LCLS-II Design and Performance

P. Emma

...with input from many others

LCLS-II Instruments Workshop
Oct. 5, 2016, SLAC
LCLS-II Introduction

Accelerator and FEL Performance
- New high-power SCRF linac (4 GeV, 0.2-5 keV)
- Existing 1-km copper linac (3-15 GeV, 1-25 keV)
- 2 new FEL undulators (adjustable gap)

Operating Modes

Future Options

Time-Line
Higher energy means larger emittance 😞

Longitudinal emittance, $\gamma \varepsilon_z$, is much too large!

$\sigma_z \approx 5 \text{ mm}$,
$\sigma_E/E \approx 0.1\%$ (1 GeV),
$\gamma \varepsilon_z = \sigma_z \sigma_E/mc^2 \approx 10000 \mu\text{m}$

Much smaller $\gamma \varepsilon_z$

$\sigma_z \approx 1 \text{ mm}$,
$\sigma_E/E \approx 0.05\%$ (5 MeV),
$\gamma \varepsilon_z = \sigma_z \sigma_E/mc^2 \approx 5 \mu\text{m}$

Emittance scaling $(1/\gamma)$!
In terms of linear accelerators, SLAC will have both kinds (Country and Western)

- Existing **Cu-Linac** allows high $e^-$ energy (15 GeV), but with pulsed RF (< 0.1% RF duty factor, 120 Hz beam rate)

- New **SCRF-Linac** allows high rate (1 MHz), but low $e^-$ energy (4 GeV) using **CW** RF

**LCLS-II will have both!** (smooth x-ray delivery)
Superconducting RF Based on XFEL (DESY)

- LCLS in CW mode (RF always “ON”)
- SRF Allows high beam rate (1 MHz)
- Avoids “Burst Mode” and transients
- Very stable; slow to change (>10 ms)
- High cost (5M$/CM)
- Needs 2 large cryo-plants (60M$/ea)
- Tight fit in existing SLAC tunnel
- Replacement of CM requires weeks
Remove old Linac from Sectors 0-10

New injector and new superconducting linac

Existing Bypass Line

2 New Cryoplants

New Transport Lines

Two New Undulators and X-Ray Transport

Exploit Existing Experimental Stations
LCLS-I FEL Lasing at 1.5 Å (April 2009)

\[ \gamma \varepsilon_{x,y} \approx 0.4 \mu m \text{ (slice)} \]
\[ I_{pk} \approx 3.0 \text{ kA} \]
\[ \sigma_E/E \approx 0.01\% \text{ (slice)} \]

(25 of 33 undulators installed)

\[ L_g = 3.3 \text{ m} \]

Saturation length: 60 m

\[ 10^{10} \]
\[ 10^9 \]
\[ 10^8 \]
\[ 10^7 \]
\[ 10^6 \]

FEL power (W)

Active undulator length (m)

measurements (04/26/09)

GENESIS simulation

Profile Monitor YAGS:DMP1.500 15-Apr-2009 12:28:01
Each main electron beam dump is rated for < 120 kW of average beam power

Beam rate must be reduced when bunch charge is increased

For example: 100 pC at 300 kHz, or 30 pC at 1 MHz (4 GeV)
Add 20 new cryomodules (35 → 55)
More RF gradient (16 → 19.6 MV/m)
8-GeV SCRF linac to feed SXR or HXR
3.6-GeV fast kicker take-off to SXR
Allows 6 different operating modes

<table>
<thead>
<tr>
<th>SXR options</th>
<th>HXR options-1</th>
<th>or</th>
<th>HXR options-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-3.6 GeV</td>
<td>4-8 GeV</td>
<td>or</td>
<td>3-15 GeV</td>
</tr>
<tr>
<td>SC-Linac (&lt; 1 MHz)</td>
<td>SC-Linac (&lt; 1 MHz)</td>
<td>or</td>
<td>Cu-Linac (&lt; 120 Hz)</td>
</tr>
<tr>
<td>0.1-1.3 keV with &gt; 20 W</td>
<td>1-13 keV with &gt; 20 W</td>
<td>or</td>
<td>1-25 keV with mJ pulses</td>
</tr>
<tr>
<td>4-8 GeV</td>
<td>4-8 GeV (tied to SXR)</td>
<td>or</td>
<td>3-15 GeV</td>
</tr>
<tr>
<td>SC-Linac (&lt; 1 MHz)</td>
<td>SC-Linac (&lt; 1 MHz)</td>
<td>or</td>
<td>Cu-Linac (&lt; 120 Hz)</td>
</tr>
<tr>
<td>0.2-13 keV with &gt; 20 W</td>
<td>1-13 keV with &gt; 20 W</td>
<td>or</td>
<td>1-25 keV with mJ pulses</td>
</tr>
<tr>
<td>3-10 GeV</td>
<td>4-8 GeV</td>
<td>or</td>
<td>3-15 GeV</td>
</tr>
<tr>
<td>Cu-Linac (&lt; 120 Hz)</td>
<td>SC-Linac (&lt; 1 MHz)</td>
<td>or</td>
<td>Cu-Linac (&lt; 120 Hz)</td>
</tr>
<tr>
<td>0.1-10 keV with mJ pulses</td>
<td>1-13 keV with &gt; 20 W</td>
<td>or</td>
<td>1-25 keV with mJ pulses</td>
</tr>
</tbody>
</table>
Undulator hall will be filled with 2 new undulators

Existing fixed-gap undulator will be removed

New VPU undulator for HXR

New HPU undulator for SXR
Many New Components and Systems

Two 4-kW Cryogenic Plants

Gallery and Tunnel Cleared

New Vertically Polarized Undulator: HXR

New High-Rate Gun

35 12-m Long Cryo-Modules
Photon Energy (0.2-5 keV & 1-25 keV)
- ±1% is fast using $e^-$ energy (10 ms)
- Full range uses gap control (5 min.)
- Cu-Linac slow if $|\Delta \lambda / \lambda| > 10\%$ (15-30 min)
- Use $e^-$ energy or gap (3-15 GeV)

Pulse Duration
- 20-300 fs (slow changes: 1-2 hrs)
- Use of slotted-foil may limit beam rate
- Cu-Linac as now (1-min, 50-500 fs, SXR’s)
- < 10 fs with low bunch charge (1 hr)

Beam Rates (< 1 MHz & 120 Hz)
- Trigger fast kickers (μsec or slower)
- Choose from ‘one-shot’ to 1 MHz
- Total beam power/FEL < 120 kW (rate limit)

X-Ray Pulse Energy
- Up to 8 mJ (250-fs pulse, 250 eV, $\rightarrow$ 800 W)
- 3-6 mJ (highest at 3-6 keV)
SC-Linac → SXR & HXR FEL Performance Simulations

Power goal of >20 W is met across photon energy range of 0.2 to 5 keV. Further optimization has improved results.

LCLS-II Power Goal (20 W)

SASE X-Ray Power [Watts]

Photon Energy [keV]

- SXR
  - 100 pC, 50 fs
  - 300 kHz, 4 GeV

- HXR
  - 100 pC, 50 fs
  - 300 kHz, 4 GeV

- HXR
  - 20 pC, 20 fs
  - 930 kHz, 4 GeV

XTES Power Limit

G. Marcus

tracking results (SXR, HXR)

...as driven by SC-Linac
## SC-Linac → HXR & SXR FEL Performance Simulations

...as driven by SC-Linac

### Table 1: Laser Parameters

<table>
<thead>
<tr>
<th>Q (pC)</th>
<th>( E_y ) (keV)</th>
<th>( f ) (MHz)</th>
<th>( E ) (μJ)</th>
<th>( \Delta t_{FW} ) (fs)</th>
<th>( \Delta E_y ) (eV)</th>
<th>( P_{pk} ) (GW)</th>
<th>( P_{avg} ) (W)</th>
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<tbody>
<tr>
<td>20</td>
<td>0.25</td>
<td>1.0</td>
<td>390</td>
<td>46</td>
<td>2.6</td>
<td>8.0</td>
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<td></td>
<td>0.75</td>
<td>1.0</td>
<td>270</td>
<td>35</td>
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<td>7.5</td>
<td>266</td>
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<td></td>
<td>1.25</td>
<td>1.0</td>
<td>220</td>
<td>35</td>
<td>2.2</td>
<td>6.3</td>
<td>222</td>
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<tr>
<td>100</td>
<td>0.25</td>
<td>0.3</td>
<td>2550</td>
<td>120</td>
<td>0.91</td>
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<td>765</td>
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<td>0.75</td>
<td>0.3</td>
<td>1640</td>
<td>110</td>
<td>2.4</td>
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<td>490</td>
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<tr>
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<td>1.25</td>
<td>0.3</td>
<td>1010</td>
<td>108</td>
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<td>9.2</td>
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<td>300</td>
<td>0.25</td>
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<td>8800</td>
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<td>339</td>
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</table>

### Table 2: Laser Parameters

<table>
<thead>
<tr>
<th>Q (pC)</th>
<th>( E_y ) (keV)</th>
<th>( f ) (MHz)</th>
<th>( E ) (μJ)</th>
<th>( \Delta t_{FW} ) (fs)</th>
<th>( \Delta E_y ) (eV)</th>
<th>( P_{pk} ) (GW)</th>
<th>( P_{avg} ) (W)</th>
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<tr>
<td>20</td>
<td>1.5</td>
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<td>3.25</td>
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<tr>
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<td>5.9</td>
<td>185</td>
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<td>0.3</td>
<td>6</td>
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<td>300</td>
<td>1.5</td>
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<td>457</td>
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<td>2060</td>
<td>206</td>
<td>8.1</td>
<td>9.9</td>
<td>206</td>
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<tr>
<td></td>
<td>5.0</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Diagram 1: Longitudinal Phase Space

- **HXR**
- **SXR**

G. Marcus, et al.
Shows estimated pulse-to-pulse jitter (rms)
Slow drift will be removed with beam-based feedback (as at LCLS-I)
Actual jitter may be even less (3-5 times) than shown
Should be considerably better than LCLS-I
Self-Seeding at *LCLS-II*

- Hard X-Ray self-seeding will be possible, as it is now (low rate, Cu-Linac, 4-12 keV).
- Crystal will be rotated as optimal for vertical polarization.
- Soft X-Ray self-seeding has been de-scoped from the project (*LCLS* directorate).

Fresh-bunch lasing of two slices at different times/energies

2-color, time-delayed X-ray pulses for pump-probe studies with up to 1 mJ/pulse (~15 to 950 fs) – “Dechirper” not in baseline

Two lasing slices

14 eV

Time [fs]

Intensity [arb. units]

Photon Energy [eV]
**Polarization Control at LCLS-II SXR (future)**

- **Delta-I** is operational
- **Delta-II** for SXR: larger $K$ & var. gap
- Add three 3.3-m long **Delta-II’s** at end of SXR und. (not in LCLS-II baseline)
- Simulations: 5-7 GW (w/3 Delta-II’s)
- 100% polarization (goal <1% stability)
- All orientations possible (planar: $x$ or $y$; circular: $L$ or $R$) – change in ~1 min.

**Delta OFF (0.002 mJ)**  
**Delta ON (0.22 mJ)**

*YAG screen in FEE*

**A. Lutman, H.-D. Nuhn, F. Peters, et al.**

**Polarization control in an X-ray free-electron laser**

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**Delta-I installed**

**3 new Delta-II’s**
Attosecond Pulses - XLEAP & XLEAP-II

- < 1 fs pulse duration
- Multi-eV BW
- 20-μJ pulse energy
- 1 or 2-color operation with sub-fs jitter
- ≤ 1 kHz w/exist. Laser
- Upgrade to 100 kHz with high-average power OPCPA
- Results in late 2017
LCLS-II Time Line

Commission...

2017 2018 2019 2020 2021


- Gun
- Cryo-plant 1
- Cryo/RF
- LCLS Restart
- SRF & Cu Linac
- First Light
- Connect plant-2
- Early Science, Ramp up power
- Install cryo & Undulators
- Cryo-plant 2
- 2 kW 5 kW 20 kW 50 kW 120 kW
- CD-4 (6/22)

Not official
**Summary**

- *LCLS-II* will be a highly flexible machine with...
  - Two separate linear accelerators (*CuRF & SCRF*)
  - Two separate FEL undulators (variable gap)
  - High-rate beam delivery at 0.2-5 keV (upgrade to 13 keV)
  - High-energy, low-rate beam delivery at 1-25 keV
  - Variable wavelength, pulse duration, power, and rate
  - Improved stability over *LCLS-I* (energy, power, timing)
  - Self-seeding, two-color, polarization, & attosecond options
  - Average x-ray power (*SCRF*) may approach 1 kW
  - Upgrade paths (8 GeV, SXRSS, SC-undulators, $\gamma_\varepsilon \downarrow$)
  - “First Light” is scheduled for start of FY-2020
Key Performance Parameters (KPP’s) for LCLS-II

- Build new 4-GeV superconducting RF linac in 1st km of SLAC tunnel
- New linac beam rate is up to 1 MHz with CW RF
- Exiting LCLS-I retains performance (gets new adjustable undulator)
- Beam to be fast switched between either of 2 new undulators

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Threshold</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Gap Undulators</td>
<td>2 (SRX &amp; HXR)</td>
<td>2 (SRX &amp; HXR)</td>
</tr>
<tr>
<td><strong>Super Conducting Linac Based FEL System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super Conducting Linac Energy</td>
<td>3.5 GeV</td>
<td>≥ 4 GeV</td>
</tr>
<tr>
<td>Electron Bunch Repetition Rate</td>
<td>93 kHz</td>
<td>929 kHz</td>
</tr>
<tr>
<td>Super Conducting Linac Charge per Bunch</td>
<td>0.02 nC</td>
<td>0.1 nC</td>
</tr>
<tr>
<td>Photon Beam Energy Range</td>
<td>250-3,800 eV</td>
<td>200-5,000 eV</td>
</tr>
<tr>
<td>High Repetition Rate Capable End Stations</td>
<td>≥ 1</td>
<td>≥ 2</td>
</tr>
<tr>
<td>FEL Average Power (10^-3 BW)</td>
<td>5×10^8 (10x spontaneous @2,500 eV)</td>
<td>&gt;10^{11} @ 3,800 eV</td>
</tr>
<tr>
<td><strong>Normal Conducting Linac Based FEL System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Conducting Linac Electron Beam Energy</td>
<td>13.6 GeV</td>
<td>15 GeV</td>
</tr>
<tr>
<td>Electron Bunch Repetition Rate</td>
<td>120 Hz</td>
<td>120 Hz</td>
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<tr>
<td>Normal Conducting Linac Charge per Bunch</td>
<td>0.1 nC</td>
<td>0.25 nC</td>
</tr>
<tr>
<td>Photon Beam Energy Range</td>
<td>1,000-15,000 eV</td>
<td>1,000-25,000 eV</td>
</tr>
<tr>
<td>Low Repetition Rate Capable End Stations</td>
<td>≥ 2</td>
<td>≥ 3</td>
</tr>
<tr>
<td>FEL Photon Energy (10^-3 BW^a)</td>
<td>10^{10} (lasing @ 15,000 eV)</td>
<td>&gt;10^{12} @ 15,000 eV</td>
</tr>
</tbody>
</table>

^a^ Calculated at 30 Hz
# Electron Parameters for SCRF Linac

<table>
<thead>
<tr>
<th>Parameter (SCRF Linac)</th>
<th>symbol</th>
<th>nominal</th>
<th>range</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>$E_f$</td>
<td>4.0</td>
<td>2.0 - 4.5</td>
<td>GeV</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>$Q_b$</td>
<td>100</td>
<td>10 - 300</td>
<td>pC</td>
</tr>
<tr>
<td>Bunch Repetition Rate in Linac</td>
<td>$f_b$</td>
<td>0.62</td>
<td>0 - 0.93</td>
<td>MHz</td>
</tr>
<tr>
<td>Average $e^-$ current in linac</td>
<td>$I_{avg}$</td>
<td>0.062</td>
<td>0.0 - 0.3</td>
<td>mA</td>
</tr>
<tr>
<td>Avg. $e^-$ beam power at linac end</td>
<td>$P_{av}$</td>
<td>0.25</td>
<td>0 - 1.2</td>
<td>MW</td>
</tr>
<tr>
<td>Norm. rms slice emittance at undulator</td>
<td>$\gamma e_{\perp,s}$</td>
<td>0.45</td>
<td>0.2 - 0.7</td>
<td>µm</td>
</tr>
<tr>
<td>Final peak current (at undulator)</td>
<td>$I_{pk}$</td>
<td>1000</td>
<td>500 - 1500</td>
<td>A</td>
</tr>
<tr>
<td>Final slice E-spread (rms, w/ heater)</td>
<td>$\sigma_{Es}$</td>
<td>500</td>
<td>125 - 1500</td>
<td>keV</td>
</tr>
<tr>
<td>X-ray pulse duration (FWHM)</td>
<td>$\Delta \tau_{FW}$</td>
<td>100</td>
<td>20 - 300</td>
<td>fs</td>
</tr>
</tbody>
</table>

**New challenges:**
- CW superconducting RF system
- High brightness CW injector
- Two variable gap undulators (both new)
- Very high beam power
- Beam dynamics of high brightness electron beams
Remove old Cu-Linac in 1st km
Install 35 12-m long cryomodules
Replacements barely clear
Driven by Cu-Linac

H.-D. Nuhn

Cu-Linac → HXR & SXR FEL Performance Simulations

![Graph showing energy vs. photon energy](image)

- **10 GeV**
  - Cu linac + SXU (not in baseline)

- **<15 GeV**
  - Cu linac + HXU
    - ~50 fs FWHM, 120 Hz

- **15 GeV**

with post-saturation taper

H.-D. Nuhn
FEL Performance Estimate

Driven by Cu-Linac

Cu-linac + HXR
2.5 - 15.0 GeV
150 pC

With Post Saturation Taper

Photon Energy / [keV]
LCLS-II relative to normal conducting LCLS-I

**Pro’s**
- Four orders of magnitude increase in beam power and efficiency relative to LCLS-I
- Can vary the bunch spacing (users generally want > 1 us)
- Better beam energy stability due to continuous feedback
- Cavities operate with only a few kWs of input RF power vs MWs

**Con’s**
- Large cryoplant required (20 % of the cost), difficult to operate
- Cavity performance very sensitive to cleanliness – requires clean room techniques
- Cavity bandwidth very narrow – non-trivial to stabilize gradient
- Linac basically inside a vacuum vessel – design, assembly and repairs are challenging
Project Collaboration

Fermilab

½ of cryomodules:
1.3 GHz

Jefferson Lab

½ of cryomodules:
1.3 GHz
Cryoplant

Berkeley Lab

e− gun & associated
injector systems

Undulators

Argonne

Undulator
Vacuum
Chamber

Undulator
R&D: vertical
polarization

Cornell University

R&D planning, prototype support
e− gun option