First Lasing of the LCLS X-Ray FEL at 1.5 Å

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SLAC National Accelerator Laboratory

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Planned/Proposed Hard X-ray FELs

- **Euro X-FEL** at DESY (0.1-6 nm)
- **SCSS** at Spring8 in Japan (0.1-3.6 nm)
- **PSI-FEL** in Switzerland (0.1-7 nm)
- **LCLS** at SLAC in USA (0.15-1.5 nm)

...and many soft x-ray FELs taking shape around the globe

**This talk will concentrate on LCLS, with first lasing and FEL saturation at 1.5 Å...**
Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing 3-km linac
Proposed by C. Pellegrini in 1992

1.5-15 Å
(14-4.3 GeV)

Existing 1/3 Linac (1 km)
(with modifications)

New $e^-$ Transfer Line (340 m)

X-ray Transport Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment Hall

Injector (35°) at 2-km point

UCLA
Argonne National Laboratory
LLNL
SLAC National Accelerator Laboratory
Commissioning Status of LCLS

- Laser, gun, & injector commissioned: 2007
- Linac & bunch compressors commissioned: 2008
- First beam through undulator beamline: Dec. 2008
- 21 undulator magnets installed & ready: April 7, 2009
- First lasing at 1.5 Å: April 10, 2009 (first try!)
- 1.5 Å FEL saturation observed: April 14, 2009 (after BBA)
- X-ray diagnostics hall is not ready until early June
- Temporary (makeshift) x-ray diagnostics used up to now
- User operations start in Sep. 2009
84 meters of FEL Undulator Installed

25 undulators installed...
8 more to go
Undulator Gain Length Measurement at 1.5 Å: 3.3 m

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

Recent Results!
(25 of 33 undulators installed)
Injector Transverse Projected Emittance <0.5 μm

Exceptional beam quality from S-band Cu-cath. RF gun...

Time-sliced emittance: 0.3-0.4 μm

22-Feb-2009 21:47:50 RMS cut area

γεₓ ≈ 0.43 μm

γεᵧ ≈ 0.46 μm

135 MeV
0.25 nC
35 A
Undulator ‘Taper Scan’ Shows 1.1 mJ per X-ray Pulse

Vary the FEL power and record the $e^-$ energy loss

Pixel sum of x-ray YAG screen CCD camera vs undulator K-taper

4.6 MeV at 0.25 nC = 1.1 mJ or $0.8 \times 10^{12}$ photons/pulse (15 GW at 75-fs FWHM pulse length)
Accelerator is last 1-km of SLAC linac (14 GeV)
RF photocathode gun and off-axis injector
Two bunch compressors + ‘laser heater’
Two transverse RF deflectors for time-resolved beam measurements
X-band (12 GHz) compression linearizer
4 emittance diagnostic stations + 4 spectrometers
Primary and secondary collimation sections
Fixed gap, planar, 132-m undulator at 14 GeV + 1-μm res. RF BPMs
Near and Far Experimental Halls + 500 m of x-ray transport
YAGS2 Laser Heater Working Well

RF deflector ON

energy

Laser OFF

σₑ/E < 12 keV

adds Landau damping

Laser: 40 µJ

σₑ/E ≈ 45 keV

Thanks Michael Borland!

Laser: 230 µJ

σₑ/E ≈ 120 keV
Laser Heater Improves FEL Power

- Laser heater off
- Laser heater on

FEL Gain:

Active undulator length (m)

- FEL intensity (a. u.)

IR Laser Energy (μJ)

Laser heater optimal (0.01%)

12 undulators inserted (FEL not saturated here)

preliminary
Undulator Girder with 5-DOF Motion Control + IN/OUT

- Beam Finder Wire (BFW)
- Cavity BPM (<0.5 μm)
- Quadrupole magnet
- 3.4-m undulator magnet
- Wire Position Monitor
- Hydraulic Level System
- sand-filled, thermally isolated supports
- CAM-based 5-DOF motion control
- X-translation (in/out)
Beam-Based Undulator Alignment

- Measure undulator trajectory at 4 energies (4.3, 7.0, 9.2, & 13.6 GeV)
- Scale all linac & upstream transport line magnets each time
- Do not change anything in the undulator
- Calculate… *(Matlab GUI)*
- Move quads and adjust BPM offsets for dispersion free trajectory
- Iterate…

**RESULT:** vary energy by factor of 3 \( \Rightarrow \) trajectory changes by <10 \( \mu \text{m} \)
Undulator Quadrupole Alignment after BBA

- Vary each quadrupole magnet gradient by 30% sequentially
- Record kick angle using both upstream & downstream BPMs, adjusting for incoming jitter
- Calculate quadrupole magnet transverse offsets

$<X> = -0.001 \text{ mm}, \ X_{\text{rms}} = 0.046 \text{ mm}, \ 17-\text{APR}-2009 \ 06:14:32$

Earth’s field effect (0.4 G)

$8 \ \mu\text{m rms}$

undulators installed (with $\mu$-metal)
<1 \mu m Undulator Quadrupole Remote Position Control

3-parameter fit to 20 BPMs along undulator ($y_0$, $y'_0$, and $\Delta y'$)

$\Delta y' = 30 \text{ nrad kick due to quad}$

$0.7 \mu m$ backlash

Thanks ANL!

<0.5 \mu m res.

S. Smith
TU3GRC05
Beam Finder Wire – Aligns ‘Loose’ End of Undulator

Also used to measure emittance in undulator

$\sigma_x \approx 40.4 \, \mu m$
Bunch Compression & CSR Measured after BC2 (0.25 nC)

$\sigma_z \approx 2 \mu m$

$\sigma_z < 5 \mu m$

$\sigma_z > 25 \mu m$

BC2 $R_{56}$ (mm)

L2

BC2 (4.3 GeV)

TCAV (5.0 GeV)

BSY (14 GeV)

550 m

4 wires

in PRSTAB
Measuring Bunch Arrival Time Jitter with an RF Deflector

$e^-$

S-band (2856 MHz)

$V(t)$

$\Delta t \approx \pm 0.6 \text{ ps}$

slope $= -2.34 \text{ mm/deg}$

$TCAV ON$

$TCAV OFF$

Timing Jitter $= (110 \ \mu\text{m})/(2.34 \text{ mm/deg}) = 0.047 \text{ deg} \Rightarrow 46 \text{ fsec rms}$

9 $\mu\text{m rms}$

110 $\mu\text{m rms}$
Feedback Systems - Bunch Length & Energy (6×6)

Laser

Read 4 BPMs & 2 bunch length monitors...

Control 4 RF voltages & 2 phases

BPMs

CER detectors

Steering Loop

J. Frisch
D. Fairley, J. Wu

DL1 energy

BC1 energy

BC2 energy

DL2 energy

BC2 peak current

BC1 peak current

250 ± 10 A

3000 ± 350 A

H. Loos, TU3GRI01

J. Wu, WE5RFP046

J. Frisch

Charge feedback: \( Q = 0.25 \) nC

\( \langle \Delta Q^2 \rangle^{1/2}/Q = 1.5\% \)

\( 250 \pm 10 \) A

BC1 peak current

\( 3000 \pm 350 \) A

BC2 peak current
Measurements and Simulations for 20-pC Bunch at 14 GeV

**MEASURED SLICE EMITTANCE**

\[ \gamma \varepsilon_x = 0.14 \, \mu m \]

**SIMULATED FEL PULSES**

1.5 Å,

3.6 x 10^{11} photons,

\[ I_{pk} = 4.8 \, kA \]

\[ \gamma \varepsilon \approx 0.4 \, \mu m \]

**Simulation** at 1.5 Å based on measured injector & linac beam & *Elegant* tracking, with CSR, at 20 pC.

15 Å,

2.4 x 10^{11} photons,

\[ I_{pk} = 2.6 \, kA \]

\[ \gamma \varepsilon \approx 0.4 \, \mu m \]

**Simulation** at 15 Å based on measured injector & linac beam & *Elegant* tracking, with CSR & 20 pC.

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Longitudinal slice emittance measurement for 20 pC at 135 MeV. Time-slicing at 20 pC tested by J. Frisch.

Y. Ding, Z. Huang
Commissioning Time-Line

- Commissioning
- Project Milestones
- Installation Periods

Injector Install
First e⁻ from gun
BC2 Install
PEP-II ends
LTU/Und Sys Install
First e⁻ to dump FEE/NEH Install
Install Undulators
First Light in FEE X-Rays in NEH First Users
PAC'09
First Light in FEE

Injector
Linac/BC2 Linac LTU/Und Sys FEL/NEH NEH FEH

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- And many of you, who have contributed your ideas, comments, codes, and many years of experience toward the design and operation of this revolutionary new light source – 17 yrs later