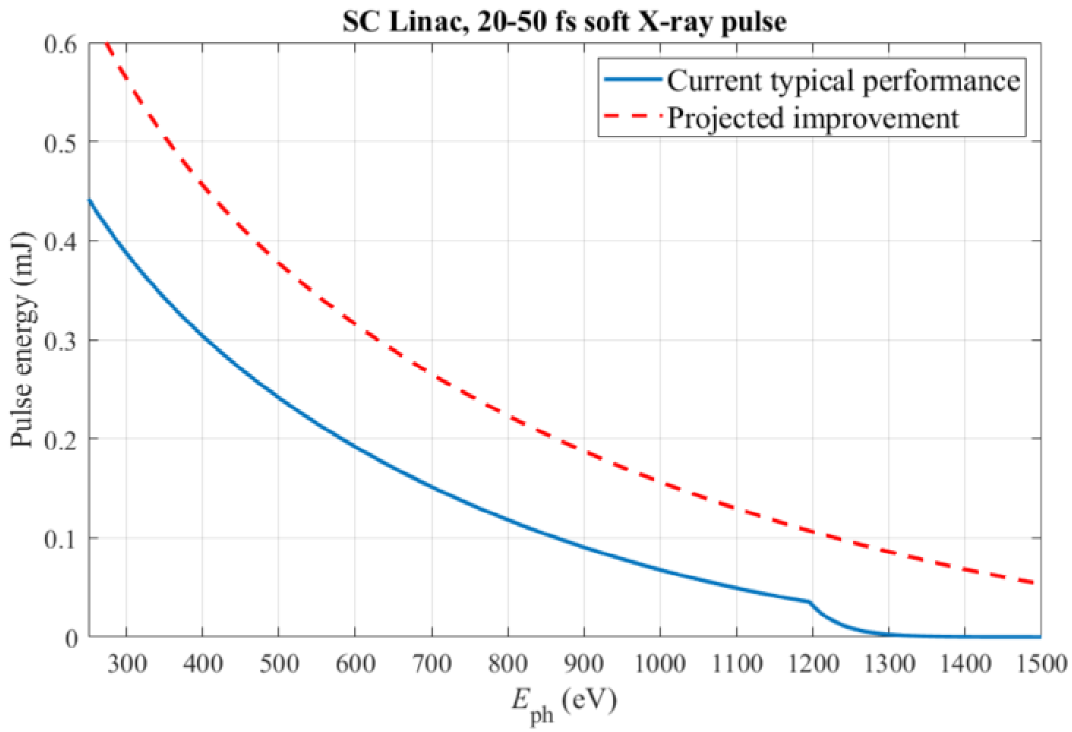
Nominal pulse energy as a function of photon energy

When driven by the NC linac, photon energy may be varied using either the electron beam energy or the variable undulator gap. Optimum performance is achieved using the maximum undulator strength (minimum gap) and corresponding electron beam energy. For the new superconducting linac, only undulator strength is varied.

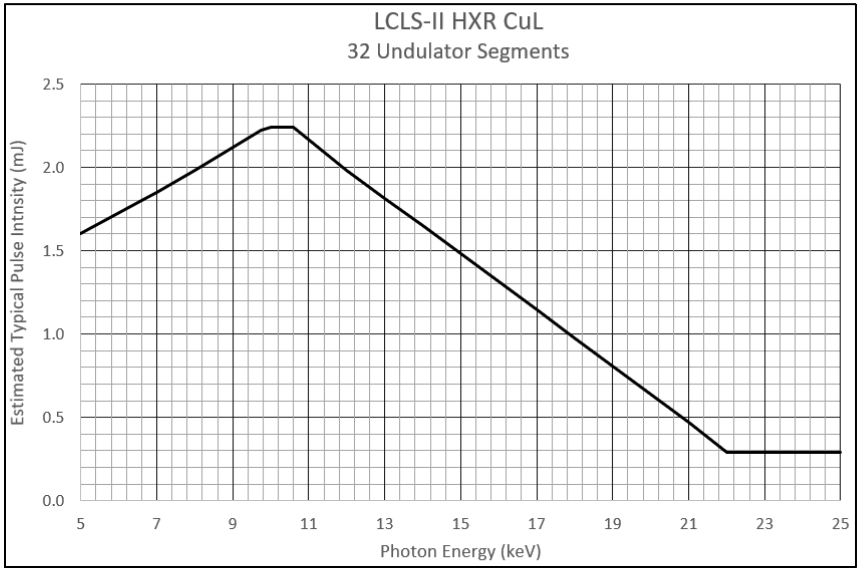
For the nominal beam parameters in the main table, these curves show max pulse energy at corresponding beam energy (NC linac) or undulator gap (SC linac).

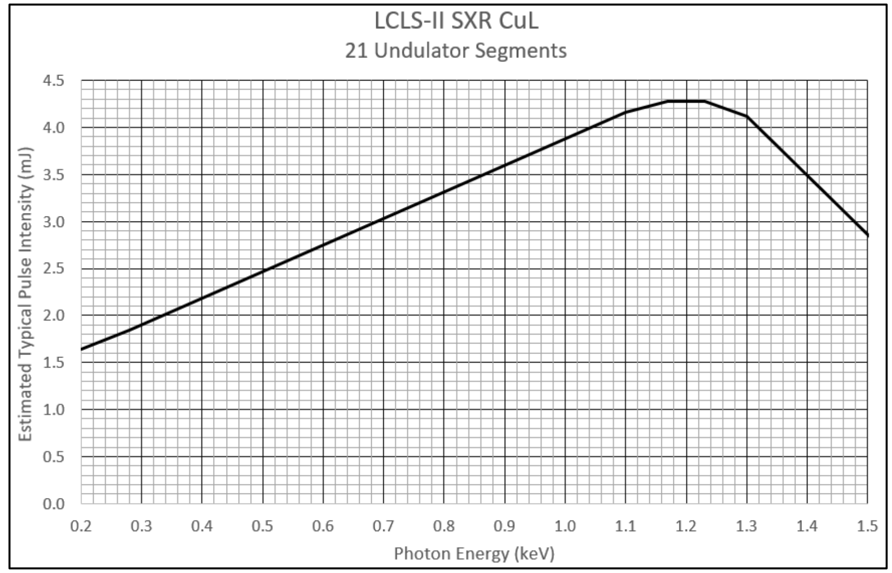
This does not reflect effects related to specific x-ray beamlines (e.g., transport efficiency/capability/rate), nor any modifications to the above operating parameters (pulse duration, etc). Please refer to Points of Contact and information pertaining to the relevant beamline for further details.

Superconducting Linac to Soft X-ray Undulator



Normal Conducting Linac to Hard and Soft X-ray Undulators





Seeded X-ray Beam Parameters

Hard x-ray self-seeding (HXRSS) is fully available with the NC linac. Soft x-ray self-seeding (SXRSS) is currently unavailable. Please contact your LCLS Point of Contact with any further questions including beamline contributions to this performance.

Mode	Linac	Energy Range	Bandwidth (FWHM)	Max Pulse Energy	Pulse Length
HXRSS*	NC	4.5 – 12.5 keV	0.35-1.5 eV	0.3 – 0.5 mJ	Up to 30 fs
SXRSS**	NC	0.4 – 1.2 keV	~ 100 meV @ 400 eV ~ 150 meV @ 530 eV ~ 200 meV @ 800 eV	< 50 – 200 µJ @ 50 fs	20 – 50 fs
	SC			< 20 – 50 µJ @ 50 fs	20 – 50 fs

* For other HXRSS energies, please inquire with your LCLS POC

** SXRSS is currently unavailable.

Multi-Color, Multi-Pulse Parameters

A variety of methods for generating two or more x-ray pulses are established for the NC linac. In Run 22, the split undulator scheme for soft x-rays was commissioned with the SC linac allowing lower intensity pulses with flexible time/energy separation at the femtosecond scale.

Multi-color Pulse Mode Table - SHORT FORM - Status December 19, 2024

SOFT X-RAYS

Technique	Pulse Separation	Linac (Max Rate)	Min Pulse Duration	Energy Separation	Max Energy/Pulse	Comments	Reference publications
Split Undulator SASE	0 - 800 fs	NC (120 Hz)	15 fs	Up to factor 2 ratio in photon energies	>50 uJ (30 fs duration)	Minimally invasive, easy to maintain.	A. Lutman et al. Phys. Rev. Lett. 110, 134801 (2013)
	0 - 800 fs	**SC (>1 kHz)**	20 fs	Up to factor 2 ratio in photon energies	~few uJ	Minimally invasive, easy to maintain. **Exact Performance TBD.** Perfomance depends on photon energy.	
Double Slotted Foil	15 - 70 fs	NC (120 Hz)	~ 10 fs	+/-1.5%	20-50 uJ	Minimally invasive, easy to maintain. Delay and energy separation are not independent, minor tuning needed between changes.	Ding et al. Appl. Phys. Lett. 107, 191104 (2015)
Two/multiple bucket (ns spacing)							
Two bucket	350 ps increments, up to 120 ns	NC (120 Hz)	30-70 fs	+/-2%	>1.0 mJ	Requires add'l setup and tuning time	Decker et al. under review.
Multiple Bucket (4 or 8 bunches)	Two trains of 4 pulses. 700 ps between each pulse in the same train.	NC (120 Hz)	30-70 fs	+/-2%	To be tested	Requires add'l setup and tuning time	Decker et al. under development
Twin Bunches (fs spacing)							
Two SASE Pulses	0 - 125 fs	NC (120 Hz)	30 fs	+/- 2.5%	0.5 mJ	Requires add'l setup and tuning time, 1st/probe pulse always higher photon energy	Marinelli et al. Nat. Commun. 6, 6369 (2015)
With slotted foil (shorter pulses)	0 - 70 fs	NC (120 Hz)	< 10 fs	+/- 2.5 %	50 uJ	Requires add'l setup and tuning time, 1st/probe pulse always higher photon energy	Marinelli et al. Proceedings of IPAC 2016, TUZA02

HARD X-RAYS

Technique	Pulse Separation	Linac (Max Rate)	Min Pulse Duration	Energy Separation	Max Energy/Pulse	Comments	Reference publications
Split Undulator SASE	0 - 30 fs	NC (120 Hz)	15 fs	Up to factor 2 ratio in photon energies	40 uJ (25 fs pulse duration)	**Available after summer 2020.**	A. Lutman et al. Phys. Rev. Lett. 110, 134801 (2013)
Twin Bunches							Marinelli et al. Nat. Commun. 6, 6369 (2015)
Two SASE Pulses	0 - 125 fs	NC (120 Hz)	~ 10 fs	0.2-2%	0.3 mJ (20 fs duration)	Requires add'l setup and tuning time, 1st/probe pulse always higher photon energy	Marinelli et al. Nat. Commun. 6, 6369 (2015)
With slotted foil (shorter pulses)	+/- 50 fs	NC (120 Hz)	~5-10 fs	~2%	40 uJ	Requires add'l setup and tuning time, 1st/probe pulse always higher photon energy	Marinelli et al. Proceedings of IPAC 2016, TUZA02
Double Slotted Foil	7-20 fs	NC (120 Hz)	~ 10 fs	+/-1.5%	100-200 uJ	Minimally invasive, faster setup than twin bunches. Delay/energy separation not independent, minor tuning needed between changes.	Ding et al. Appl. Phys. Lett. 107, 191104 (2015)
Two-(multiple) bucket							Decker et al. under review.
Two bucket	350 ps increments, up to 120 ns	NC (120 Hz)	20 fs	~ 1%	0.5-1 mJ (30 fs duration SASE)	Requires add'l setup and tuning time	Decker et al. under review.
Multi bucket (4 or 8 bunches)	Two trains of 4 pulses. 700 ps between each pulse in the same train.	NC (120 Hz)	20 fs	~ 1%	To be tested	Under development	Decker et al. under development

For detailed information and trade-off decisions, contact the LCLS Point Of Contact

Short Pulse Parameters

Hard X-rays

Two methods have been demonstrated at the LCLS for generating sub-fs pulses in the hard x-ray domain with the normal conducting linac. Both methods used 20 pC bunch charges. One is based on a nonlinear electron bunch compression scheme; the other method used a new version of the slotted foil with optimized beam optics. A third option using an XLEAP-like approach is being developed and characterized with potential advantages in long-term stability.

Spectral measurements show about half of shots containing single-spike spectra, while other shots have a few spectral spikes. The estimated duration for the single-spike pulse is about 200 - 400 as with the nonlinear compression scheme giving a bit wider bandwidth. For example, the measured bandwidth was about 11 eV using the nonlinear method at 5.6 keV, while the slotted foil measured bandwidth is about 4.5 eV. These two schemes work in the hard x-ray range of about 6 – 12.5 keV with the normal conducting linac.

Soft X-rays

For soft x-rays, the XLEAP system was commissioned in Run 19 with the NC linac. It uses the interaction of a beam-generated burst of light with the electron beam itself to modulate the beam energy across the beam pulse. Subsequent compression using an undulator and chicane generates sub-femtosecond pulses of up to 50 μJ.

Initial commissioning of XLEAP pulses with the SC linac was also completed in June of 2024. For availability and detailed parameters, please inquire with your LCLS Point of Contact.

Energy Range	Parameter	Value	Unit
HXR (NC Linac)	Pulse Energy	5-10	μJ
	Pulse Duration	200 – 400	as
	Photon Energy	5 – 10	keV
	Bandwidth [FWHM]	4 – 11	eV
SXR (NC Linac)	Pulse Energy	20	μJ
	Pulse Duration	500	as
	Photon Energy	500 - 1000	keV
	Bandwidth [FWHM]	5	eV

(See table on next page for more details on short pulses including SC linac.)

Ultra short pulse duration - SHORT FORM - Status December 19, 2024

FEW FEMTOSECONDS

Technique	Min Pulse Duration	Linac (Max Rate)	Energy range	Energy/Pulse	Single Spike rate	Comments	Reference publications
Slotted foil + low charge	< 8 fs	NC (120 Hz)	**SXR**	10-20 uJ	Up to 20%	Requires add'l setup and tuning time	Ding et al. Appl. Phys. Lett. 107, 191104 (2015)
Laser Heater Shaping	< 8 fs	**SC (1 kHz+)**	**SXR**	10-20 uJ	TBD	**Under development. Please discuss with Point of Contact.**	Marinelli et al. under development.

ATTOSECONDS

Technique	Min Pulse Duration	Linac (Max Rate)	Energy Range	Energy/Pulse	single-spike rate	Comments	Reference publications
Slotted foil / optics / taper	400 as	NC (120 Hz)	**HXR**	5 uJ (76% fluct.)	65%	Requires some add'l tuning	Marinelli et al. Appl. Phys. Lett. 111, 151101 (2017)
Non-linear bunch compression	200 as	NC (120 Hz)	**HXR**	10 uJ	45%	Requires some add'l tuning	Ding et al. Phys. Rev. Lett. 119, 154801 (2017)
XLEAP	< 1 fs	NC (120 Hz)	**HXR**	15 uJ average, Spikes to 50 uJ	TBD	Initially demonstrated, performance TBD.	TBD
	300-400 as	NC (120 Hz)	**SXR**	Spikes to 100 uJ	--	Requires add'l setup and tuning time	Marinelli et al. under review.
	TBD	**SC (1 kHz+)**	**SXR**	TBD	TBD	**Successfully demonstrated, transitioning to operation. Please discuss with Point of Contact.**	Marinelli et al. under development.

Ultra-short pulse duration can be in general coupled with the split undulator scheme (PRL 110, 134801) to produce pairs of ultra-short pulses at reduced intensity. Please discuss with POC for your application.