LCLS Performance: Exceeding Expectations

April 10, 2019

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April 10, 2009: birth of the first hard x-ray laser

- After 2.5 years of the LCLS accelerator commissioning, the first lasing campaign started on April 10, 2009
- Insert one undulator magnet (3.4 m) at a time. Observe spontaneous radiation at a downstream YAG
- After inserting 11-12 undulators, correct for electron orbit, we see a black dot in the middle of YAG screen
- Then slowly raise the peak current to 3000 A…
Introduction

LCLS performance and enhancement
- Higher photon and pulse energy
- Femtosecond pulses and controls
- Better electron beams

New FEL capabilities
- Self-seeding
- Polarization control
- Two color and multiple pulses
- Attosecond X-rays
- Machine learning

Summary
LCLS performance

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**Parameter** | **Design** | **Typical** | **Unit**
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Photon energy range | 800–8000 | 270–11 200 | eV
Peak x-ray power | 10 | Up to 100 | GW
X-ray pulse energy | 2 | 2–4 | mJ
Pulse repetition rate | 120 | 120 | Hz
SR\(^4\) bandwidth (FWHM) | 0.1 | 0.2–2 | %
SRX pulse duration (FWHM) | 200 | 50–500 | fs
SRX pulse energy jitter (rms) | 20 | 3–10 | %
SRX wavelength jitter (rms) | 0.2 | 0.15 | %
HXR\(^8\) bandwidth (FWHM) | 0.1 | 0.2–0.5 | %
HXR pulse duration (FWHM) | 200 | 30–100 | fs
HXR pulse energy jitter (rms) | 20 | 5–12 | %
HXR wavelength jitter (rms) | 0.2 | 0.05 | %

Thanks ANL!

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First lasing and operation of an ångström-wavelength free-electron laser

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Linac Coherent Light Source: The first five years

Christoph Bostedt\(^{1}\), Sébastien Boutet\(^{1}\), David M. Fritz\(^{1}\), Zhihong Huang\(^{1}\), Hao Ja Lee\(^{1}\), Henrik T. Lamkø\(^{1}\), Aymeric Robert\(^{1}\), William F. Schlotter\(^{1}\), Joshua J. Turner\(^{1}\) and Garth J. Williams\(^{1}\)
FEL photon and pulse energy reach

Routine pulse energy approximately **doubled** (since 2015)

Many small improvements, with a step-function due to ‘Horn-Cutting’ (later)

Energy loss scan (automation tools)

A. Brachmann, T. Maxwell et al.,

Paul is happy!
Electron streak camera (XTCAV) with time-dependent energy loss revealing FEL pulse temporal structure.

An ultra-short soft x-ray pulse with a measured 2.6-fs pulse duration.

C. Behrens, Y. Ding, P. Krejcik et al., Nature Comm. 5, 4762 (2014)
Femtosecond control of single/double pulses

- Energy chirped e-beam has x-t correlation in region of high dispersion
- Insert foil with triangular width to continuously tune the pulse duration

High-power FEL with a horn-cut beam

Electron bunch head and tail are cut in BC1 ➞ shape longitudinal phase space and reduce collective effects.

Horn-cutting as a routine operating mode, delivering over 4-mJ SASE FEL pulses.

Extreme cutting + compression ➞ Hard X-ray pulses with peak power over 200 GW.

Outline

- Introduction
- LCLS performance and enhancement
  - Higher photon and pulse energy
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  - Better electron beams
- New FEL capabilities
  - Self-seeding
  - Polarization control
  - Two color and multiple pulses
  - Attosecond X-rays
  - Machine learning
- Summary
Hard x-ray self-seeding

SASE temporal coherence can be drastically improved by seeding (self or external seeding)

A simple self-seeding scheme was proposed at DESY and implemented by SLAC/ANL/Moscow team


SASE FEL spectrum

Seeded FEL spectrum

J. Amann et al., Nature Photon. 6, 693 (2012)
Improved self-seeding performance

- Single shot spectrometer
- Centering seed line on SASE peak

• Electron energy jitter reduction
• Horn-cutting and wake control

**Goal: Energy jitter < 1/2 SASE bandwidth**

- Pre 2012: Unoptimized System
- 2012-2013: RF Station improvements
- 2014 - Present: Optimization of Linac Phasing / Configuration

A single-shot transmissive spectrometer for hard x-ray free electron

Linac Coherent Light Source, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA

500 shots
Average 750 μJ
Chicane delay 35 fs

2016 data
(A. Lutman)

Seeded brightness 3-4 times higher than 4 mJ SASE!
Soft X-ray self-seeding

Spectral brightness ~5x higher than SASE
Spectral pedestals better understood, mitigation methods developed.
DELTA undulator for polarization control

- DELTA concept developed at Cornell (A. Temnykh), SLAC designed/built the 3-m DELTA

- Four independent rows of permanent magnets move longitudinally at fixed gap.
- Polarization state of the radiation can be controlled over the full range.
- Background linear polarization cut by microbunching rotation technique.

2-color FEL by splitting undulator

- Split undulator in 2 parts (works for soft X-rays)
- Use magnetic chicane to introduce delay
- Easy to tune!
- ~1/10 of SASE saturation power

A. Lutman et al., PRL 134801 (2013)
Femtosecond beam gymnastics

- Fresh-slice scheme allows multi-color X-ray pulses with high power and arbitrary pulse delay.
- Fresh-slice opens avenues enabling multi-stage amplification schemes.

Multiple bunches

\[ \lambda_{1,2} = \frac{1 + K^2}{2 \gamma^2_{1,2}} \]

Camera gates:

\[ \leftarrow 5\text{ns} \rightarrow \]

Fast-diode measurement at XCS endstation.

A. Marinelli et al., Nature Comm. 6, 6369 (2015)

SASE

Seeded 80 eV apart

2- color Hard X-ray FEL spectra

F.-J. Decker et al., 2018

Time-resolved phase spaces of 4 bunches
Attosecond pulses with XLEAP

- **Current-Enhanced SASE with a modulated electron beam**
- Instead of laser modulation, use coherent undulator radiation to create modulation

- **350 as** pulses, tens of uJ pulse energy
- **6 orders of magnitude** higher peak brightness compared to other attosecond pulses at SXR

**J. Duris, S. Li, J. MacArthur, J. Cryan, A. Marinelli, et al.**
Machine learning for FELs

Accurate prediction of X-ray pulse properties from a free-electron laser using machine learning


Ghost imaging / Compressed sensing

PHYSICAL REVIEW LETTERS 121, 114801 (2018)

Electron Ghost Imaging

S. Li, F. Cropp, K. Kabra, T.J. Lane, G. Wetzstein, P. Musumeci, and D. Ratner

Bayesian/GP Optimize from Noise

Model-independent optimization

PHYSICAL REVIEW LETTERS 121, 044801 (2018)

Demonstration of Model-Independent Control of the Longitudinal Phase Space of Electron Beams in the Linac-Coherent Light Source with Femtosecond Resolution

Alexander Scheinik, A. Aurinque Edehn, Dorian Bohle, Claudia Emma, and Alberto Lutman

Target

Feedback + NN Final

ΔE (GeV)

time (fs)

ΔE (GeV)

time (fs)

Bayesian/GP Optimize from Noise

J. Duris

Step number

X-ray pulse energy (mJ)

simplex

gp

gp w/ correlations

MP, MSE=0.022

target

ground truth

0 1 2 3 4

0 10 20 30 40 50

18
With partners worldwide, many more developments…

Fast Wire Scanner

Injector Performance Improvements
cathode flange

Compact X-Band SLED

Machine Optimization Toolkit (EuXFEL-SLAC)

Compact Mid-IR Spectrometer

Controls Display Management

COTR-Mitigating Camera (PAL-PSI-SLAC)

RF BPM (PAL-SLAC)

…to name just a few
LCLS performance exceeded expectations.

Wonderful collaborations among scientists/engineers from accelerator, beamline, X-ray sides.

Flexibility of the machine/people to accommodate new ideas and modes.

Femtosecond beam control now pushes to attosecond regime.

New capabilities will be extended to LCLS-II.
Thanks DOE for the support and LCLS facility team for all the fun!