Attosecond X-ray Science Opportunities at X-ray Free Electron Lasers

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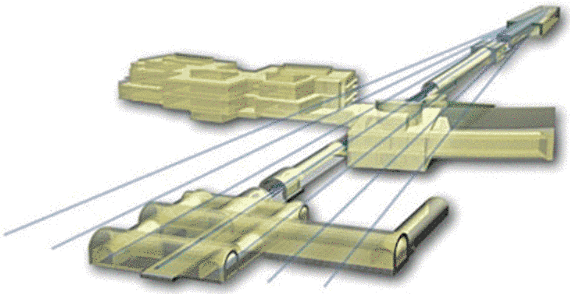

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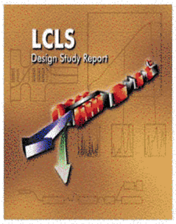
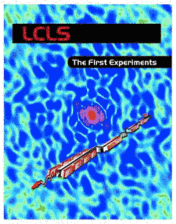
On-Line References



LCLS Conceptual Design Report SLAC-R-593, UC-414
http://www-ssrl.slac.stanford.edu/lcls/cdr/
Chapter 4 is a good FEL tutorial



LCLS: The First Experiments
http://www-ssrl.slac.stanford.edu/lcls/papers/lcls_experiments_2.pdf

Other talks at this workshop:

Friday, 11:50 AM: Zholents

Also acknowledge: Neil Thompson, Daresbury

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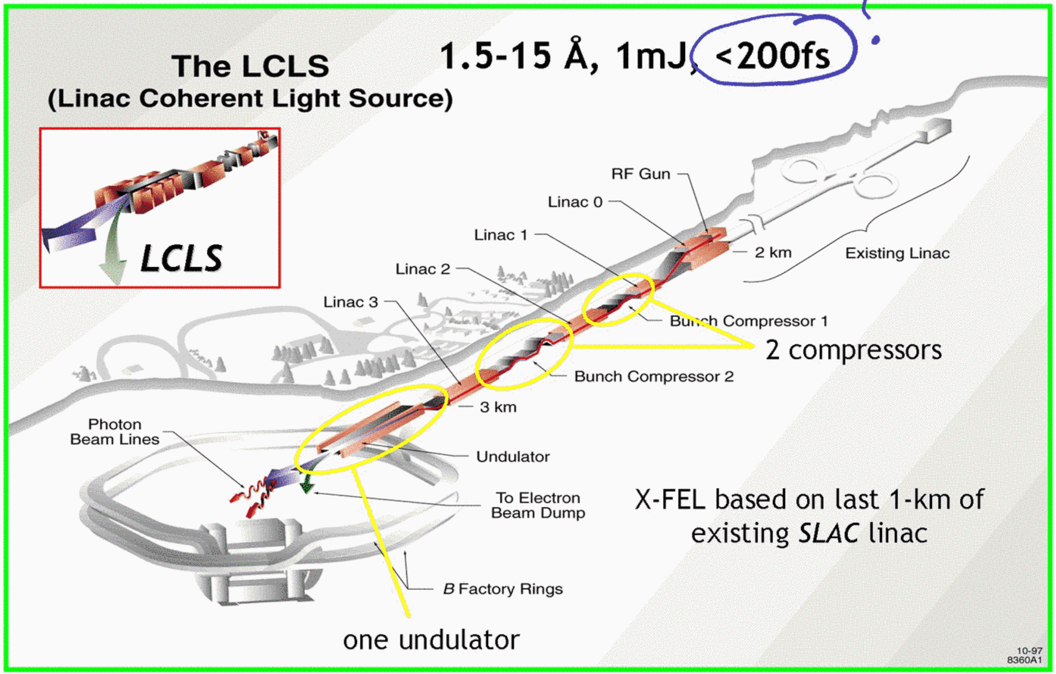
LCLS at *SLAC*

The LCLS
(Linac Coherent Light Source)

1.5-15 Å, 1mJ, <200fs ?



2 compressors

X-FEL based on last 1-km of existing *SLAC* linac

one undulator

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XFEL’s and Sub-Femtosecond Light Pulses

- What’s an XFEL?
- Gain process leads to sub-femtosecond pulses (cooperation length)
- Methods for coherent pulse width reduction (much more by Zholents later)
- Experimental challenges
- Research opportunities

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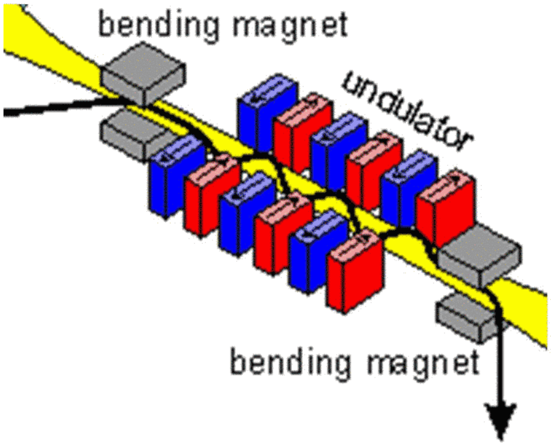
What’s an FEL?

A **relativistic electron beam** and a **electromagnetic wave**
(the “laser light”) co-propagating through
An **oscillating magnetic** field



Relevant parameters:

- Electron energy= γmc^2
- Wavelength = λ_r
- Undulator period =λ_u
- rms Magnetic field = B_{rms}

http://www.fz-rossendorf.de/FWK/MITARB/fwkf/figs/fel_schema_en.gif

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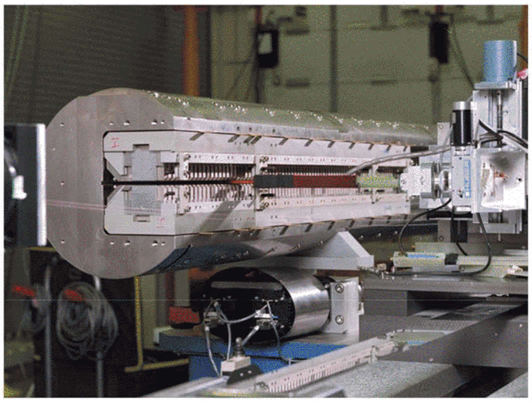
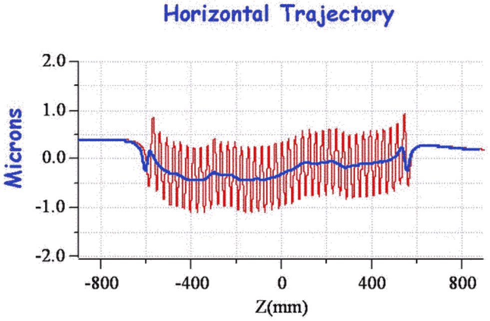
Hardware (LCLS undulator)





Advanced Photon Source

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Electrons and light in resonance

- The relativistic electrons and the light are traveling together, but the electrons don't go as fast, or in a straight line
- Resonance occurs when the electrons slip one optical wavelength λ_r after each undulator period λ_u:

Slippage from non-collinearity

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)$$

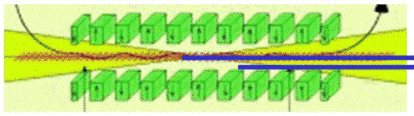
Slippage because v<c

Slippage from wiggling

The parameter K is the angle of maximum deviation of the electron wiggle times γ. K is also the vector potential normalized to mc:

$$\sqrt{2}a = K = eB_{rms}\lambda_u / 2\pi mc$$

$$= 0.934B(T)\lambda(cm)$$



www.sanken.osaka-u.ac.jp/ English/jpeg/61_1.jpg

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FEL light comes from synchrotron radiation

- The undulator resonance condition is the same as the FEL resonance
- Undulator bandwidth $\Delta\omega/\omega = 1/N_u$
- Photons are diffraction-limited: divergence x source size ~ $\lambda_r/4\pi$

- So, what's different in an FEL?

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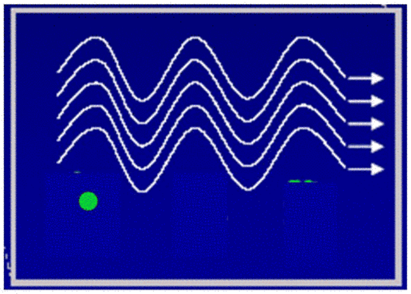
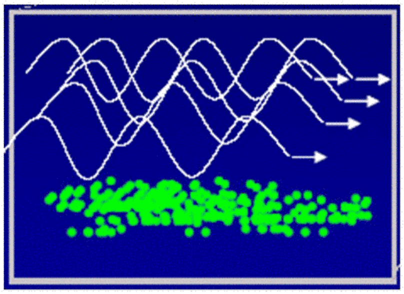
A question of coherence

Undulator conditions:



Photons produced on different undulator bends, but from the same electron, are *in phase*. (longitudinal or temporal coherence)



Photons from different electrons are out of phase

Undulators are weak radiators: photons per electron ~ 0.01

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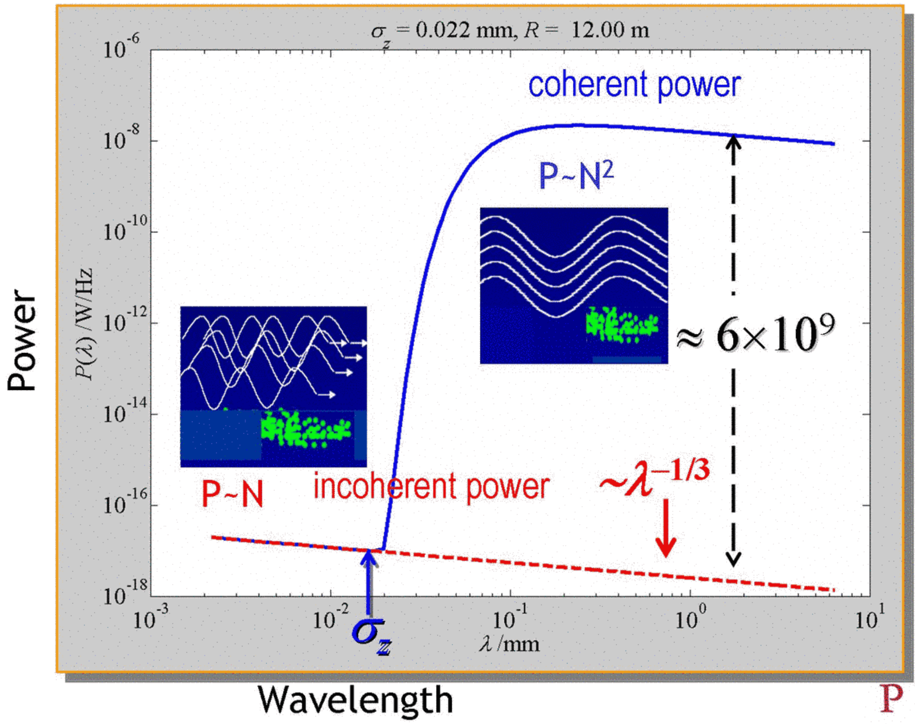
Temporal coherence



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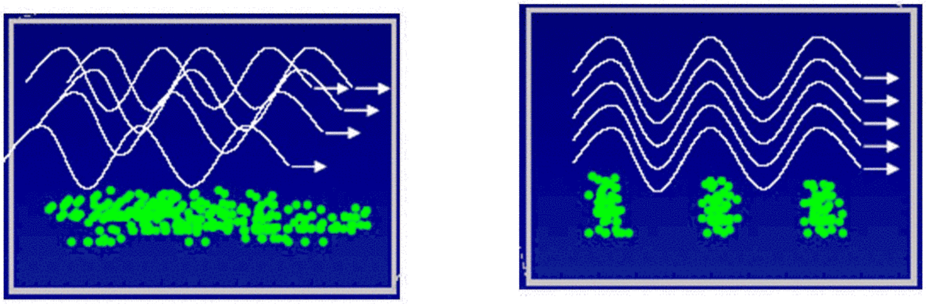
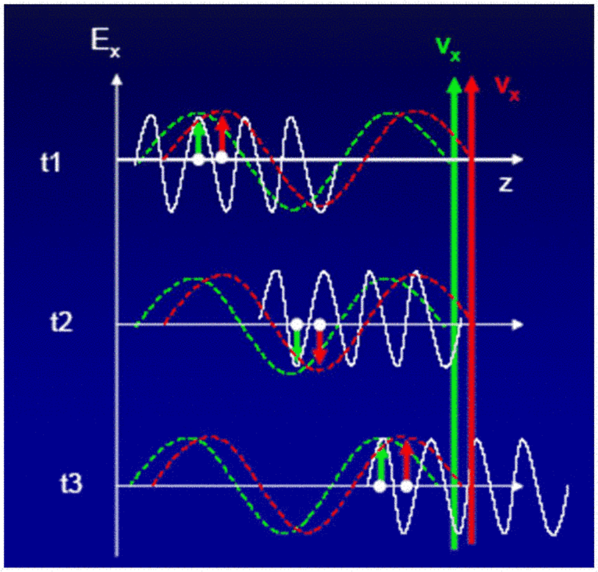
Bunching turns an undulator into an FEL



But how?

The light acts back on the electrons

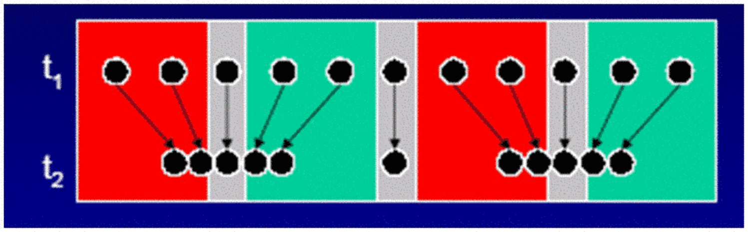


Some electrons accelerate on every cycle

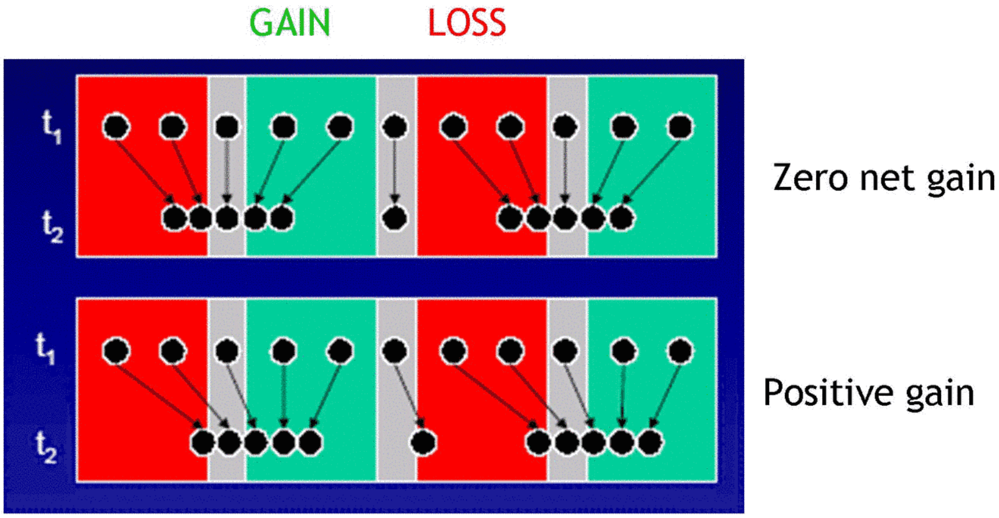
Some decelerate on every cycle

Back-action leads to bunching

Accelerated or Decelerated Electrons

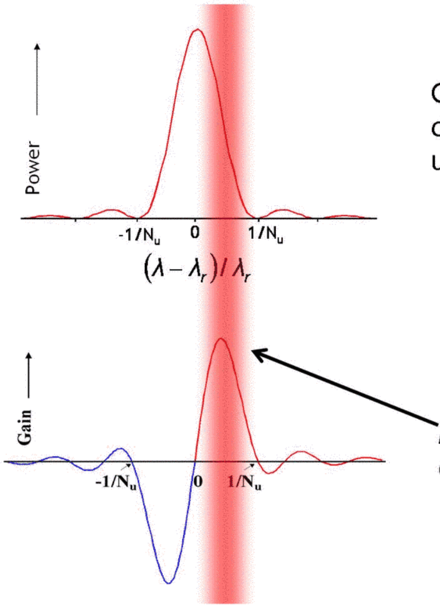


GAIN: The DECELERATED electrons give energy back to the field. That’s GAIN.



NET gain requires some detuning above resonance

Gain, tuning, and Madey’s Theorem



Gain is a tradeoff between positive detuning and spontaneous undulator power.

Madey Theorem: Gain is proportional to the negative derivative of spontaneous radiation.

Maximum gain at δ=2.6
δ=2πN(Δλ/λ)

The FEL gain:

More rigorous calculation: [see R. Bonifacio, C. Pellegrini, and L. Narducci, *Opt. Commun.*, **50**, 373 (1984)].

Intensity grows exponentially: $I \sim \exp(z/L_G)$

Where L_G is the gain length: $L_G = \dfrac{\lambda_u}{2\pi\rho}$

ρ is the FEL parameter
the gain per radian in the undulator: $\rho = \left(\dfrac{a_u}{4\gamma}\sqrt{F(a_u)}\,\dfrac{\Omega_p}{\omega_u}\right)^{2/3}$

$\omega_u = 2\pi c/\lambda_u$ is the undulator frequency,

$\Omega_p = (4\pi c^2 r_e n_e/\gamma)^{1/2}$ is the beam plasma frequency, and

n_e is the electron density.

$F_1(a_u)$ is the fraction of undulator power in the first harmonic, and is O(1).

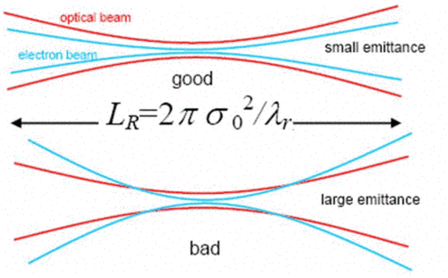
$a_u = K/2^{1/2}$

Best conditions for FEL

- Beam emittance on the order of or smaller than the undulator radiation emittance

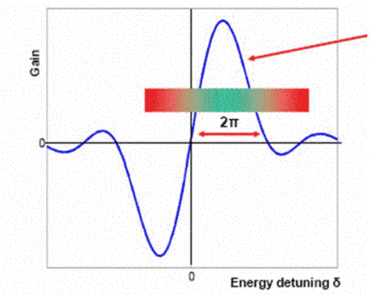
$$\varepsilon \le \frac{\lambda}{4\pi}$$

- Gain length shorter than the Rayleigh range L_R



- Beam relative energy spread smaller than the FEL parameter

$$\sigma_E / E < \rho$$



Small detuning range for positive gain.

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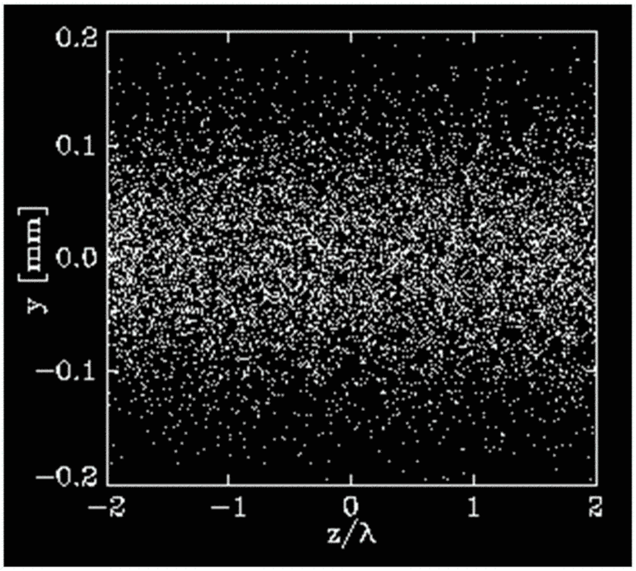
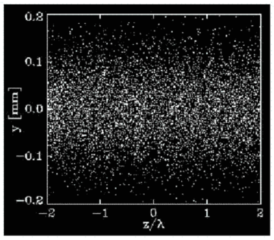
Microbunching through SASE Process

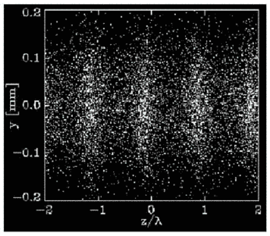


GENESIS - simulation for TTF parameters
Courtesy - Sven Reiche (UCLA)

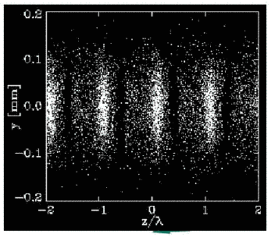
undulator entrance



half-way saturation



full saturation



What stops the FEL from going on forever?

Cooperation length: Slippage in one gain length

$$L_c = \frac{\lambda_r}{\lambda_u} L_G = \frac{\lambda_r}{4\pi\rho}$$

The radiation builds up with coherent spikes of length $2\pi L_c$, a less than a femtosecond at LCLS.

The radiation saturates when the bunch parameter B approaches unity:

$$L_{sat} \approx 10 L_G$$

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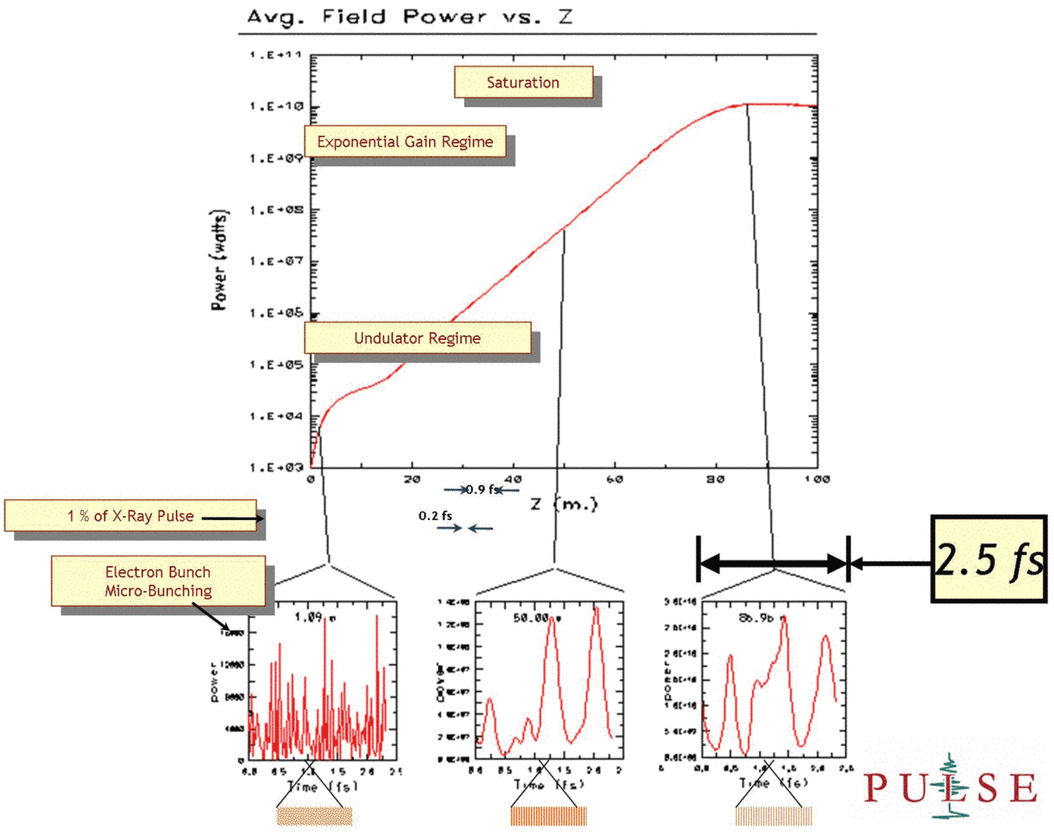

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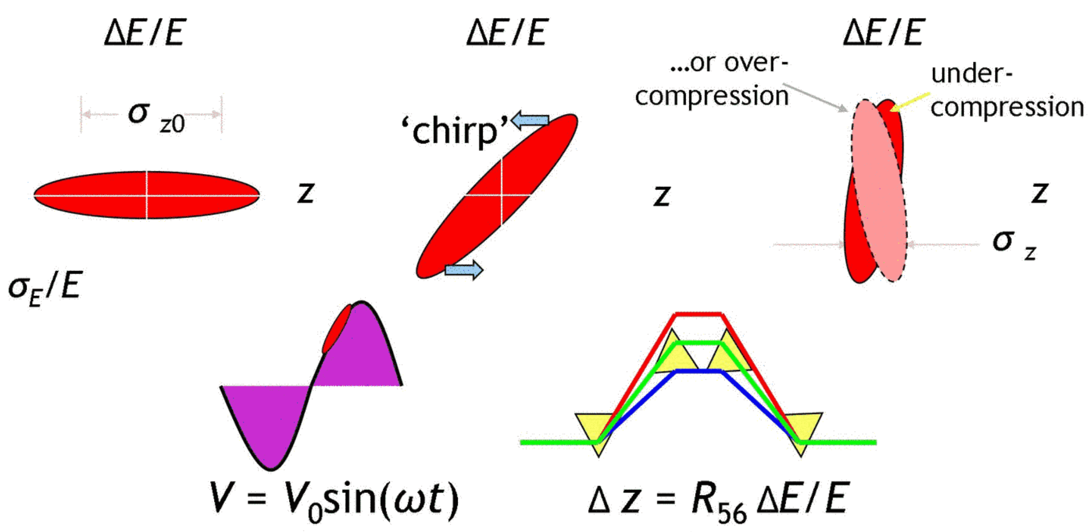
FEL parameters

LCLS FEL parameters	**Value**	**Unit**
Radiation wavelength	1.5	Å
FELparameter,ρ	5×10-4	
Power gain length	4.8	m
EffectiveFELparameter,ρ*eff*	2.93×10-4	
Pulses repetition rate	120	Hz
Peak coherent power	8	GW
Peak brightness	0.8×1033	*
Average brightness	4×1022	*
Cooperation length	25	nm
Intrinsic RMS intensity fluctuation	6	%
Number of spikes	270	
RMS line-width	12×10-4	
Total synchrotron radiation energy loss	1.8×10-3	
RMS Energy spread due to synchrotron radiation emission	2×10-4	

- * photon/(s mm2 mrad2 0.1% BW)

Some control strategies: Electron bunch compression

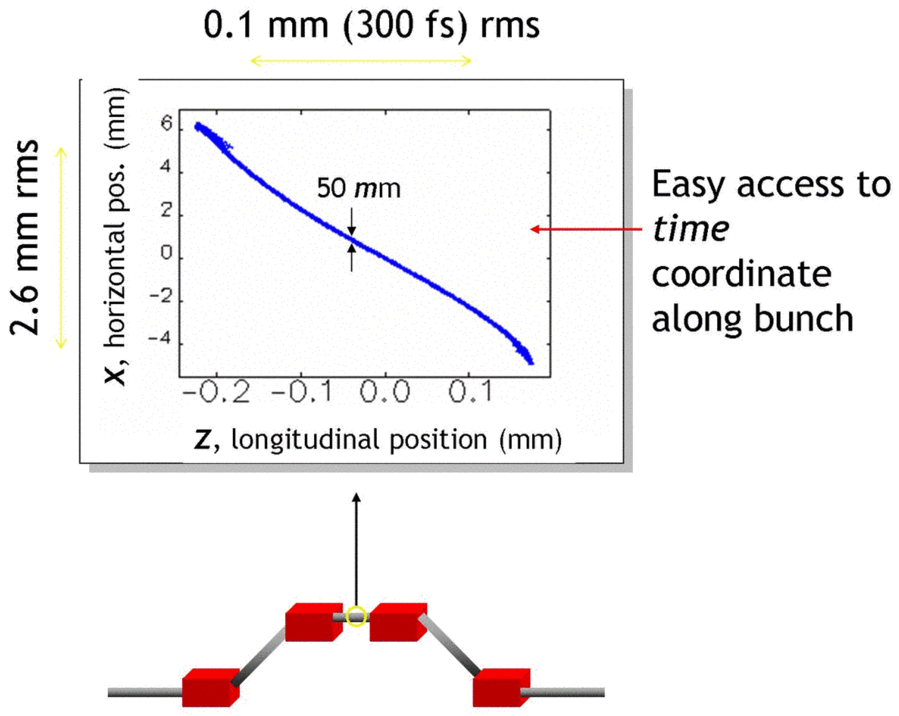


$V = V_0 \sin(\omega t)$

$\Delta z = R_{56} \Delta E/E$

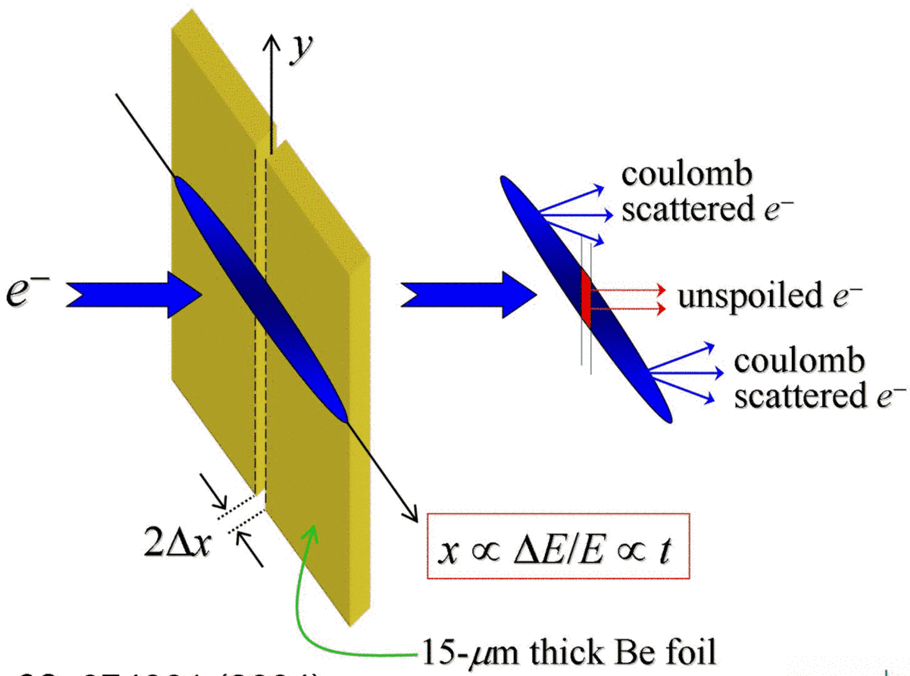
RF Accelerating Voltage

Path Length-Energy Dependent Beamline

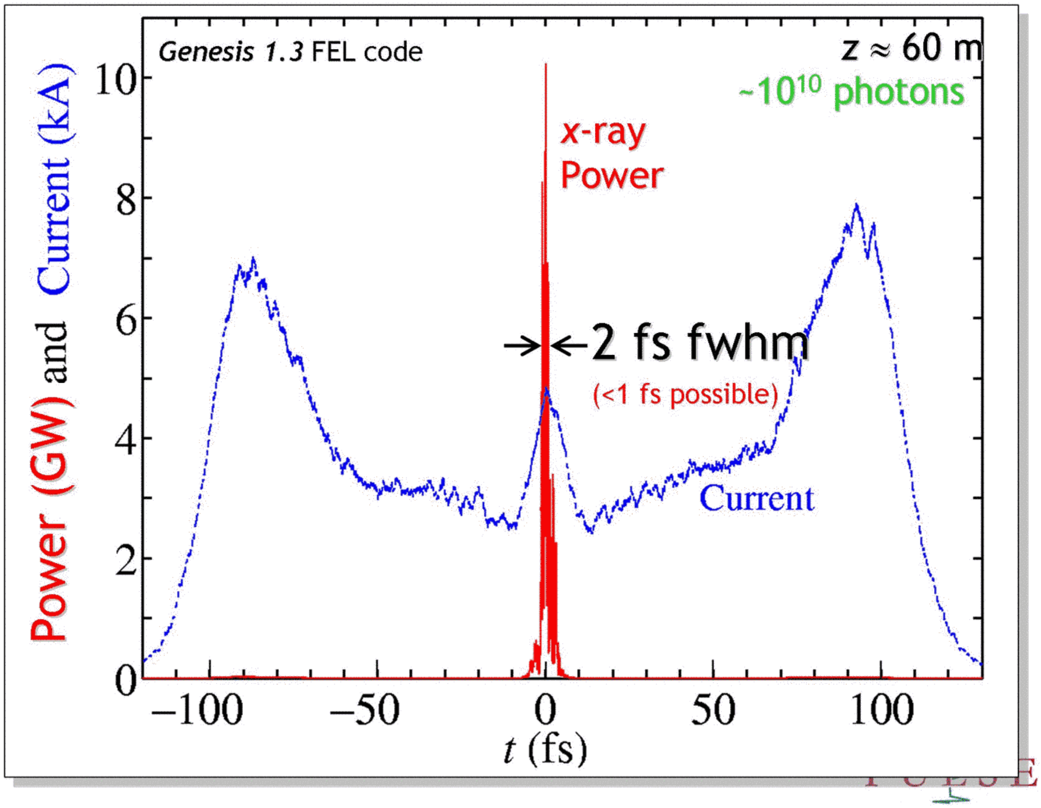


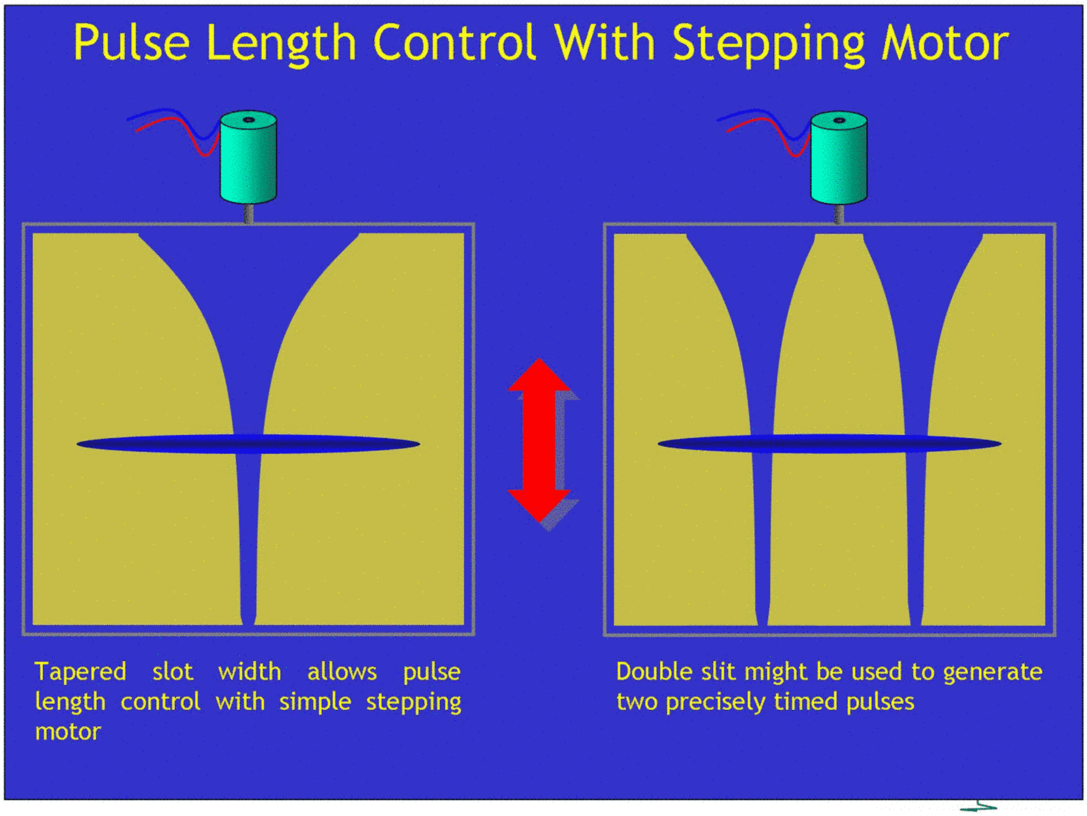
LCLS BC2 bunch compressor chicane
(similar in other machines)

Add thin slotted foil in center of chicane



PRL **92**, 074801 (2004).
P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)



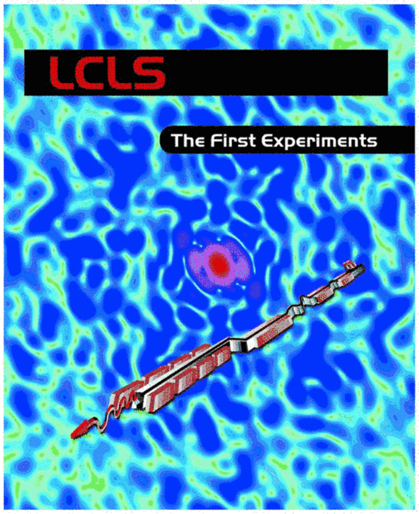


Pulse Length Control With Stepping Motor

Tapered slot width allows pulse length control with simple stepping motor

Double slit might be used to generate two precisely timed pulses

Experiments at LCLS



The LCLS Science Thrust Areas

Coherent scattering at the nanoscale (XPCS)

Atomic, Molecular, and Optical Science

Pump/probe diffraction dynamics

Pump/probe high-energy-density (HED) science

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

http://www-ssrl.slac.stanford.edu/lcls/papers/lcls_experiments_2.pdf

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Unique aspects

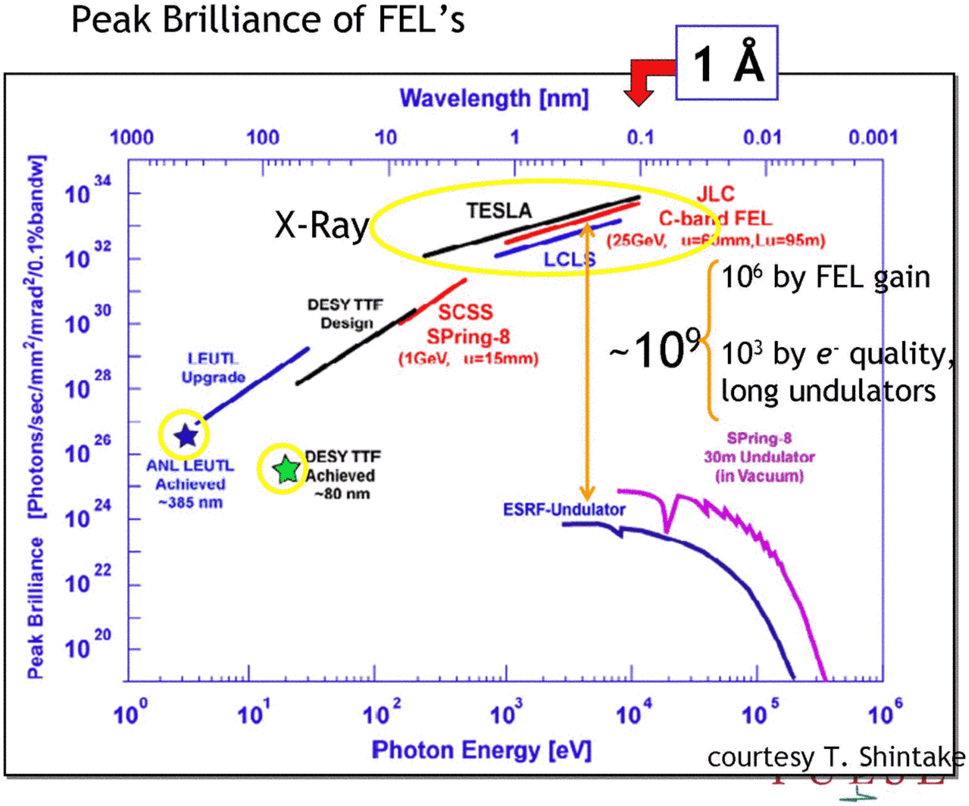
- High peak power
- High coherence compared to synchrotron x-rays
- Short pulse duration – spikes below 1 fsec

Challenges for Attoscience

- Handling high intensity x-rays
- Synchronization to laser sources
- Large fluctuations in time structure

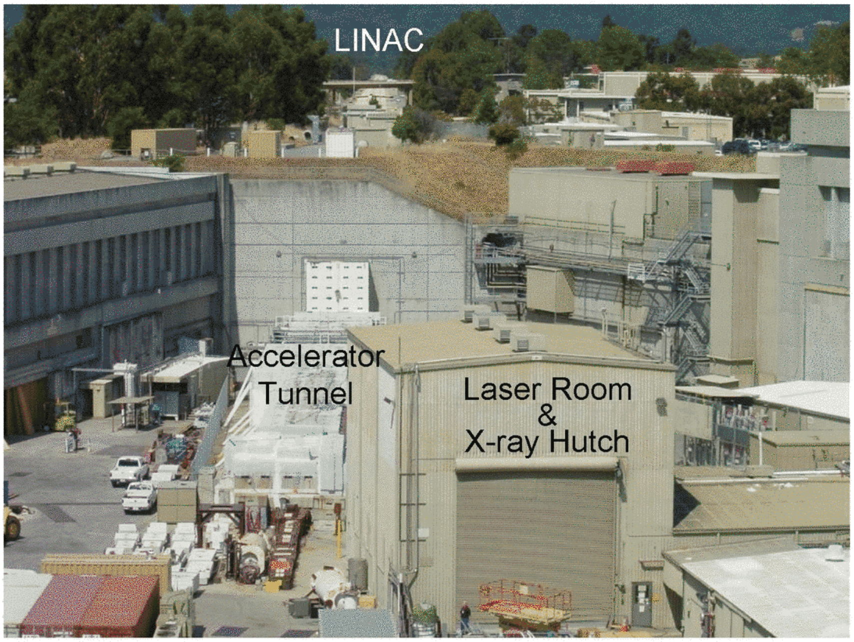
Peak Brilliance of FEL's

photons
per
phase-
space
volume
per band-
width



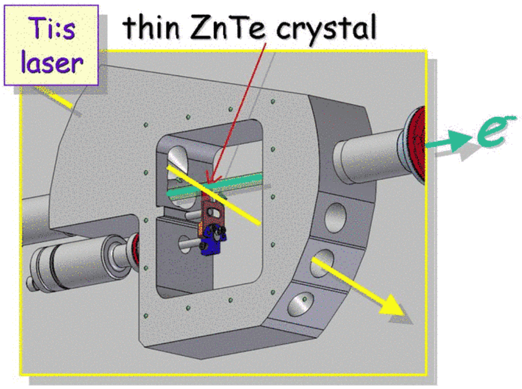
courtesy T. Shintake

SPPS Facility



1 fs synchronization is equivalent to controlling the arrival of the electron bunch to 1 part in 10 billion of its total travel.

Electro-optic measurement of the compressed pulse



e^- temporal information is encoded on transverse profile of laser beam

Adrian Cavalieri, et al.

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The Movie:

Things to look for: Transition radiation; Cerenkov radiation; *JITTER!*

Sub-Picosecond Pulse Source

Adrian Cavalieri, et al.

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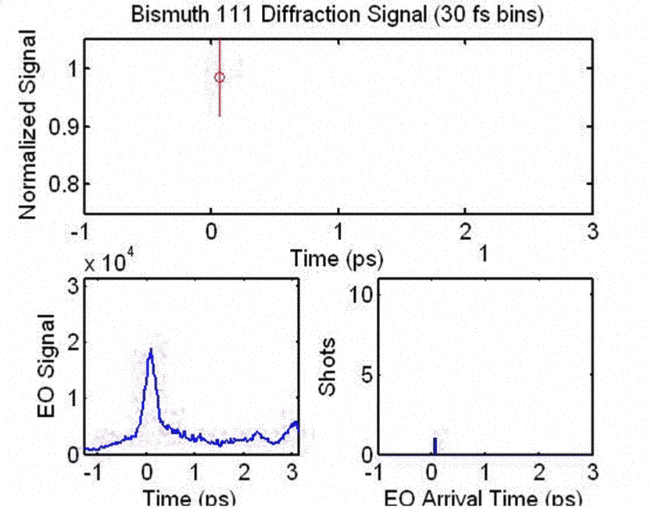
Data sampling method works for spontaneous undulator radiation



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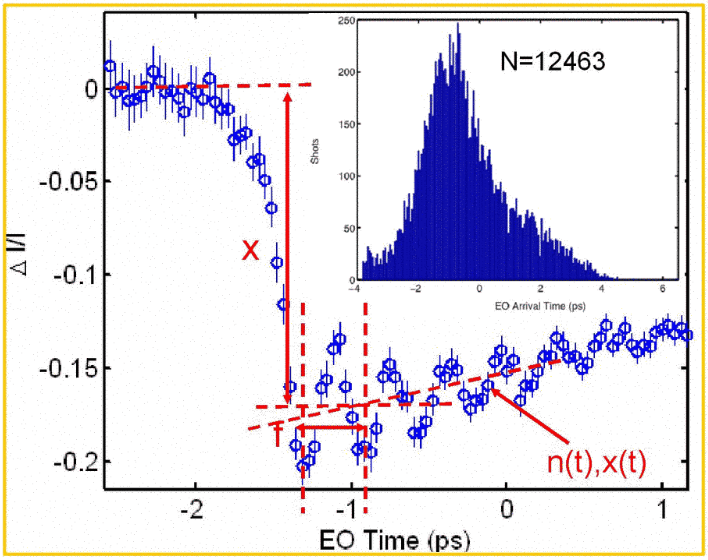
Laser pump x-ray probe



XFEL x-rays don’t follow the shape of the electron bunch, so this technique won’t work for attoseconds

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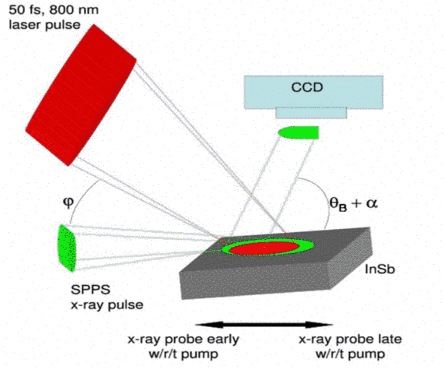
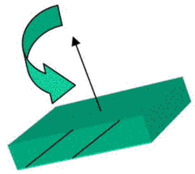
Single-shot determinations of timing:

Ultrafast Melting in InSb using undulator x-rays

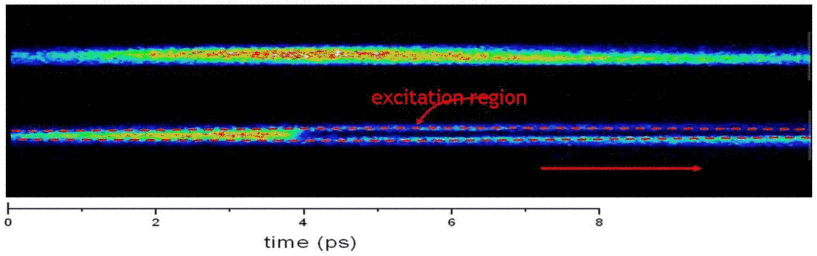
(A. Lindenberg ***et al.***, Science 308, 2005 K. Gaffney ***et al.***, PRL 95, 2005.)



- Azimuthal rotation changes crystal angle without changing the x-ray absorption depth (fixed to equal the laser penetration)



$$fs/pixel = \frac{\delta(\cos\theta_I - \cos(\theta_I + \phi))}{c\sin(\theta_B + \alpha)}$$



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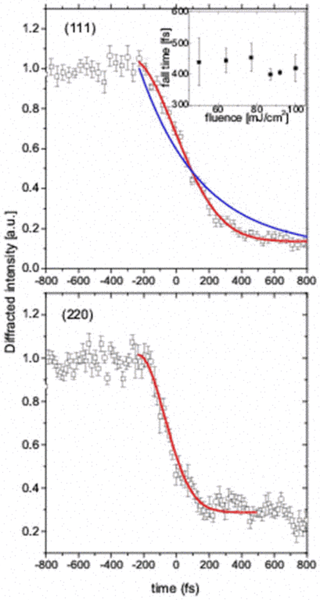
(111) vs. (220) Reflection

The different reflections decay at different rates.
The decay is approximately *Gaussian*



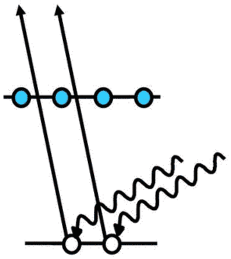
- X-ray probe depth is the same for the two reflections (~50 nm)
Measurements conducted under identical laser excitation conditions.

$$\frac{\tau_{(111)}}{\tau_{(220)}} = 1.6 \pm 0.2 = \frac{G_{(220)}}{G_{(111)}}$$

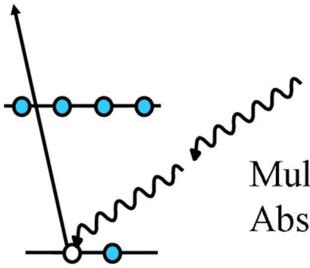
$$\sqrt{2^2 + 2^2 + 0^2} / \sqrt{1^2 + 1^2 + 1^2} = \sqrt{\frac{8}{3}}$$

1fsec resolution
means a few microns
spatial resolution

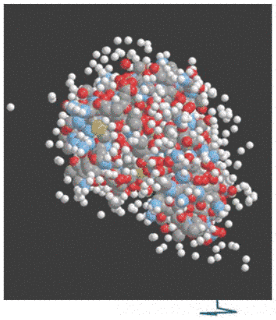
Opportunities to investigate strong field sub-femtosecond science at LCLS



Multiple ionization beats relaxation:
Hollow atoms

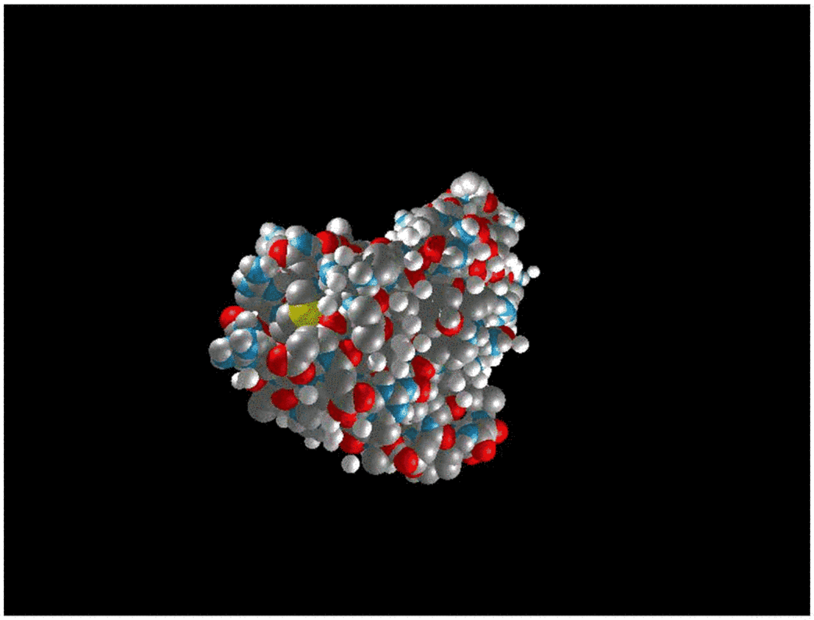


Multiphoton ionization:
Absorption below the edge



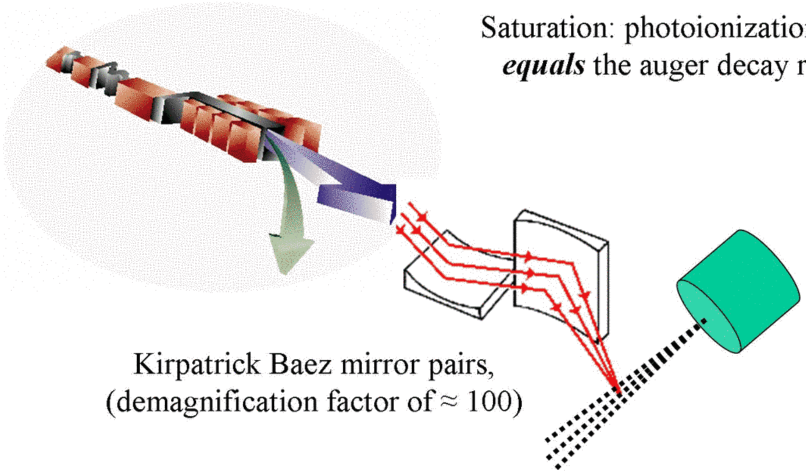
Giant Coulomb explosions
of clusters

High power simulation of exploding T4 Lysozyme: A lot happens in the first few femtoseconds



1×10^{11}W/cm^2 irradiation for 200 fs by LCLS pulse in 1mm spot (unfocused)

Focused beam experiments will be among the first at LCLS



Saturation: photoionization rate ***equals*** the auger decay rate.

Kirpatrick Baez mirror pairs,
(demagnification factor of ≈ 100)

2-Photon Rate (unfocused)

$\sigma_{2\gamma} \sim \sigma_{\gamma}^{2}/\Delta E \sim (10^{-18})^2(10^{-17}) = 10^{-53}\text{cm}^4\text{s}$, and

$\Gamma_{2\gamma} = \sigma_{2\gamma} I^2 = (10^{-53}\text{cm}^4\text{s})(10^{31}\gamma/\text{cm}^2\text{s})^2 = 10^8\text{s}^{-1}$

$2\text{x}10^{-5}$ two-photon absorptions per atom

$2\text{x}10^{6}$ events per pulse

Event rate could be a good beam intensity diagnostic

Explosion scenario

- Xe clusters (10^9 atoms)
- Each atom exposed to the unfocused beam will undergo approximately (10^{31}x10^{-19}x10^{-13}) ~1 ionization event -- the ionization will saturate.
- the dominant relaxation mechanism is Auger decay, so each ionized atom creates 2 or more electrons.
- The cluster becomes a ball of charge with ~ 10^9 ions in at least the first ionization stage.

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Focused explosions

- If we focus the LCLS beam to 0.01μm, then each atom in the cluster will be-classically-ionized nearly 10,000 times over.
- The atom will continue to ionize, since the Auger rates (~0.1Fsec) are nearly 1000 times faster than the ionization rate
- Thus each atom will ionize until it strips down to the core level of the initial ionization event).

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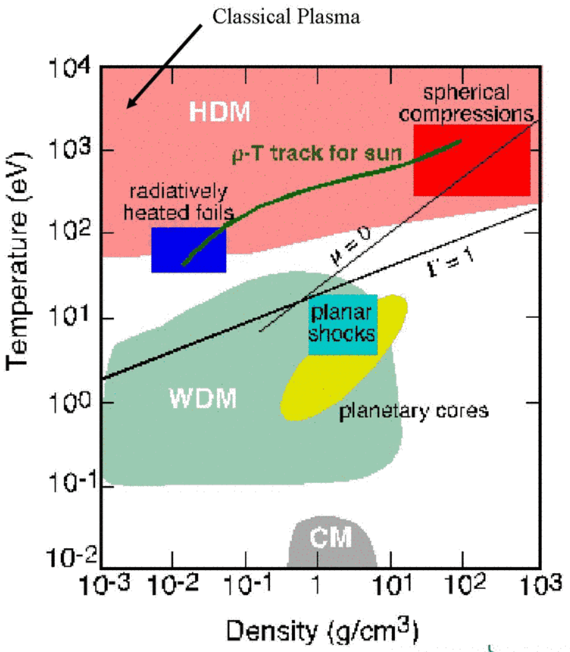
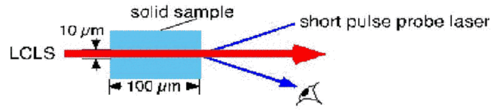
Warm Dense Matter Studies

- **Hot Dense Matter (HDM) occurs in:**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly driven inertial fusion plasma
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion implosion

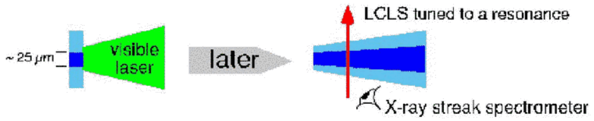


Highlight of Three HED Experiments with LCLS

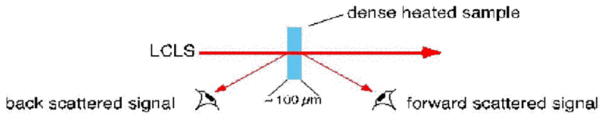
- **Creating WDM**
  - **Generate ≤10 eV solid density matter**
  - **Measure the fundamental nature of the matter via equation of state**



- **Probing resonances in HDM**
  - **Measure kinetics process, redistribution rates, kinetic models**



- **Probing WDM and HDM**
  - **Perform, *e.g.*, scattering from solid density matter**
  - **Measure n_e, T_e, <Z>, *f*(v), and damping rates**



On-Line References

LCLS Conceptual Design Report SLAC-R-593, UC-414
http://www-ssrl.slac.stanford.edu/lcls/cdr/
Chapter 4 is a good FEL tutorial

LCLS: The First Experiments
http://www-ssrl.slac.stanford.edu/lcls/papers/lcls_experiments_2.pdf

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LCLS Electron Beam and Undulator

LCLS Electron Beam Parameters @1.5 Å	**Value**	**Unit**
Electron energy	14.35	GeV
Peak current	3.4	kA
Normalized RMS slice emittance	1.2	µmrad
RMS slice energy spread	1×10-4	
RMS bunch length	77	fs
LCLS undulator parameters		
Undulator period	3	cm
Saturation length (including breaks)	92	m
Peak undulator field	1.32	T
Undulator parameter, *K*	3.711	
Undulator gap	6	mm