Science with the LCLS

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Palo Alto 1878-1879

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1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…


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Ultrafast Sources and Science

X-ray sources:

Current lasers:

Science:

X-ray sources:
- Strings, Cosmology
- Particle Collisions
- Electron dynamics

Current lasers:
- Ultrafast lasers

Science:
- Acoustic phonons
- Vibrations (Optical phonons)
- Chemistry and Biochem
- Particle Collisions
- Electron dynamics

Pulse duration (seconds):
- harpo $10^{-27}$
- yocto $10^{-24}$
- zepto $10^{-21}$
- atto $10^{-18}$
- femto $10^{-15}$
- pico $10^{-12}$
- nano $10^{-9}$
- micro $10^{-6}$
- milli $10^{-3}$
$\sigma_z = 0.022 \text{ mm}, \ R = 12.00 \text{ m}$

$N \approx 6 \times 10^9$

$\sim \lambda^{-1/3}$

$\sigma_z$

$Wavelength$

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SASE FELs

- Undulator radiation starts up from noise to interact with the e-beam

- Energy modulation $\rightarrow$ density modulation at $\lambda$ (microbunching) $\rightarrow$ coherent radiation at $\lambda$ $\rightarrow$ exponential growth ($L_G$)

- At sufficiently high power, electrons fully microbunched with large energy spread $\rightarrow$ reach saturation ($P_{sat}$)
GENESIS - simulation for TTF parameters
Courtesy - Sven Reiche (UCLA)
X-FEL based on last 1-km of existing SLAC linac
Peak Brilliance of FEL’s

photon per phase-space volume per bandwidth

\[ \text{X-Ray} \]

\[ 10^6 \text{ by FEL gain} \]

\[ \sim 10^9 \]

\[ 10^3 \text{ by } e^- \text{ quality, long undulators} \]

courtesy T. Shintake
• $E(t) = \sum_j E_0(t-t_j)$, $t_j$ is the random arrival time of $j^{th}$ e-

$E_0$: wave packet of a single e-

• $l_c \sim 100-1000 \lambda < \text{bunch length}$

• Sum of all packets $\Rightarrow E(t)$
Atomic, molecular and optical science

Nano-particle and single molecule (non-periodic) imaging

Diffraction studies of stimulated dynamics (pump-probe)

High energy density science

Coherent-scattering studies of nanoscale fluctuations

Program developed by international team of scientists working with accelerator and laser physics communities

“the beginning.... not the end”

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Focused beam (100nm):

**Formation of Hollow Atoms:**

- Ne Photoionization

![Diagram](image)

\[ hv = 900 \text{eV} \]

\[ \tau_{\text{Auger}} = 2.5 \text{fs} \]

All atoms have multiple core holes per pulse (10^5 atoms)
Structural Studies on Single Particles and Biomolecules

Conventional method: x-ray diffraction from crystal

Proposed method: diffuse x-ray scattering from single protein molecule

Implementation limited by radiation damage:
In *crystals* limit to damage tolerance is about 200 x-ray photons/Å²
For *single protein molecules* need about $10^{10}$ x-ray photons/Å² (for 2Å resolution)

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Predicted scattering from a single RUBISCO molecule ($R_{\text{electronic}} = 15\%$)
Ultrafast Coherent Single Shot X-ray Diffraction
– The First Demonstration at the VUV-FEL at DESY

Pulse #1: Diffraction reveals structure before radiation damage occurs

Pulse #2: Structure was completely destroyed by pulse #1

Incident VUV-FEL pulse:
30 fs, 32 nm, $3 \times 10^{13}$ W cm$^{-2}$

1x3 µ SiN membrane with 200 nm pattern

multilayer mirror

To beam dump

CCD
VUV-FEL Pump-probe Experiments Measure the FEL-induced explosion with 30 fs Time Resolution

The pattern is the interference of the waves scattered from the unexploded particle (reference wave) and the same particle during explosion. Many particles generate speckle also.
Scattering experiments

Ultrafast X-Ray Diffraction

Movie of Atomic Movement

X-Ray Pulse

Light Pulse
EOS and “Pump-Probe”

Typical time resolved experiment utilizes intrinsic synchronization between pump excitation and probe

Electro-Optic Sampling (EOS) delivers arrival time to users

- Pump-Probe experiments now possible at XFELs
- Machine jitter exploited to sample time-dependent phenomena
(Typical) Single-Shot EOS Data at SPPS (100µm ZnTe)

\[ \Delta \tau \sim 200 \text{fs} \]
Dynamics of high amplitude coherent optical phonons

Bi structure
X-rays diffraction – direct probe of atomic motion

111 forbidden in simple cubic

222 “perfect” in simple cubic

Using the jitter @ SPPS for Random Sampling

D. M. Fritz et al. unpublished

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Using the jitter @ SPPS for Random Sampling

1.74 mJ/cm² (absorbed), \(<n>\sim 1\%\) \(\langle x\rangle = 5\text{pm}\)

\(f = 2.5\ \text{THz}^*\) \(\ A = 0.92\ \text{pm}\)

Arrival time distribution

Sorted normalized data

D. M. Fritz et al. unpublished

*precise time calibration still in progress

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Measured (Mean) Equilibrium Position

D. M. Fritz et al. unpublished
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Exciting science with the baseline LCLS

Atomic physics in a new regime

Potential to collect and invert diffraction patterns from ‘single molecules’ providing atomic resolution

Study directly the atomic scale motions on the time scales of interest to chemistry and materials science

And MUCH more
Looking to the future:

Can we get attosecond pulses ??
Select a single spike ~ 300 attoseconds

Saturation

Exponential Gain Regime

Undulator Regime

1 % of X-Ray Pulse

Electron Bunch Micro-Bunching

2.5 fs
Transverse Emittance is Critical for X-ray FEL

\[ \varepsilon_N < \gamma \frac{\lambda_r}{4\pi} \]

\(< 1 \ \mu m \ at \ 1 \ \AA, \ 15 \ GeV\)

\[ \varepsilon_N = 1.2 \ \mu m \Rightarrow P = P_0 \]

\[ \varepsilon_N = 2.0 \ \mu m \Rightarrow P = P_0/100 \]

Can we spoil most of the \(e^-\) bunch and leave 1-fs to lase?
single bunch, 1-nC, 120-Hz

SLAC linac tunnel

7 MeV
$\sigma_z \approx 0.83 \text{ mm}$
$\sigma_\delta \approx 0.2 \%$

150 MeV
$\sigma_z \approx 0.83 \text{ mm}$
$\sigma_\delta \approx 0.10 \%$

250 MeV
$\sigma_z \approx 0.19 \text{ mm}$
$\sigma_\delta \approx 1.8 \%$

4.54 GeV
$\sigma_z \approx 0.022 \text{ mm}$
$\sigma_\delta \approx 0.76 \%$

14.35 GeV
$\sigma_z \approx 0.022 \text{ mm}$
$\sigma_\delta \approx 0.02 \%$

...existing linac

...existing linac

Linac-0
$L = 6 \text{ m}$

Linac-1
$L = 9 \text{ m}$
$\varphi_{rf} = -38^\circ$

Linac-X
$L = 0.6 \text{ m}$
$\varphi_{rf} = 180^\circ$

Linac-2
$L = 330 \text{ m}$
$\varphi_{rf} = -43^\circ$

Linac-3
$L = 550 \text{ m}$
$\varphi_{rf} = -10^\circ$

undulator
$L = 120 \text{ m}$

DL-1
$L = 12 \text{ m}$
$R_{56} \approx 0$

BC-1
$L = 6 \text{ m}$
$R_{56} = -36 \text{ mm}$

BC-2
$L = 22 \text{ m}$
$R_{56} = -22 \text{ mm}$

DL-2
$L = 66 \text{ m}$
$R_{56} = 0$
Magnetic Bunch Compression

\[ V = V_0 \sin(\omega \tau) \]

\[ \Delta z = R_{56} \Delta E/E \]

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

0.1 mm (300 fs) rms

\( x, \) horizontal pos. (mm)

\( z, \) longitudinal position (mm)

2.6 mm rms

50 \( \mu \)m

...or over-compression

under-compression

\[ \Delta E/E \]
Add thin slotted foil in center of chicane

\[ x \propto \frac{DE}{E} \propto t \]

15-mm thick Be foil

*PRL 92, 074801 (2004).*

P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)
The graph shows the power and current as functions of time (t) in femtoseconds (fs). The x-ray power is indicated by a peak at approximately 2 fsec fwhm, and the current shows two peaks, with one at z ≈ 60 m.
Summary

The fun begins in 2008 -2009 and the unexpected is the most exciting!