LCLS Operation Experience and LCLS-II Design

Tor O. Raubenheimer
for the LCLS and LCLS-II teams
Two Mile Linac

1962: Start of accelerator construction

1967: 20-GeV electron beam achieved

Nobel Prizes

- 1976 Physics, J/psi, Richter and Ting
- 1990 Physics, Deep inelastic scattering, Taylor, et al
- 1995 Physics, Tau lepton, Perl
- 2006 Chemistry, Eukaryotic transcription, Kornberg
- 2008 Physics, broken symmetries; confirmed at SLAC & KEK
- 2009 Chemistry, structure of the ribosome, early work at SSRL
SPEAR 3.7 GeV Storage Ring and Synchrotron Radiation

1972: SPEAR operations begin
1973: Stanford Synchrotron Radiation Project (SSRP) started – First Light
1977: SSRP becomes Stanford Synchrotron Radiation Laboratory (SSRL)
1990: SPEAR II - a dedicated synchrotron radiation facility
2003: SPEAR III synchrotron source
SLAC Linear Collider

1989: SLC operations begin, 50 GeV electron and positron beams achieved

• Power-pulse compression using SLAC Energy Doubler (SLED)

The first linear collider

Operation until June 1998
1998: First colliding beams
March 2008: Completion of Run
C. Pellegrini, A 4 to 0.1 nm FEL Based on the SLAC Linac, Workshop on Fourth Generation Light Sources, February, 1992

Herman Winick’s Study Group

**SHORT WAVELENGTH FELs at SLAC - STUDY GROUP**

**SOURCE**
- Karl Bane
- Jeff Corbett
- Max Cornacchia
- Klaus Halbach (LBL)
- Albert Hofmann
- Kwang-je Kim (LBL)
- Phil Morton
- Heinz-Dieter Nuhn
- Claudio Pellegrini (UCLA)

**SCIENTIFIC CASE**
- Art Bienenstock
- Keith Hodgson
- Janos Kirz (SUNY-Stony Brook)
- Piero Pianetta
- Steve Rothman (UCSF)
- Brian Stephenson (IBM)

Engaged Bjorn Wiik and Gerd Materlik during sabbaticals at SLAC
Linac Coherent Light Source Facility
First Light April 2009, CD-4 June 2010

Injector at 2-km point
Existing Linac (1 km) (with modifications)
New $e^-$ Transfer Line (340 m)
Undulator (130 m)
X-ray Transport Line (250 m)
Near Experiment Hall
Far Experiment Hall
Generation of low emittance beam
Preservation of 6D brightness in accelerator and compressors
Undulators meeting tolerance and trajectory control
LCLS Undulators

Roughly 110m installed

3.4-m undulator magnet

beam direction

cam-based 5-DOF motion control – 0.7 mcron backlash
SLAC/LCLS Main Control Center (MCC)

LCLS Summary Display
Undulator Summary
FEL power vs. time
Jitter Summary
LCLS Experiment Stations

Near Experimental Hall

X-ray Transport Tunnel
200 m

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<th>Start of User Operation</th>
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<td>AMO</td>
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Far Experimental Hall

Linac'12, Tel Aviv, Sept. 2012
LCLS Operational Performance
(480 eV – 10 keV)

Energy Loss Scan History all pC
08/2011 to 09/2011

- One Sigma
- Mean
- Max

Single Photon Energy (eV)
X Ray Pulse Energy (mJ)
# LCLS Experimental Program

## Run 1

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<tr>
<th>Proposals Received</th>
<th>Sept'08</th>
<th>May '09</th>
<th>Nov'09</th>
<th>Jun'10</th>
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- "User Assisted Commissioning"
- Dedicated User Facility > August 2010

## Run 2

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LCLS Achievements

- Exceptional $e^-$ beam quality from RF gun ($\gamma \varepsilon_{x,y} \approx 0.4 \ \mu m$)
- Pulse length *easily* adjustable for users (60 - 500 fs FWHM) with $\ll 10$ fs pulses at low charge (20 pC)
- Wider photon energy range: 480 - 10000 eV (design was: 830 - 8300 eV)
- Peak FEL power $> 70$ GW (10 GW in CDR)
- Pulse energy up to 6 mJ (2 mJ in CDR)
- 96.7% accelerator availability, 94.8% photon availability
- Total of 133 publications, 35 in high impact journals

Linac'12, Tel Aviv, Sept. 2012
LCLS-I FEL R&D Program
Exploring new capabilities for X-ray FELs

HXRSS (hard x-ray self seeding)

XTCAV (X-band trans. cavity)

HXSSS (Hard x-ray single-shot spectrometer)

EXRLT (experimental x-ray to laser timing)

MBXRP (Multi-bunch x-ray production)

DELTA (Delta undulator)

THXPP (THz/x-ray pump/probe)

XRDBL (X-ray R&D Beamline)

LCLS Cathode Test Facility

CTF

LCLS-II CD-2 Director’s Review / June 25-27, 2012
Hard X-ray Self-Seeding
Hard X-Ray Self-Seeding
New Capability in LCLS Operation

Figure 5. Single-shot (a) and averaged (b) x-ray spectrum in SASE mode (red) and self-seeded mode (blue). The FWHM single-shot seeded bandwidth is 0.4 eV, whereas the SASE FWHM bandwidth is approximately 20 eV. Vertical scales have the same arbitrary units in both plots (a) and (b). The chicane is turned off for the SASE measurements, but necessarily switched on for the self-seeded mode.

Demonstration of self-seeding in a hard x-ray free-electron laser

J. Amann1, W. Berg2, V. Blank3, F.-J. Decker1, Y. Ding1, P. Emma1, Y. Feng1, J. Frisch1, D. Fritz1, J. Hastings1, Z. Huang1, J. Krzywinski1, R. Lindberg2, H. Loos1, A. Lutman1, H.-D. Nuhn1, D. Ratner1, J. Rzepiela1, D. Shu2, Yu. Shvyd'ko2, S. Spampinati1, S. Stoupin2, S. Terentyev1, E. Trakhtenberg2, D. Walz1, J. Welch1, J. Wu1, A. Zholents2, D. Zhu1

Affiliations for authors: 1SLAC National Accelerator Laboratory, Stanford, CA 94309, USA;
2Argonne National Laboratory, Argonne, IL 60439, USA; 3Technical Institute for Superhard and Novel Carbon Materials, Troitsk, Russia 142190; 4Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
Linac Coherent Light Source II

Injector @ 1-km point
Sectors 10-20 of Linac (1 km) (with modifications)
Bypass LCLS Linac in PEP Line (extended)
New Beam Transport Hall

SXR, HXR Undulators
X-ray Transport Optics/Diagnostics
New Underground Experiment Hall

2010: April-
2011: October-
2012: March-
2012: August-
2013: June-
2018: Sept.
2019: Sept.

Critical Decision 0 approved
Critical Decision 1 approved
Critical Decision 3a approved
Critical Decision 2 approved
Critical Decision 3b approved
First FEL Light
Critical Decision 4
LCLS-II Enhanced Capability

LCLS-II will provide expanded spectral range using two beamlines and variable gap undulators

- Up to 13 keV (above Selenium K-edge) @ 10.5-13.5 GeV
- Down to 250 eV (Carbon K-edge) @ 7-10 GeV

• 300 meter undulator tunnel
  - Adequate space to accommodate future enhancements:
    - Seeding
    - Two-color generation
    - Polarization control
    - TW peak power
  - Details will be determined by ongoing LCLS R&D program
LCLS-II Greater Capacity

- Dedicated new injector at Sector 10
- Two new SASE undulator x-ray sources, both variable gap
- High Field Physics Soft X-Ray Experiment Station
- Immediately:
  - 4X increase in operations hours for soft x-rays
  - Generally, soft x-ray experiments run one-at-a-time
- Immediate 20% increase in operations hours for hard x-rays
  - Since hard x-ray instruments will someday run simultaneously, perhaps 2 or even 3 at a time, this can mean nearly 20% more time per station
- Future: Room in new experiment hall for at least 3 more new instruments with new scientific capabilities
- Future: 4\textsuperscript{th} undulator in existing tunnel, 2 more instruments

Linac'12, Tel Aviv, Sept. 2012
Two New FEL Sources with Expanded Spectral Range

Tuning the X-Rays with both undulator gap and Electron Beam Energy

Maintain the flexible beam format vital to the LCLS success

Linac’12, Tel Aviv, Sept. 2012
SLAC X-ray FEL R&D roadmap

- **X-ray seeding & brightness**
  - HXRSS: Soft X-Ray Self-Seeding
  - ECHO-7: HHG efficiency and control

- **E-beam brightness & manipulation**
  - ASTA (Cathode, Gun): S0 ITF: advanced beam generation, high-energy compression and laser seeding

- **Ultrafast techniques**
  - Temporal diagnostics & timing: Attosecond x-ray generation

- **THz & Polarization**
  - THz: Polarization control

- **Technology development**
  - HXRSS: X-ray sharing
  - Multi bunches, detectors, novel undulators, high-rep. rate

- **Status**
  - Completed
  - Ongoing
  - Under development
Summary

• LCLS has been a great success
  - Very flexible beam operations allows for wide range of photon science studies
  - R&D program is defining new capability
    • Short fs-scale bunches
    • Wide photon energy range
    • Self-seeding with >0.01% BW
    • Two color operation
    • Polarized x-rays
    • Strongly tapered operation
• LCLS-II will be the next addition to the SLAC photon science portfolio \(\rightarrow\) expands LCLS capability and capacity greatly
End of Presentation
Pulse Length Easily Adjusted (500-60 fs)*

LEM is run at each peak current setting – 12-May-2010 22:17:09 (1.7 keV, 250 pC)

**X-Ray Pulse Energy vs. Pulse Length**
(2.5 – 3.8 mJ)

**e⁻ Peak Current vs. Pulse Length**
(500-4000 A)

**Peak Power vs. Pulse Length**
(5-40 GW, now>70 GW)

\[ e⁻ \text{ bunch length is quickly adjustable (<1 min) from 60 to 500 fs (hard x-rays: 60 to 100 fs)} \]

* for soft x-rays (0.5-2 keV)
Ultra-Short Pulses in Operation at LCLS

Measurements at 20 pC

X-ray pulse duration is <10 fs at 20 pC (not measured)

peak current monitor (CSR)
gas detector (FEL power)

over-compressed \( \Delta \varphi = -0.5^\circ \)

under-compressed \( \Delta \varphi = +0.6^\circ \)

fully compressed

1.5 Å

135 MeV
BC1
250 MeV
BC2
4.3 GeV
L2-linac
L3-linac
DL1
135 MeV
L1S

gun
undulator 4-14 GeV

peak current monitor (CSR)
gas detector (FEL power)

over-compressed \( \Delta \varphi = -0.5^\circ \)

under-compressed \( \Delta \varphi = +0.6^\circ \)

fully compressed

1.5 Å

135 MeV
BC1
250 MeV
BC2
4.3 GeV
L2-linac
L3-linac
DL1
135 MeV
L1S

gun
undulator 4-14 GeV

X-ray pulse duration is <10 fs at 20 pC (not measured)
Ultra-short bunch length measurement

- Transverse deflector lacks resolution to measure ultra-short low charge bunch (< 10 fs)
- A technique is developed to map time to energy, which can be measured with a high-resolution spectrometer (~1 fs resolution)

40 pC compressed bunch length