X-ray Free Electron Lasers

An introduction to the science of XFEL’s

2005 SSRL Summer School

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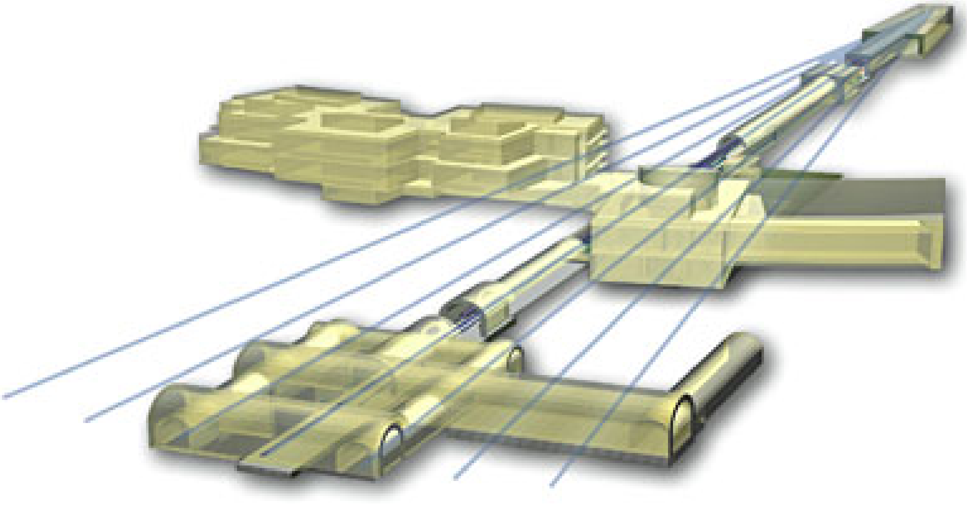
2004/2005 Sabbatical at the
The Stanford Ultrafast Science Center



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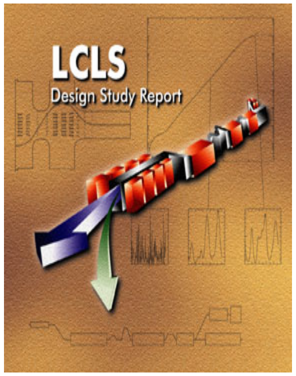
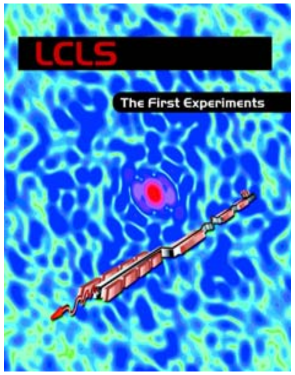
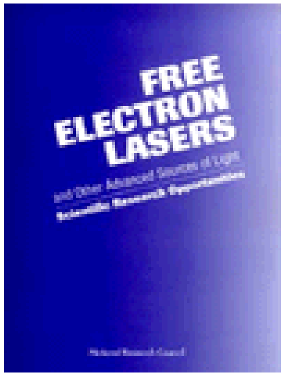
On-Line References



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



Free Electron Lasers and Other Advanced Sources of Light: Scientific Research Opportunities
National Research Council (1994)
http://www.nap.edu/catalog/9182.html

Also acknowledge: Neil Thompson, Daresbury

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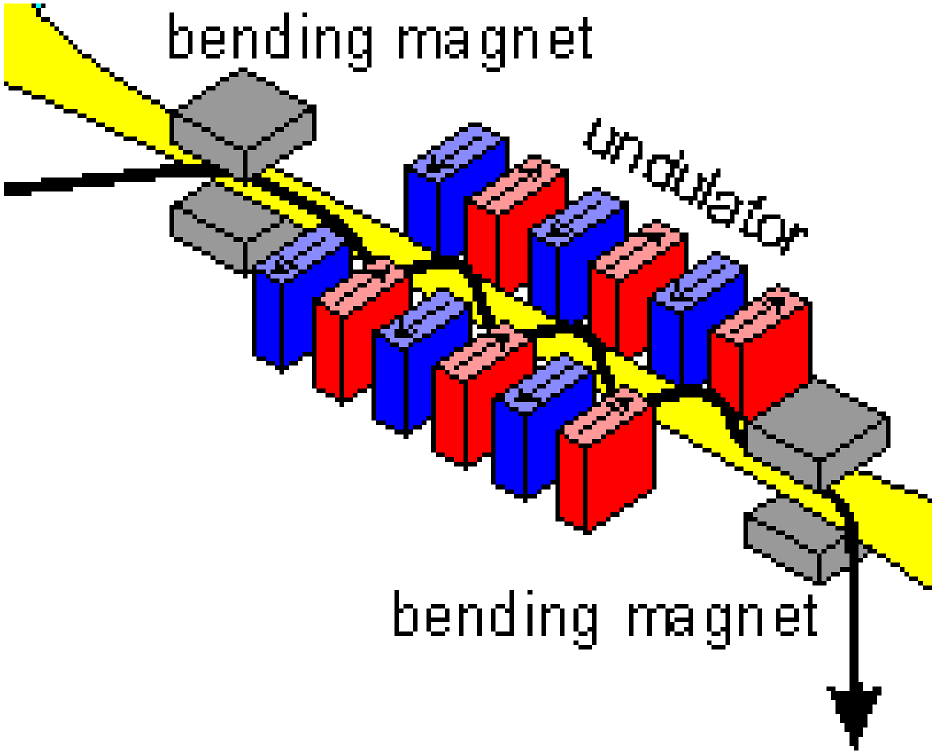
What's an FEL?

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



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

Relevant parameters:

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

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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:

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

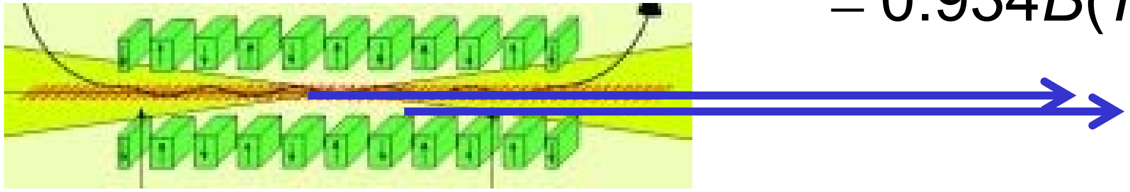
Slippage because v<c

Slippage from wiggling

The parameter a is related to K, the angle of maximum deviation of the electron wiggle times γ:

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

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



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

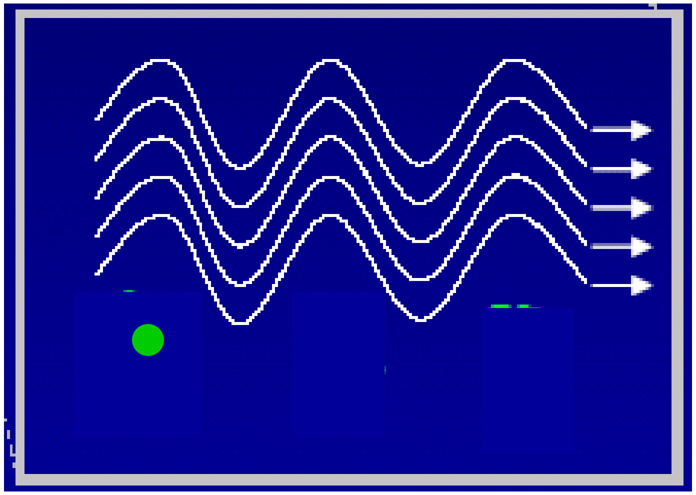
The light comes from synchrotron radiation

- 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 ~ $\lambda_r/4\pi$

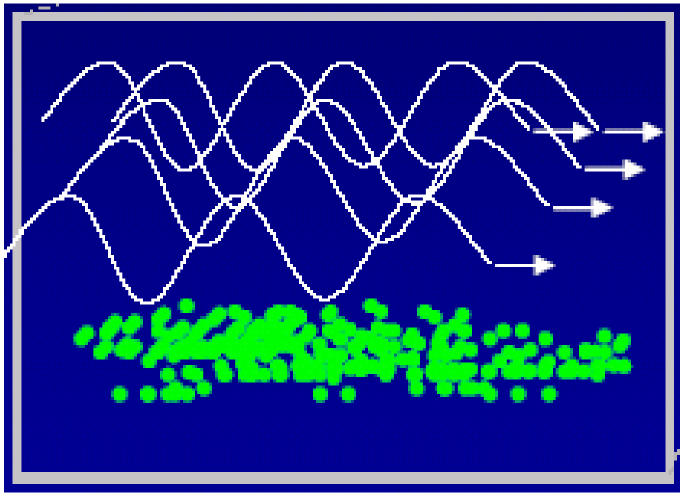
  - So, what’s different in an FEL?

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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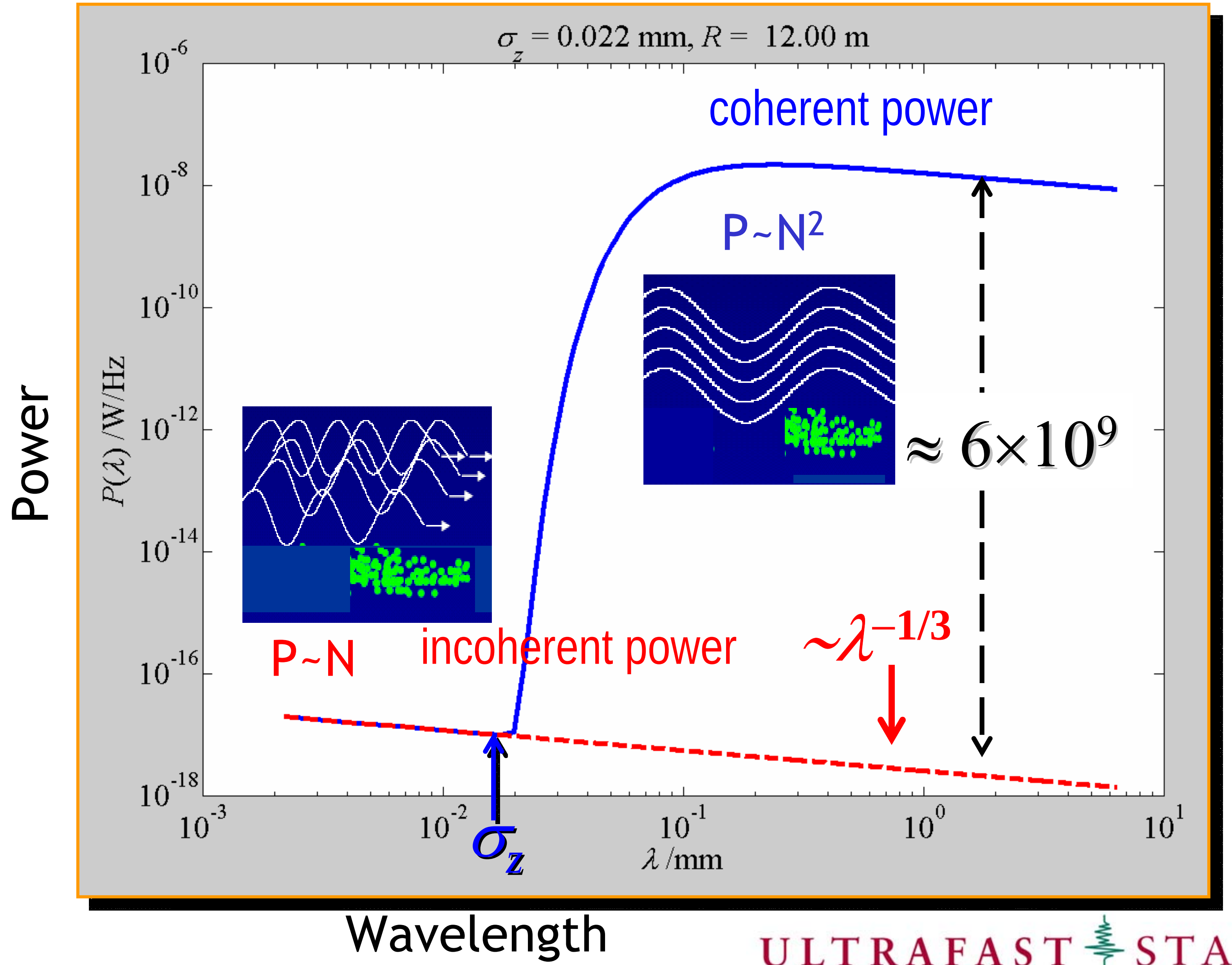
Temporal coherence



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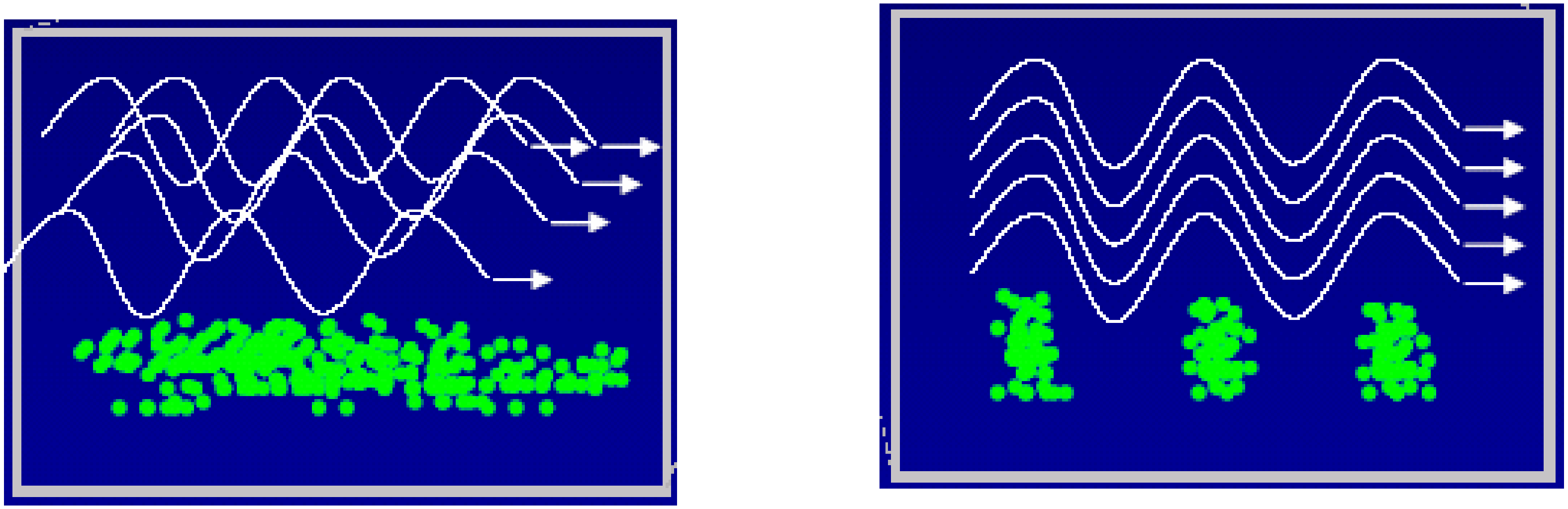
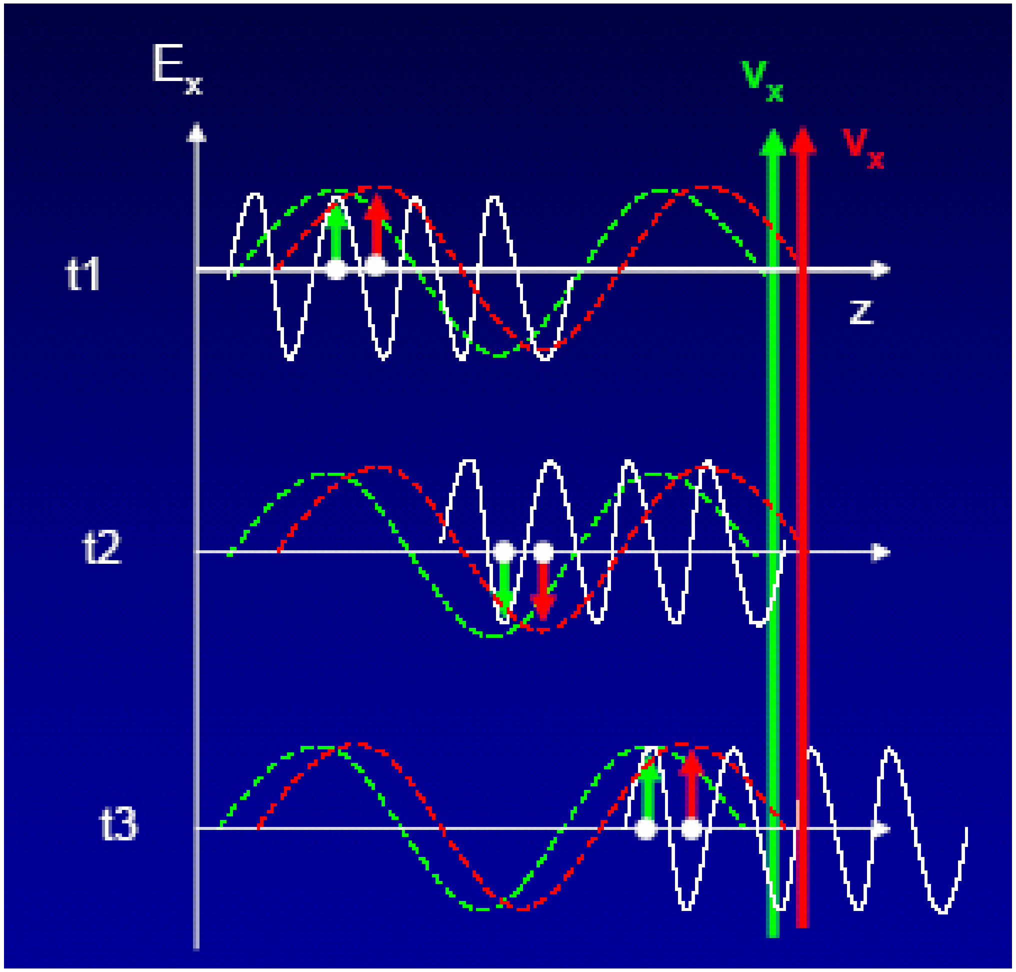
Bunching turns an undulator into an FEL



But how?

The light acts back on the electrons

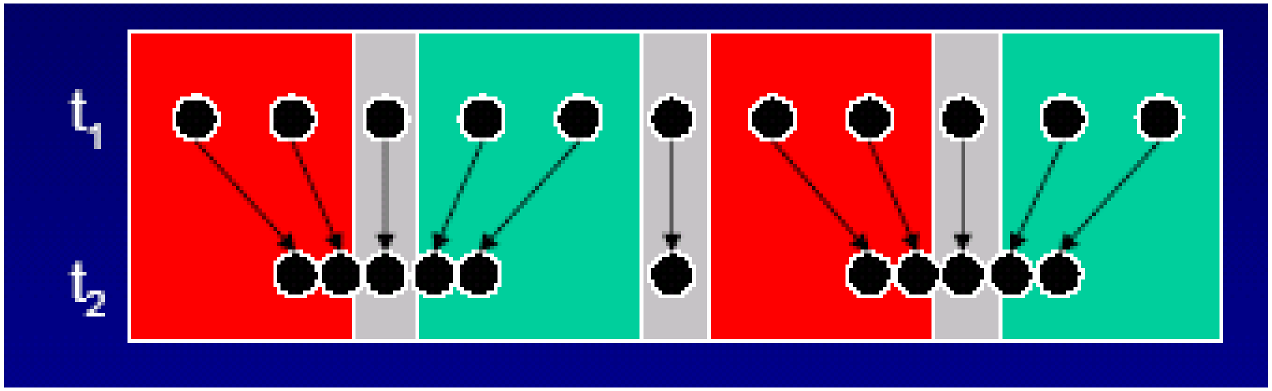


Some electrons accelerate on every cycle

Some decelerate on every cycle

Back-action leads to bunching

Accelerated or Decelerated Electrons



Bunched or not bunched?

The kth electron produces a field with it's own particular phase:

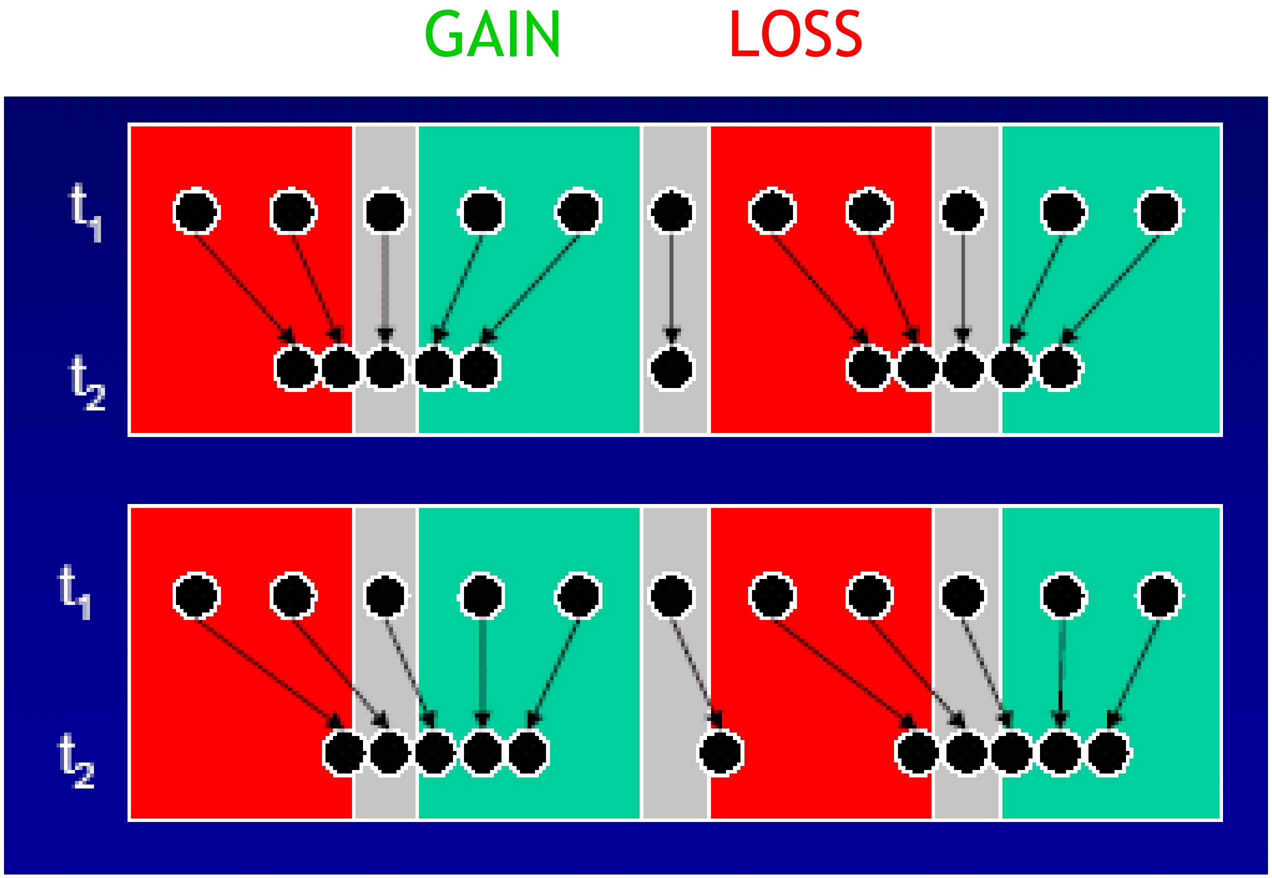
$$E_k = E_0 e^{i\omega t_{o,k}}$$

Then these fields superpose. The Bunching parameter:

$$B_0 = \frac{1}{N_e} \sum_{k=1}^{N_e} e^{i\omega t_{0,k}}$$

$B_0=0$: Perfectly uniform electron distribution. The fields add to zero.
$B_0=1$: Perfectly bunched electron distribution. Constructive interference
$0<B_0<1$: Random distribution; normal undulator operation

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



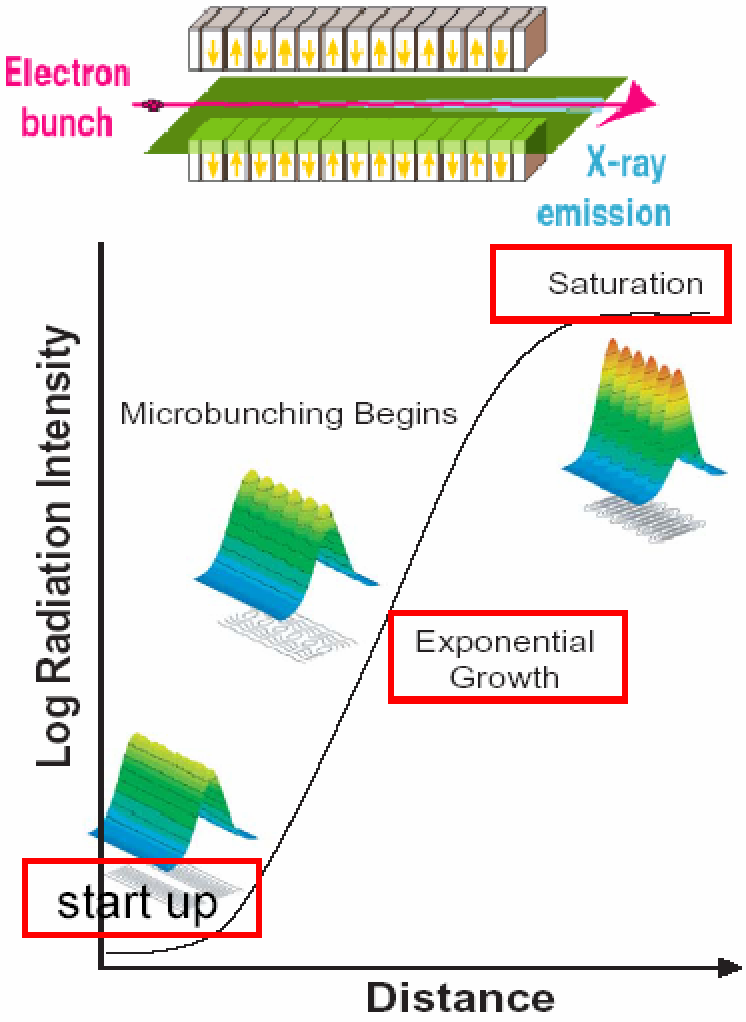
Zero net gain

Positive gain

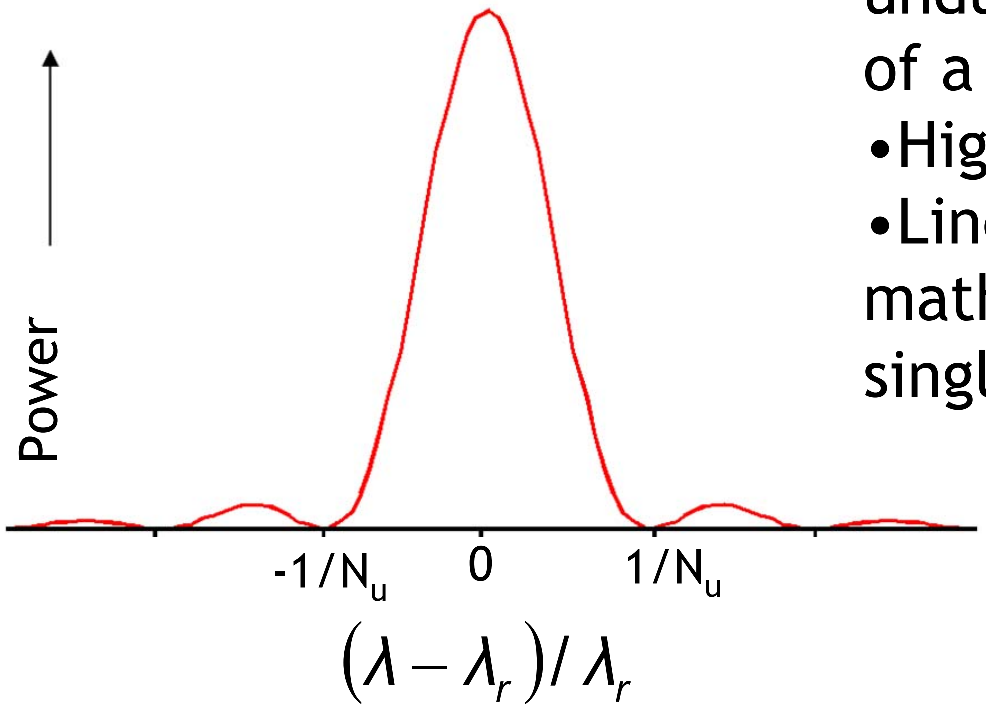
Gain requires some detuning above resonance

SASE FEL's

- Undulator radiation starts up from noise to interact with the e-beam
- Energy modulation → density modulation at λ (microbunching) → coherent radiation at λ → exponential growth (L_G)
- At sufficiently high power, electrons fully microbunched with large energy spread → reach saturation (P_{sat})



Undulator spontaneous emission linewidth

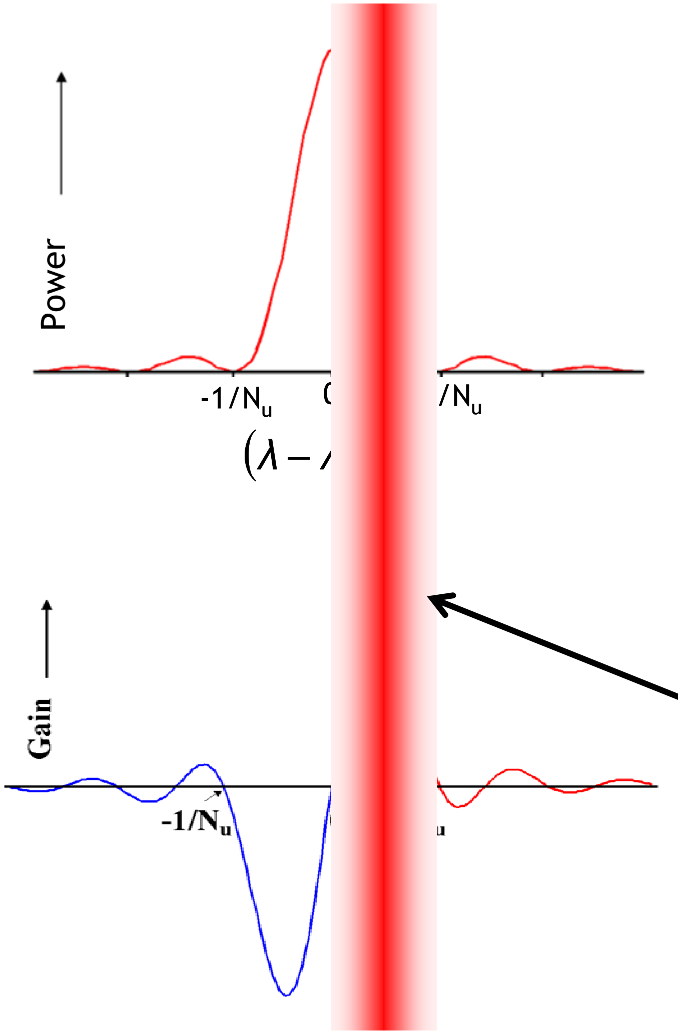


- Electron slips one cycle per undulator period, so the length of a coherent pulse is <N_u cycles
- Highest field if $\lambda=\lambda_r$.
- Lineshape vs. detuning is mathematically similar to single-slit diffraction pattern.

Detuning parameter
$\delta=2\pi N(\Delta\lambda/\lambda)$

http://www.rijnh.nl/n4/n3/n2/FELbasics.htm

Gain, tuning, and Madey’s Theorem

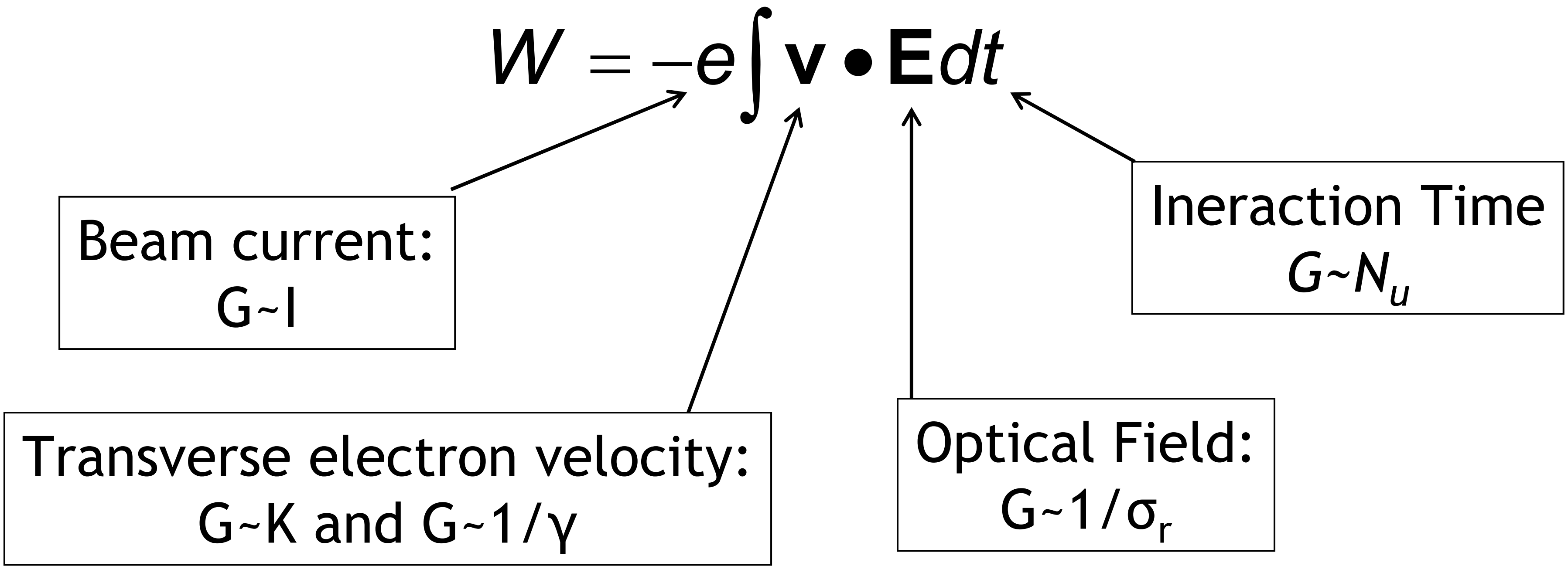


Gain is a tradeoff between positive detuning and spontaneous undulator power.

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

Maximum gain at δ=2.6
δ=2πN(Δλ/λ)

Improving Gain means increasing the work done by the field on the electrons



$$W = -e\int \mathbf{v}\bullet\mathbf{E}\,dt$$

Beam current:
G~I

Transverse electron velocity:
G~K and G~1/γ

Optical Field:
G~1/σ_r

Ineraction Time
$G \sim N_u$

The FEL gain:

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

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

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

ρ is the FEL parameter: $\rho = \left(\frac{a_u}{4\gamma} \sqrt{F(a_u)} \frac{\Omega_p}{\omega_u} \right)^{2/3}$

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

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

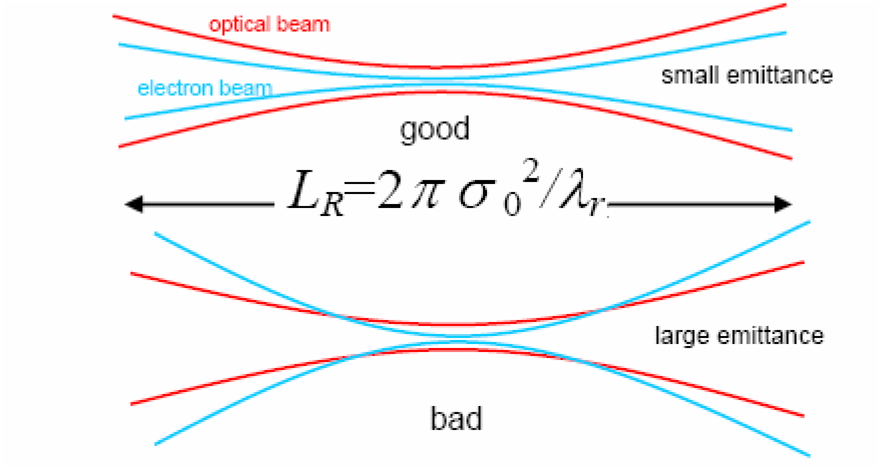
n_e is the electron density.

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

Best conditions for SASE FEL

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

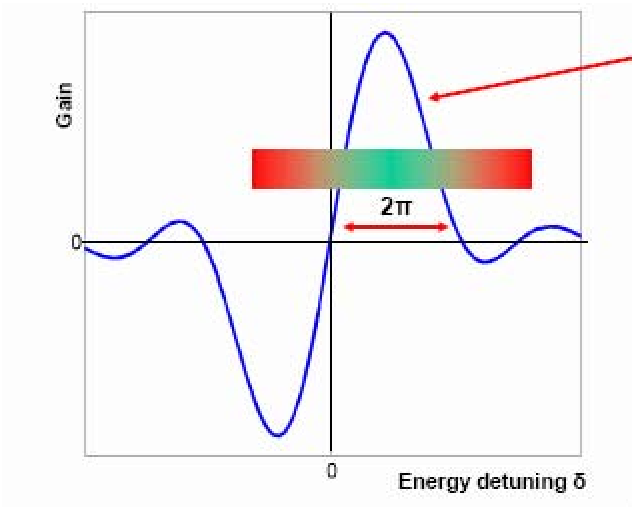
$$\varepsilon \leq \frac{\lambda}{4\pi}$$



- Gain length shorter than the Rayleigh range L_R

- Beam relative energy spread smaller than the FEL parameter

$$\sigma_E / E < \rho$$



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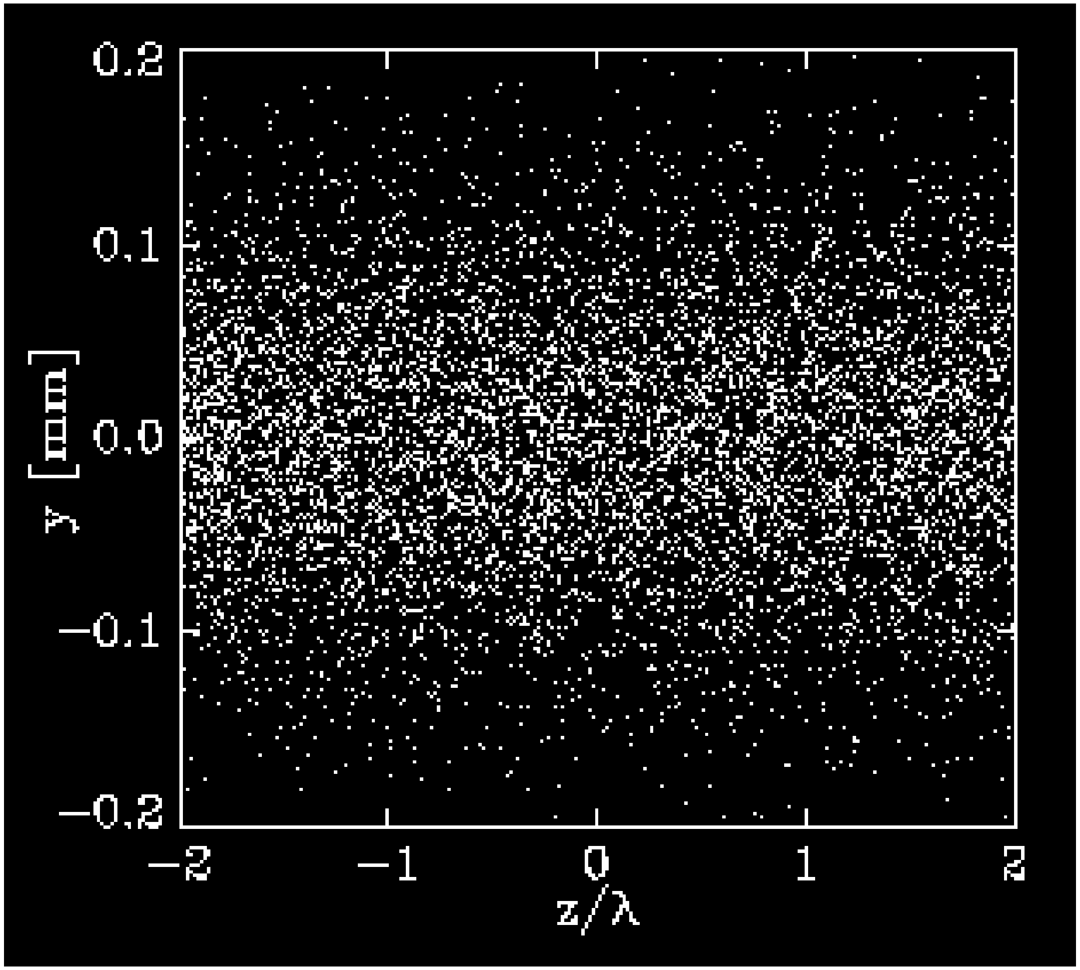
Microbunching through SASE Process

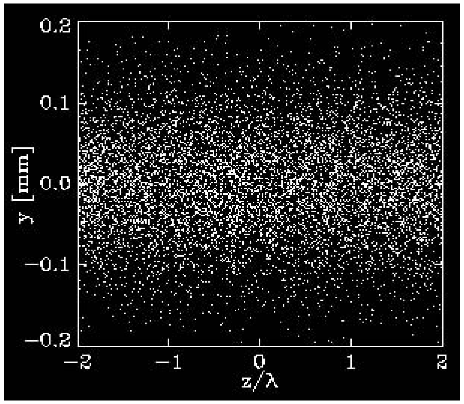


GENESIS **-**

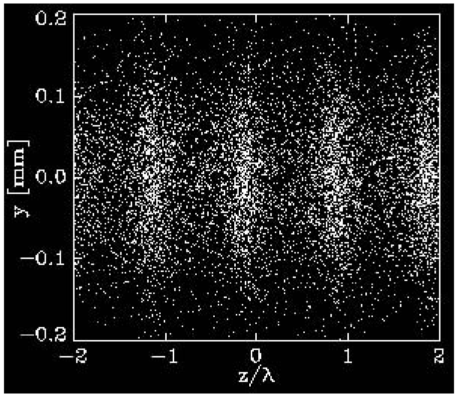
simulation for TTF parameters

Courtesy - Sven Reiche (UCLA)

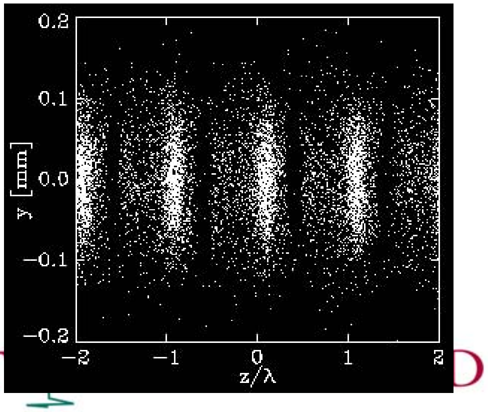
undulator entrance



half-way saturation



full saturation



What stops the FEL from going on forever?

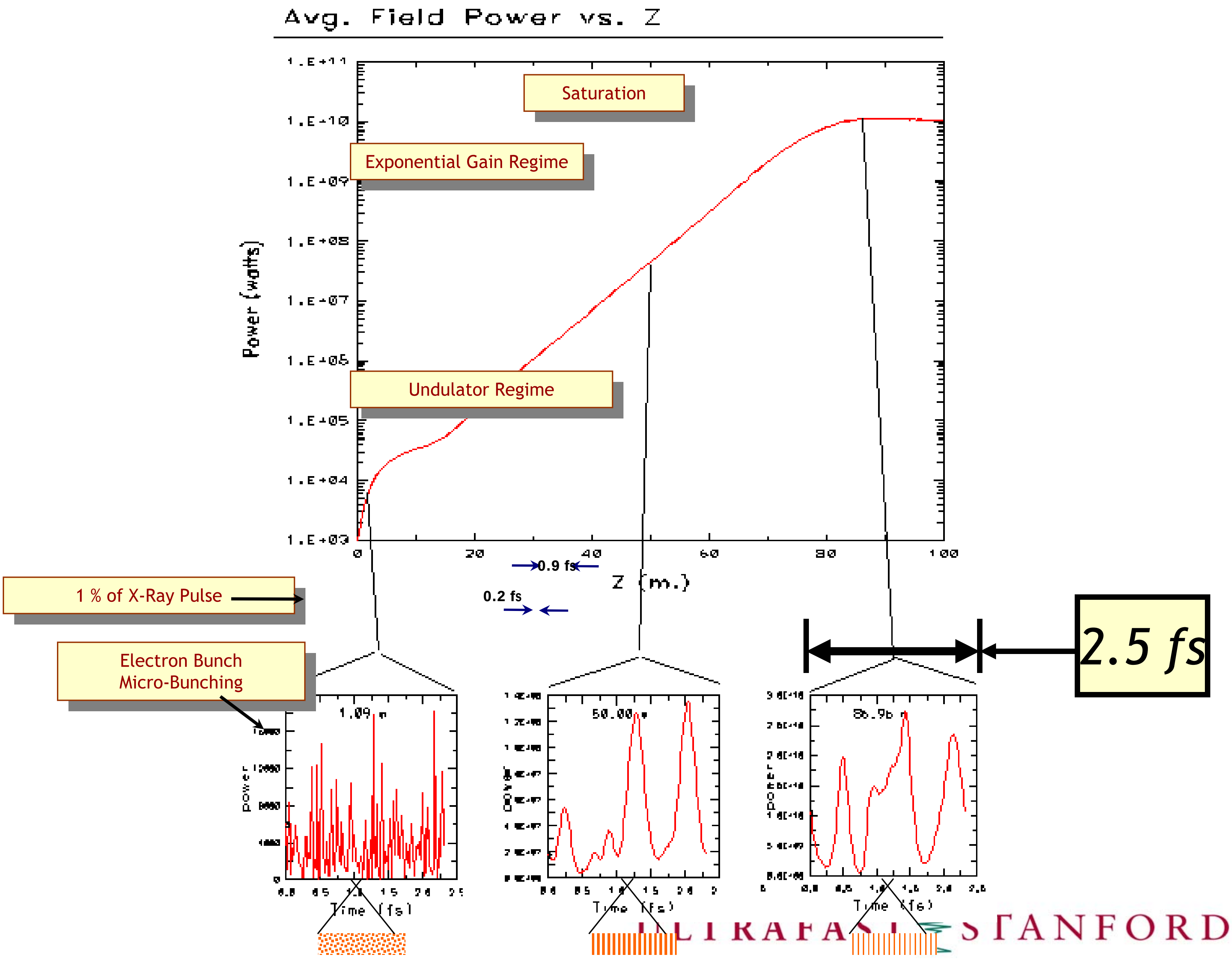
Cooperation length: Slippage in one gain length

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

The radiation builds up with coherent spikes of length $2\pi L_c$, a few femtoseconds at LCLS.

The radiation saturates when the bunch parameter B approaches unity:

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



Saturation

Exponential Gain Regime

Undulator Regime

1 % of X-Ray Pulse

Electron Bunch
Micro-Bunching

2.5 fs

SASE-FEL Physics Summary

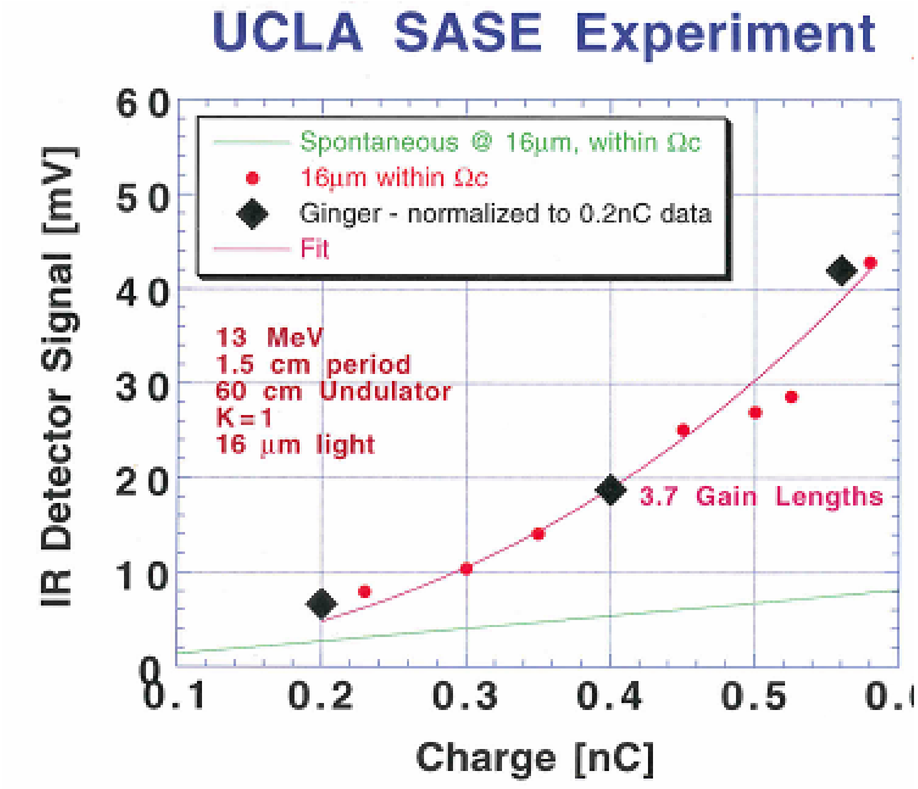
- *A SASE-FEL is completely characterized by one universal FEL parameter, ρ (Bonifacio, Pellegrini, Narducci, 1984).*
- *FEL parameter:* $\rho=\{(a_u/4\gamma)(\Omega_P/\omega_u)JJ\}^{2/3}$

  where $\omega_u=2\pi c/\lambda_u$,, Ω_P*=beam plasma frequency*
- *Exponential growth rate (Power Gain Length):* $L_G=\lambda_u/2\pi\rho$
- *Saturation power:* $P\sim\rho\, I_{beam}\, E$
- *Undulator saturation length:* $L_{sat}\sim 10L_G \sim\lambda_W/\rho$
- *Line width:* $\sim 1/N_W\sim\rho$
- *Cooperation length* $L_C=\lambda_r/4\pi\rho$
- *Number of spikes* $M=L_{bunch}/2\pi L_c$

SASE-FEL experiments

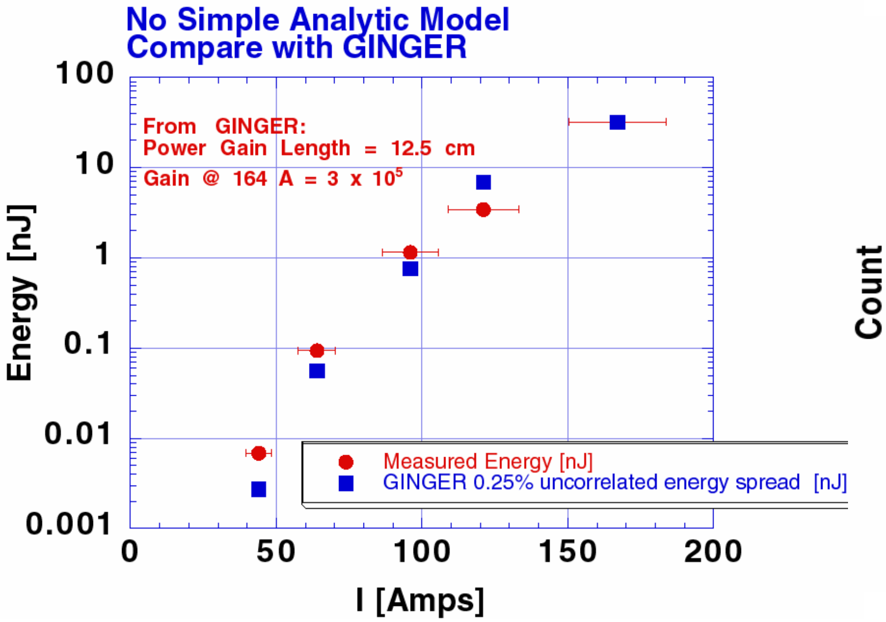
UCLA/Kurchatov

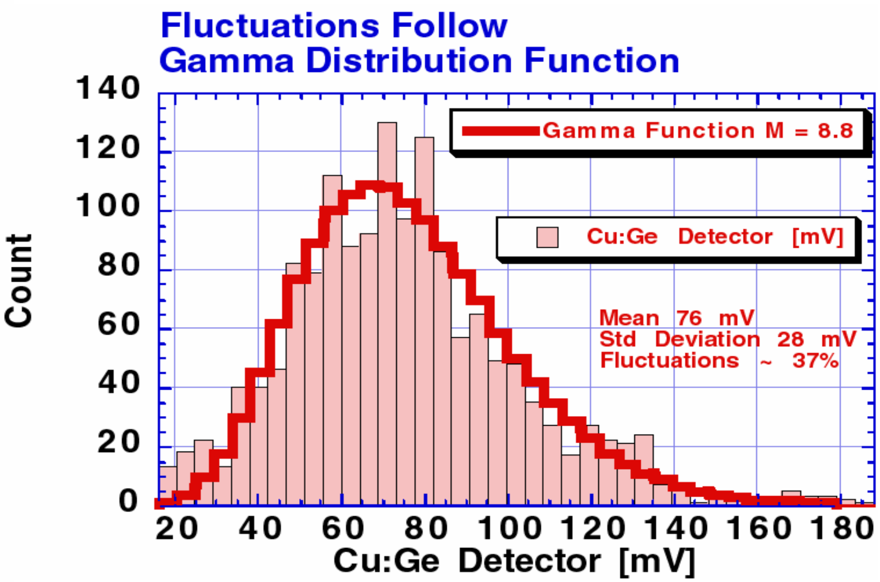
M. Hogan et al. Phys. Rev. Lett. 80, 289 (1998).



Analysis of SASE

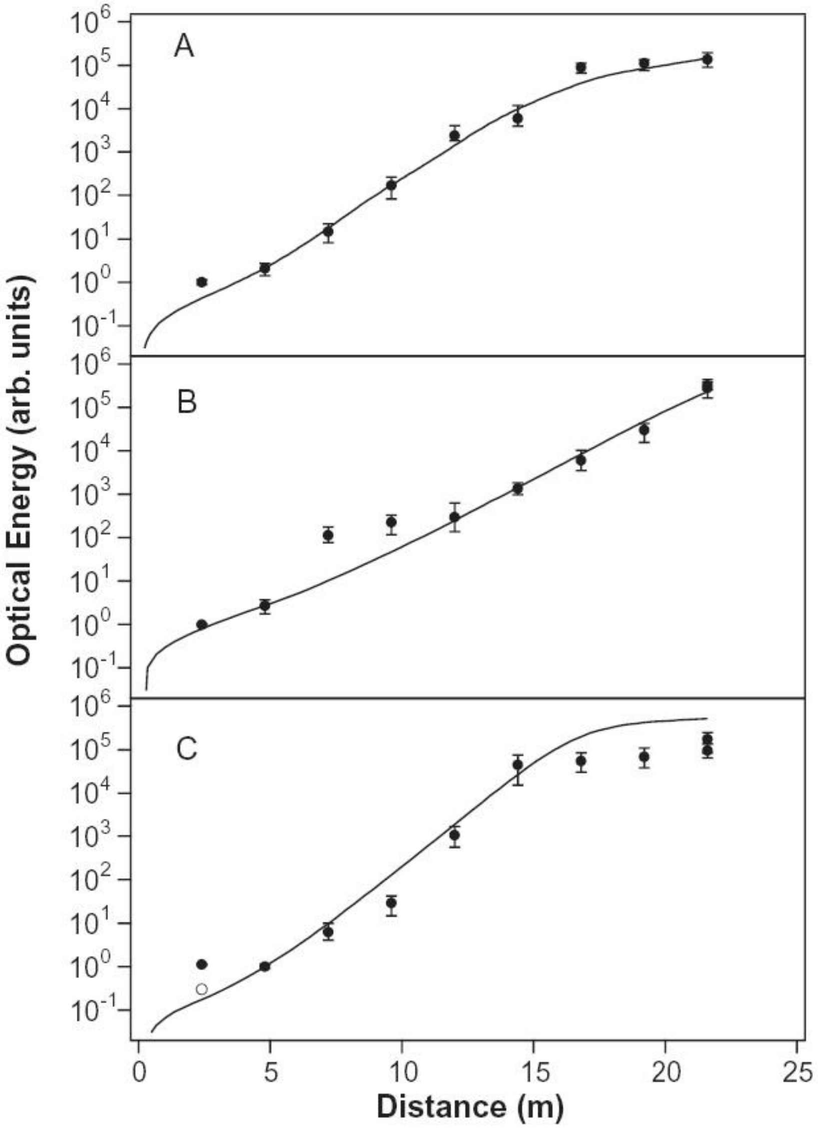
- UCLA/Kurchatov/LANL/SSRL: Gain of 3x10^5 at 12 μm. Demonstration of fluctuations and spikes, in agreement with theory. M. Hogan et al. Phys. Rev. Lett. 81, 4897 (1998).





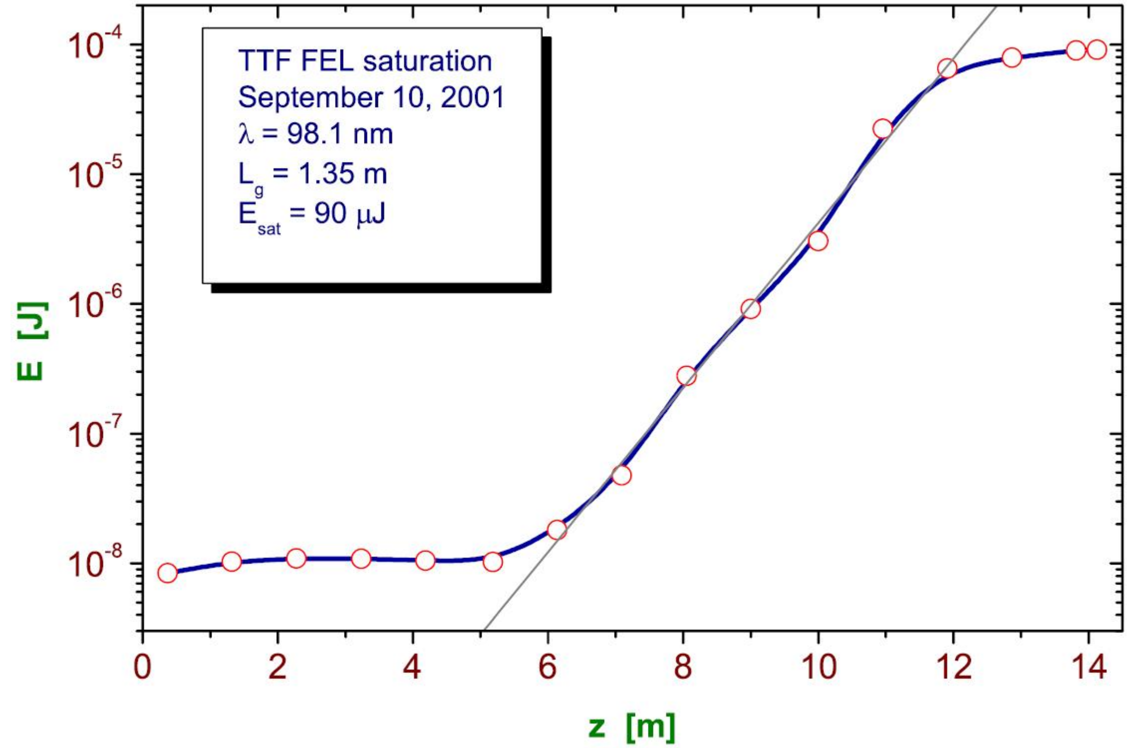
LEUTL results

- LEUTL exponential gain and saturation at 530 nm, A &B, and 385 nm, C. The gain reduction for case B was obtained by reducing the peak current. *Milton et al., Sciencexpress, May 17, 2001. LEUTL has saturated also at 130nm. The solid lines are Theoretical predictions.*



Saturation in a VUV FEL

- TESLA-TTF SASE-FEL. Saturation at 98.1nm. Ayvazyan et al., Ph. Rev. Lett. 88, 104802 (2002).



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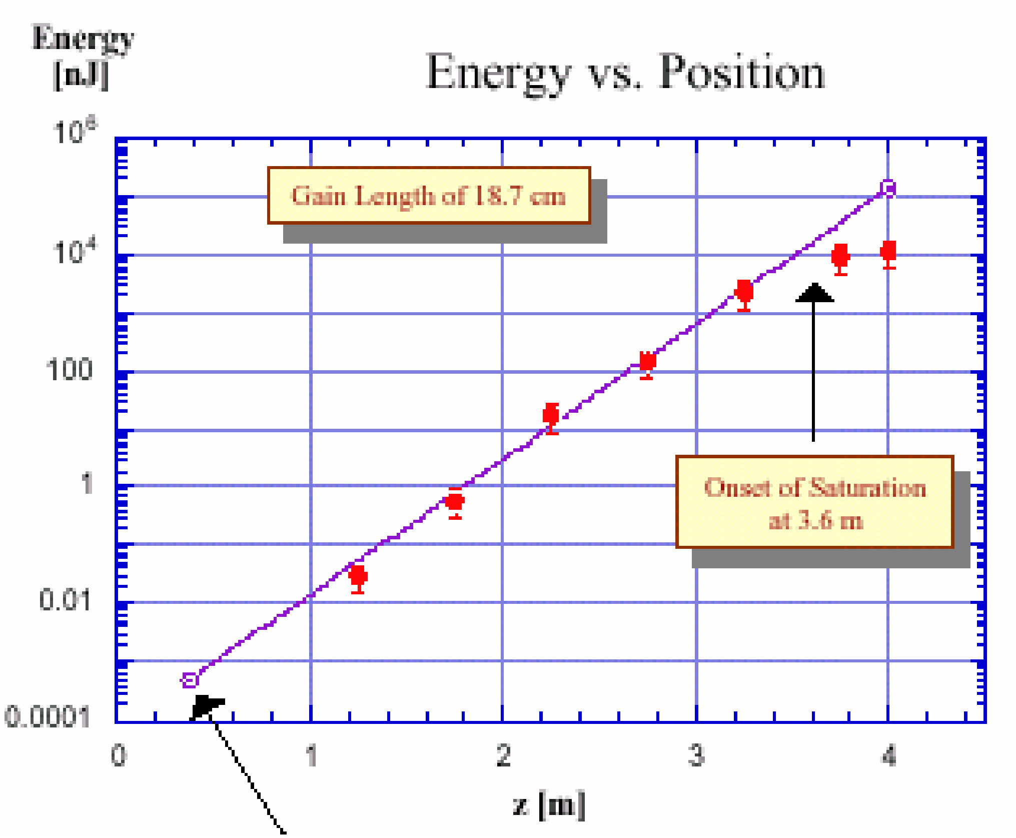
SASE-FEL experiments

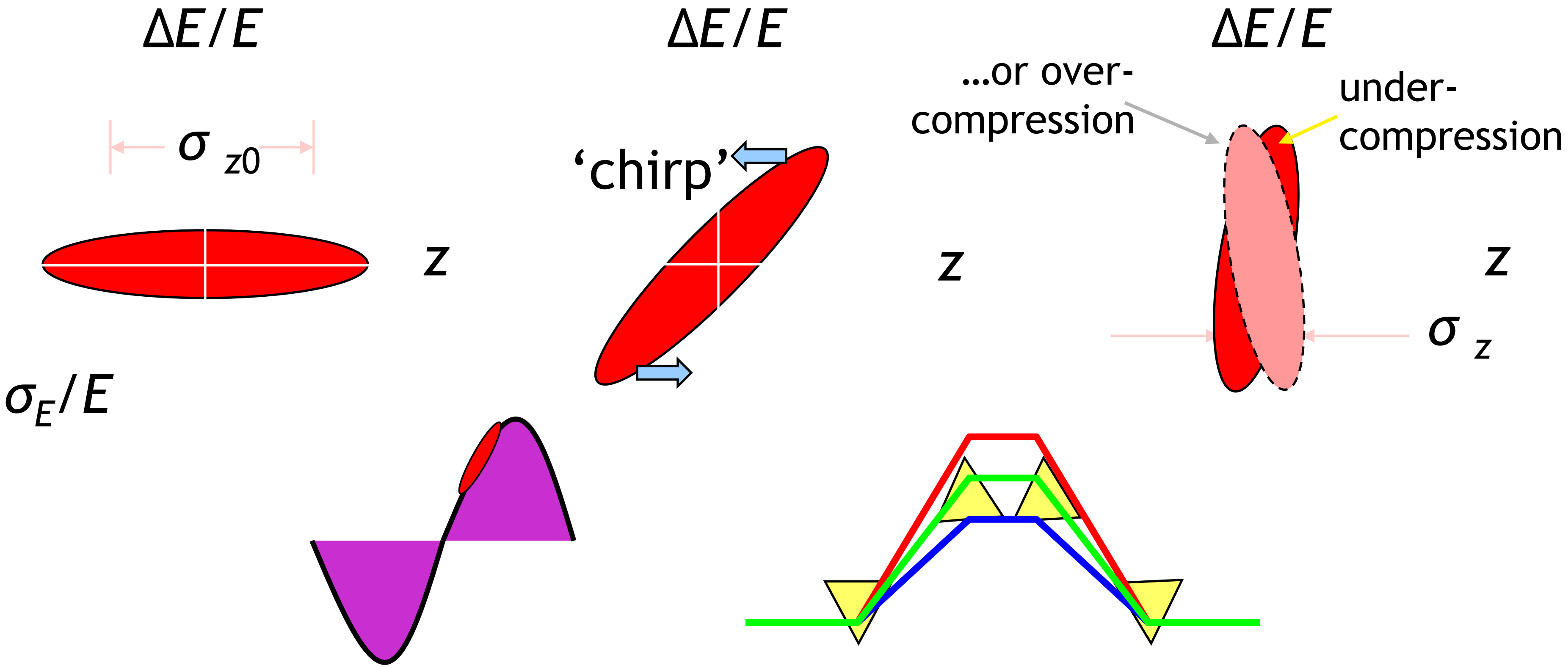
- VISA: a BNL-LLNL-SLAC-UCLA collaboration (A. Murokh et al., PAC 2002, Int. FEL Conf. 2002)

  Saturation results

Wavelength: 830nm
Average Charge:170 pC
Gain Length 18.5 cm
SASE Energy:10 μJ
Total Gain: 2×10^8



FEL for x-rays: Electron bunch compression



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

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

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

Early test of electron bunch compression to increase the peak current

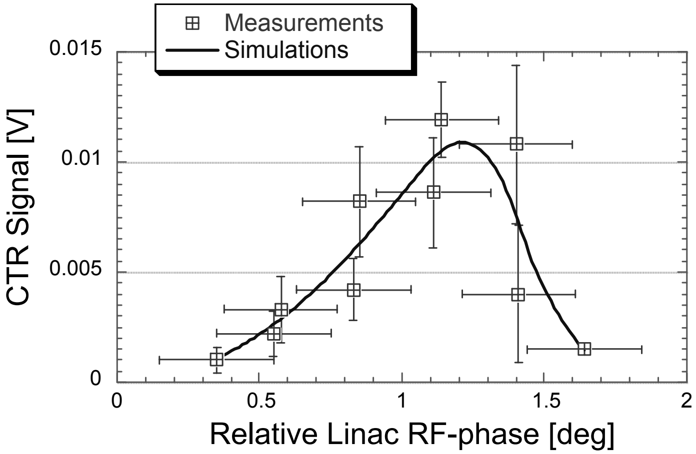
- VISA Operates in 2 set of conditions:

  a) with no compression, emittance of 1.5 to 2.3 mm mrad, peak current of 55A, charge ~0.2nC. Gain of about 10^3.

  b) with strong compression, obtaining a peak current of 250A, Q~0.2nC; the compression is nonlinear and produces a strongly correlated beam phase-space, with a larger emittance; both the current and the emittance change along the bunch; in this case one obtains a power gain length ~18cm, and saturation.

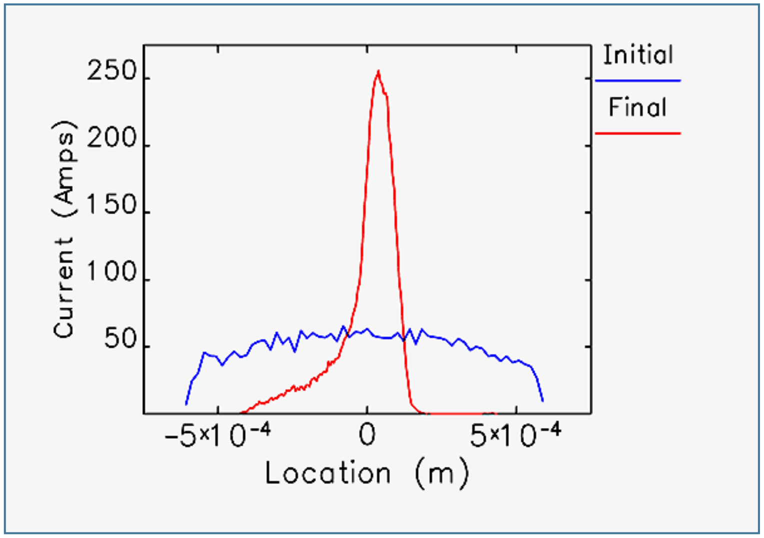
Bunch compression at VISA

- Case b). Strong nonlinear bunch compression, peak current about 250A. Complicated beam phase space distribution.



Bunch length measurements,

and simulation results



Longitudinal distribution before and after compression

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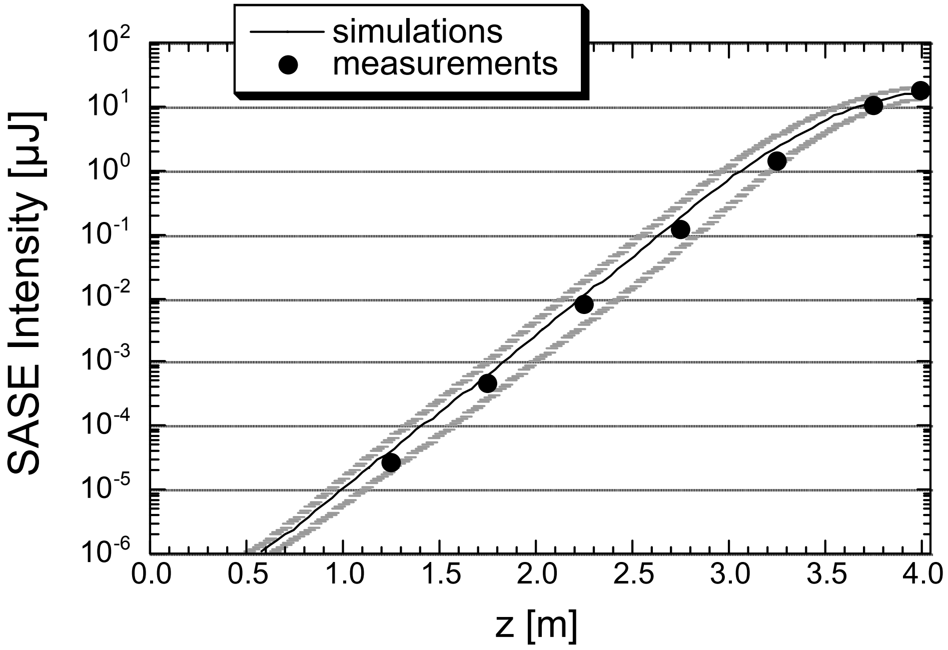
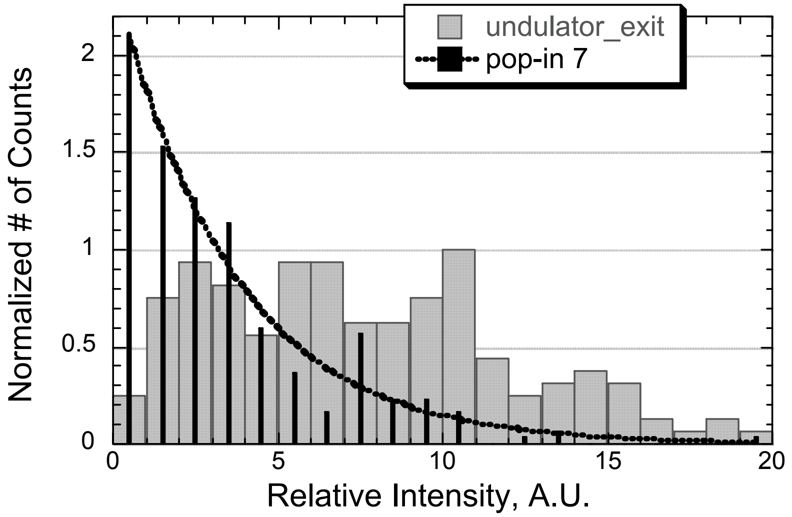
Evidence for single spikes

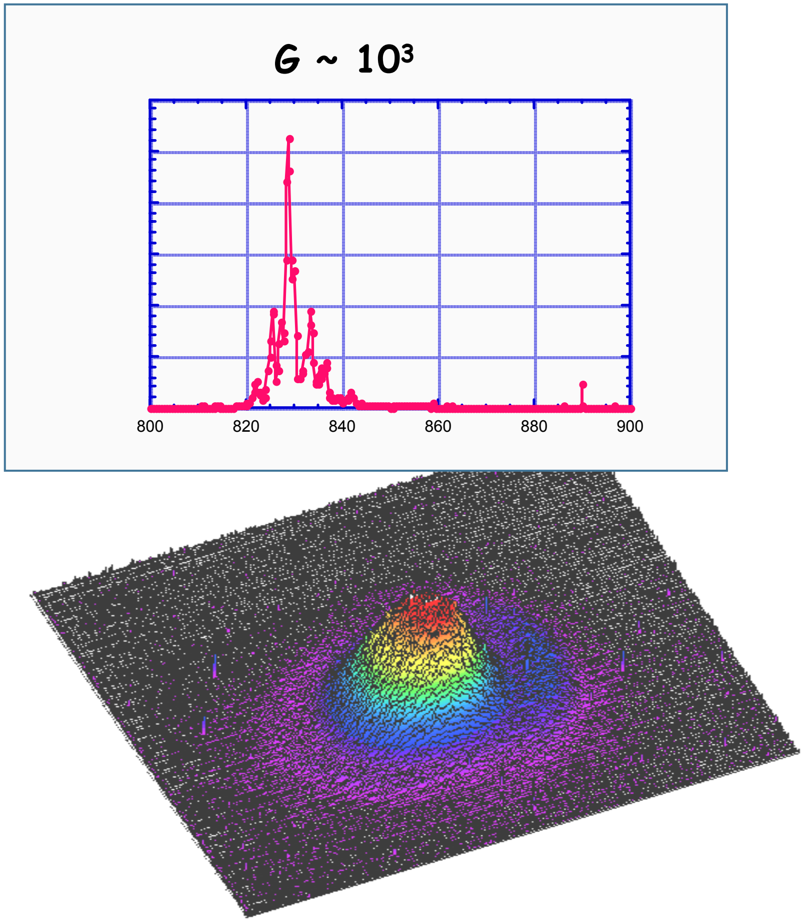
- Case b measured SASE intensity and intensity fluctuations during exponential growth and saturation. Results show single spike, and change in fluctuations after saturation.

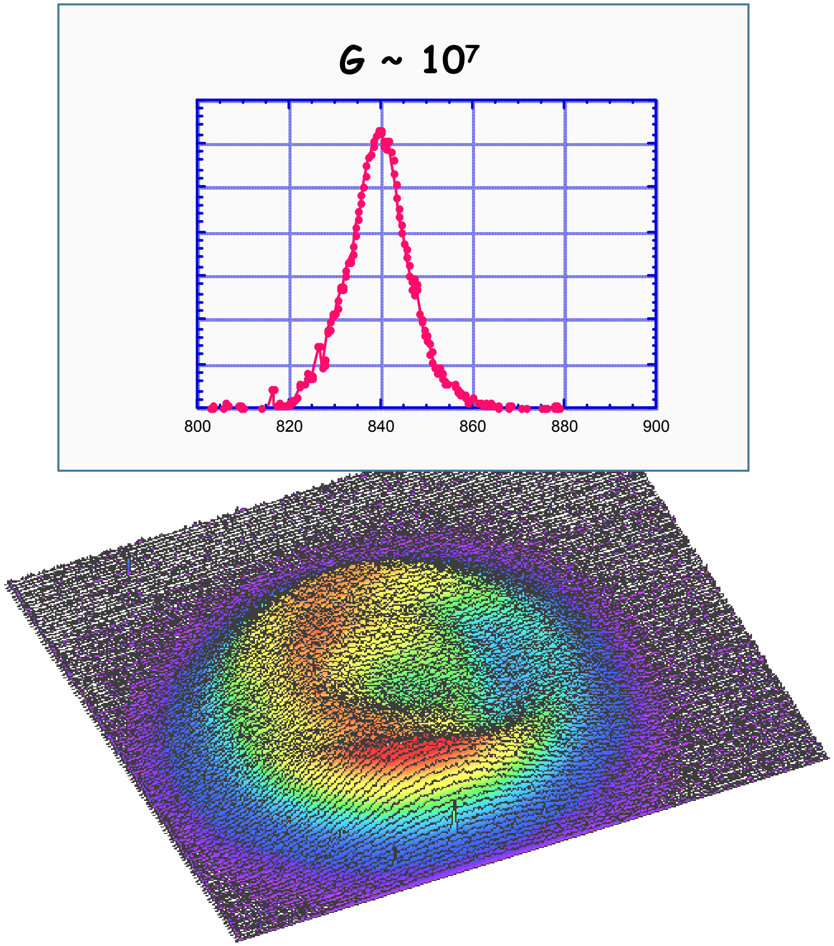




Increased gain

- VISA spectral and angular distributions in cases a and b.





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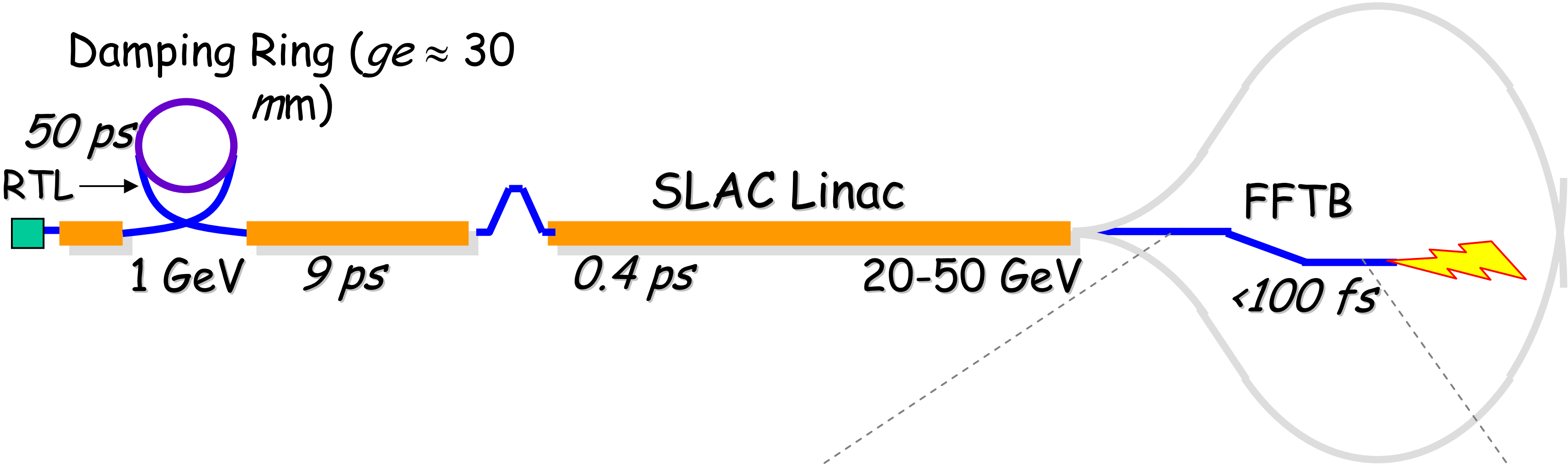
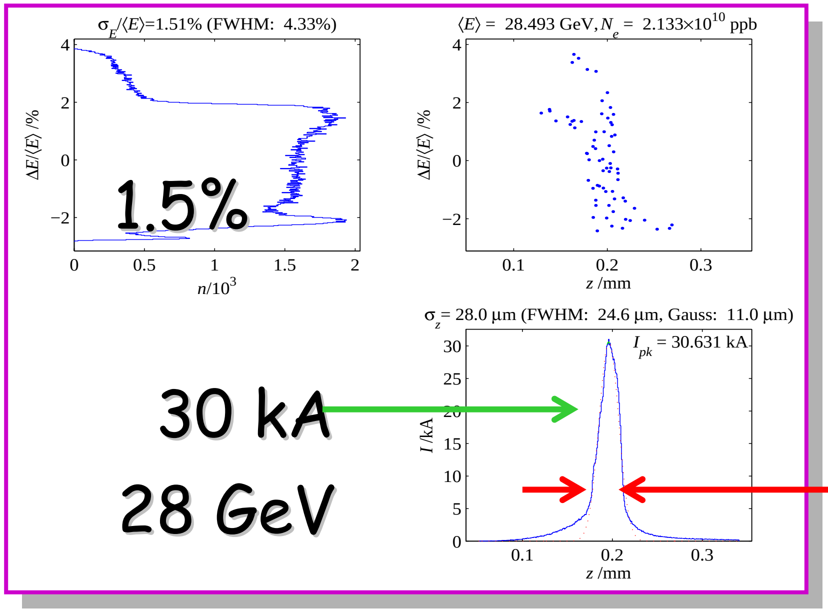
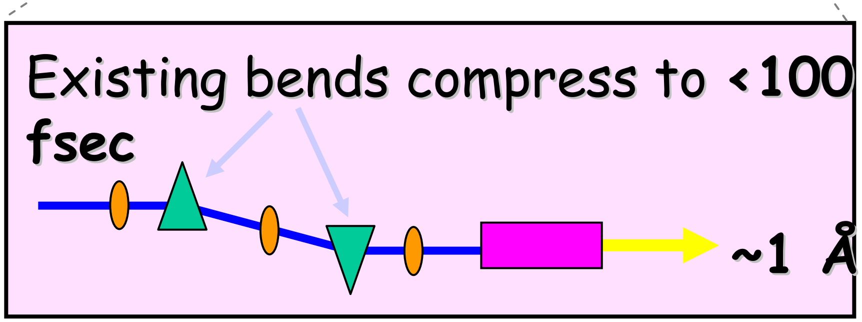
SPPS: Testing bunch compression at SLAC



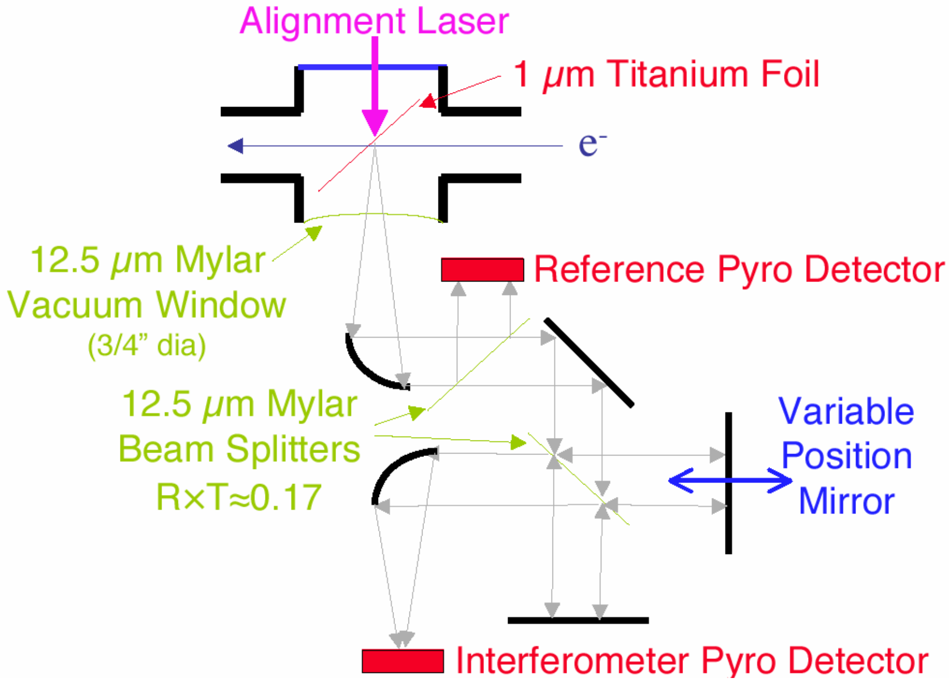


80 fsec FWHM



Existing bends compress to <100 fsec

Diagnosing compressed pulse:
Field autocorrelation:



Alignment Laser

1 μm Titanium Foil

e^-

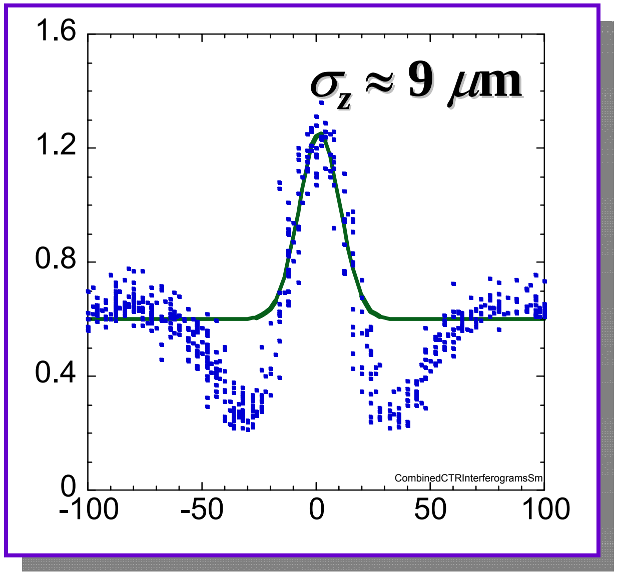
12.5 μm Mylar
Vacuum Window
(3/4" dia)

Reference Pyro Detector

12.5 μm Mylar
Beam Splitters
R×T≈0.17

Variable
Position
Mirror

Interferometer Pyro Detector

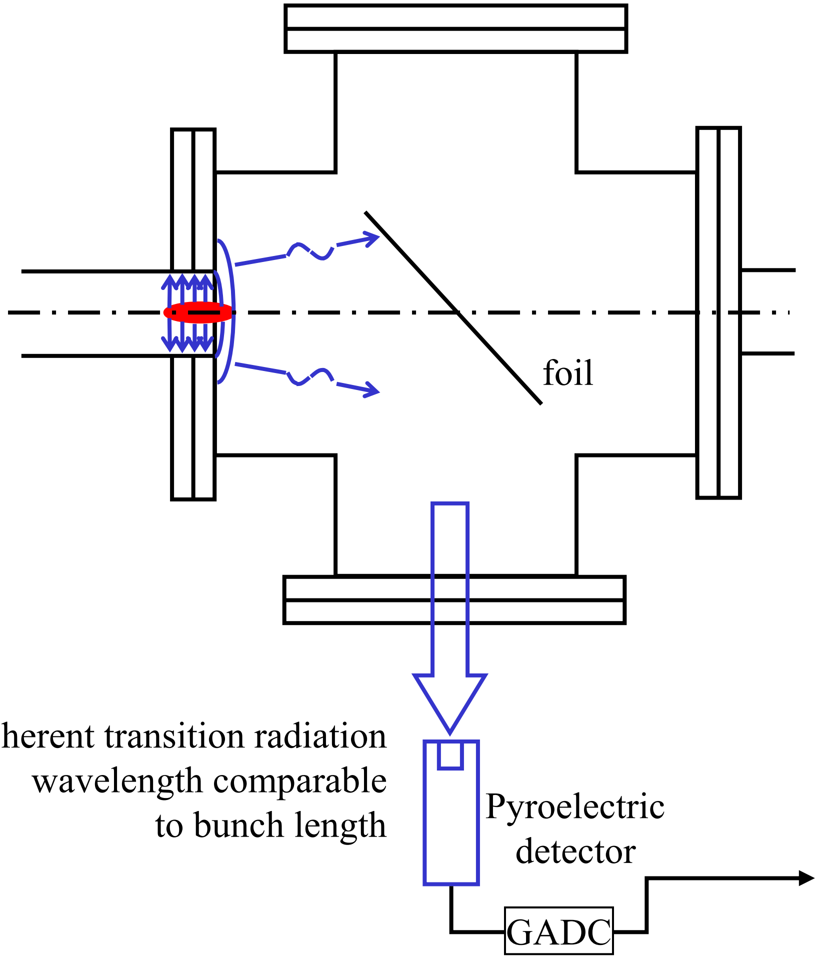


Transition radiation is coherent at wavelengths longer than the bunch length, $\lambda > (2\pi)^{1/2}\sigma_z$

Limited by long wavelength cutoff and absorption resonances

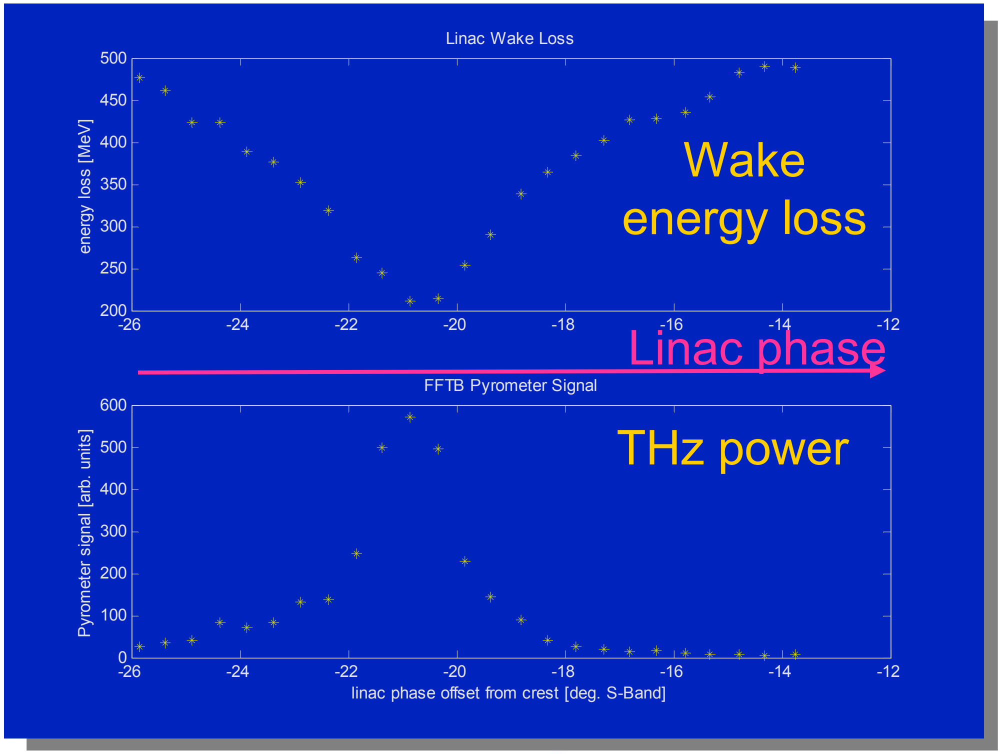
SLAC **SPPS** measurement:
P. Muggli, M. Hogan

Bunch length scan performed while observing spectral power with THz detector



Coherent transition radiation wavelength comparable to bunch length

Comparison of bunch length minimized according to wakefield loss and THz power



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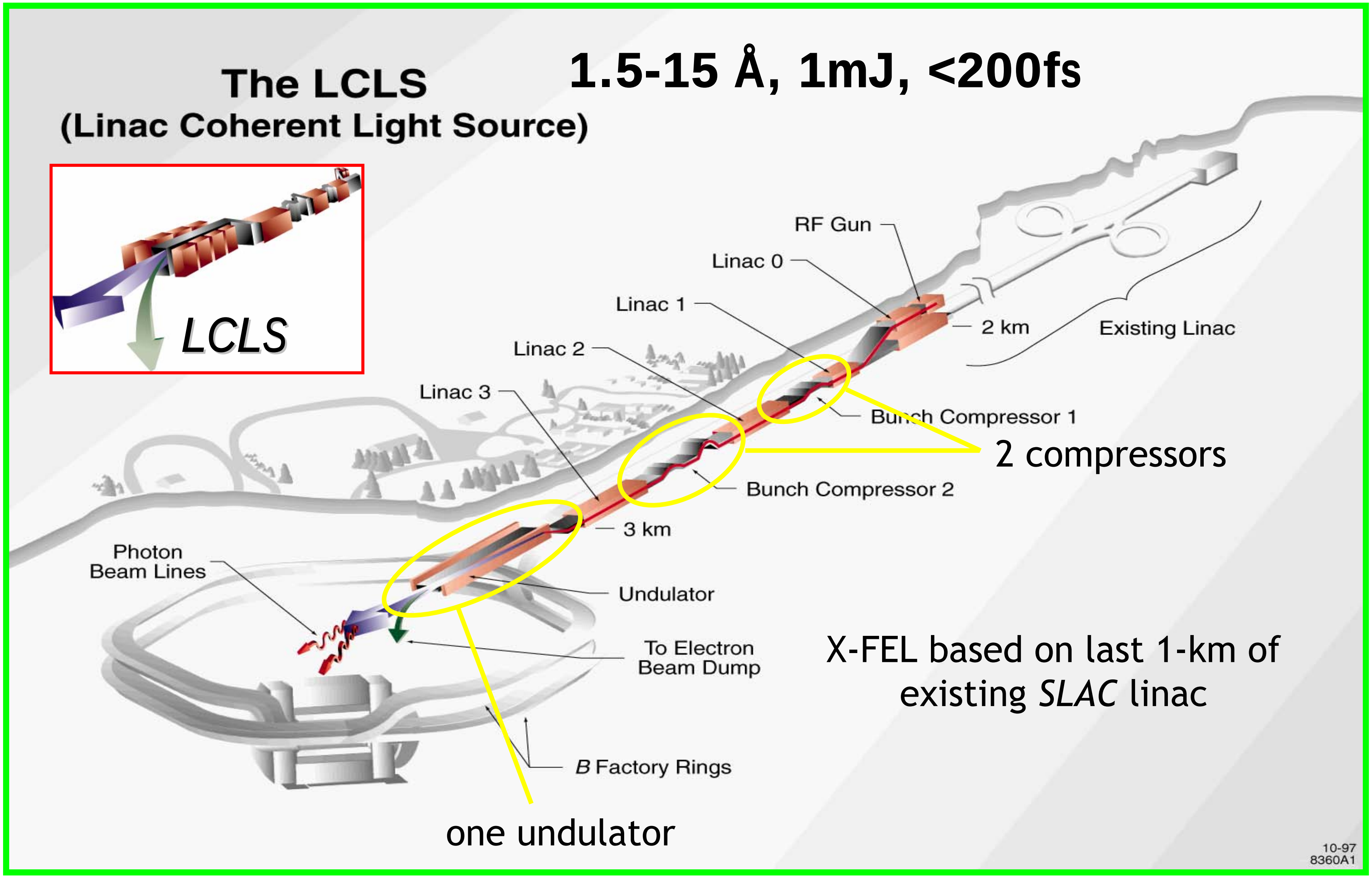
LCLS at *SLAC*



1.5-15 Å, 1mJ, <200fs

2 compressors

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

one undulator

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

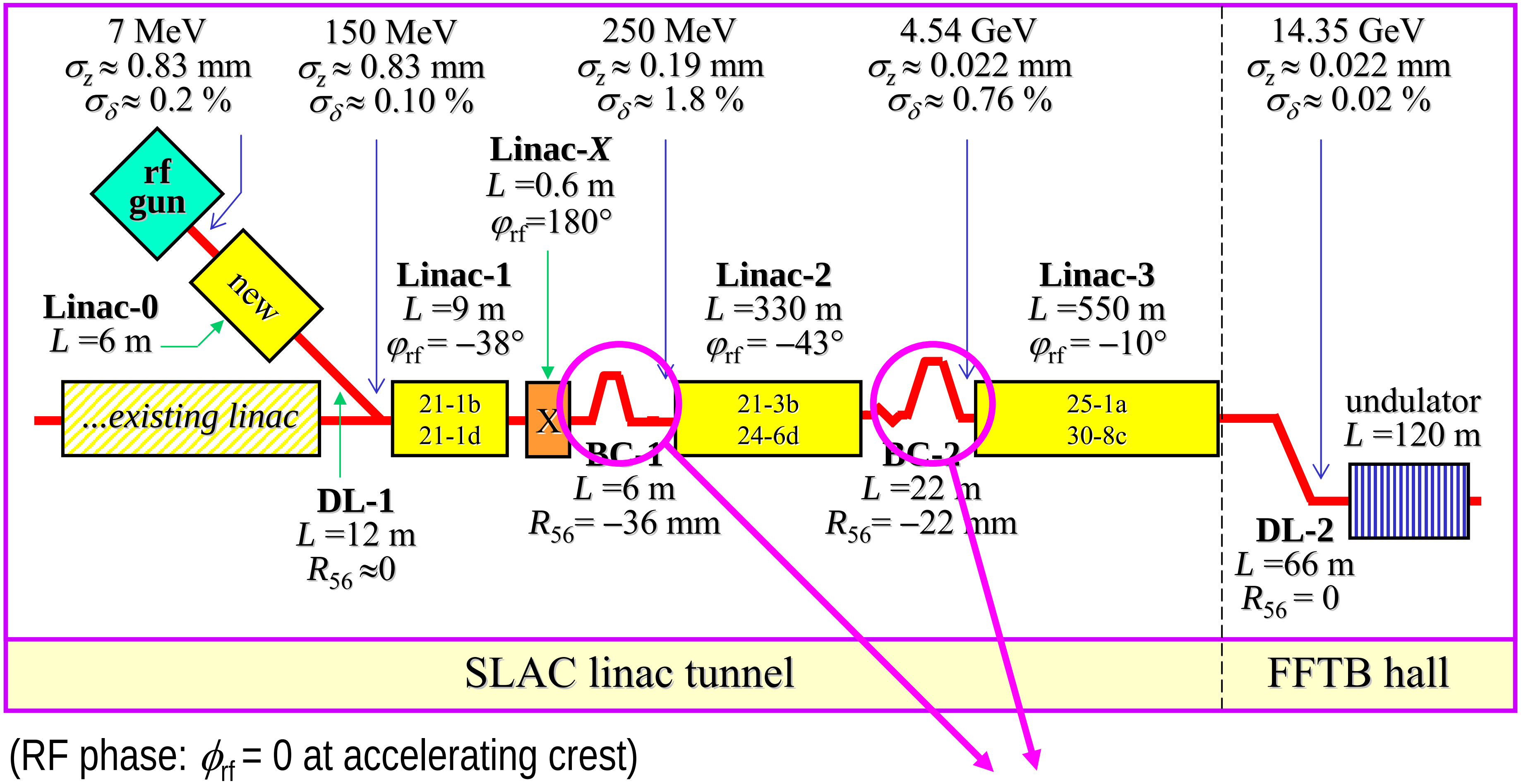
FEL parameters

LCLS FEL parameters	Value	Unit
Radiation wavelength	0.15	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)

LCLS Linac Parameters for 1.5-Å FEL

single bunch, 1-nC, 120-Hz



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

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

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

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

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

rf gun

new

Linac-0
L =6 m

Linac-*X*
L =0.6 m
φ_{rf}=180°

Linac-1
L =9 m
$\varphi_{rf} = -38°$

Linac-2
L =330 m
$\varphi_{rf} = -43°$

Linac-3
L =550 m
$\varphi_{rf} = -10°$

...existing linac

21-1b
21-1d

X

21-3b
24-6d

25-1a
30-8c

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

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

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

undulator
L =120 m

DL-2
L =66 m
$R_{56} = 0$

SLAC linac tunnel

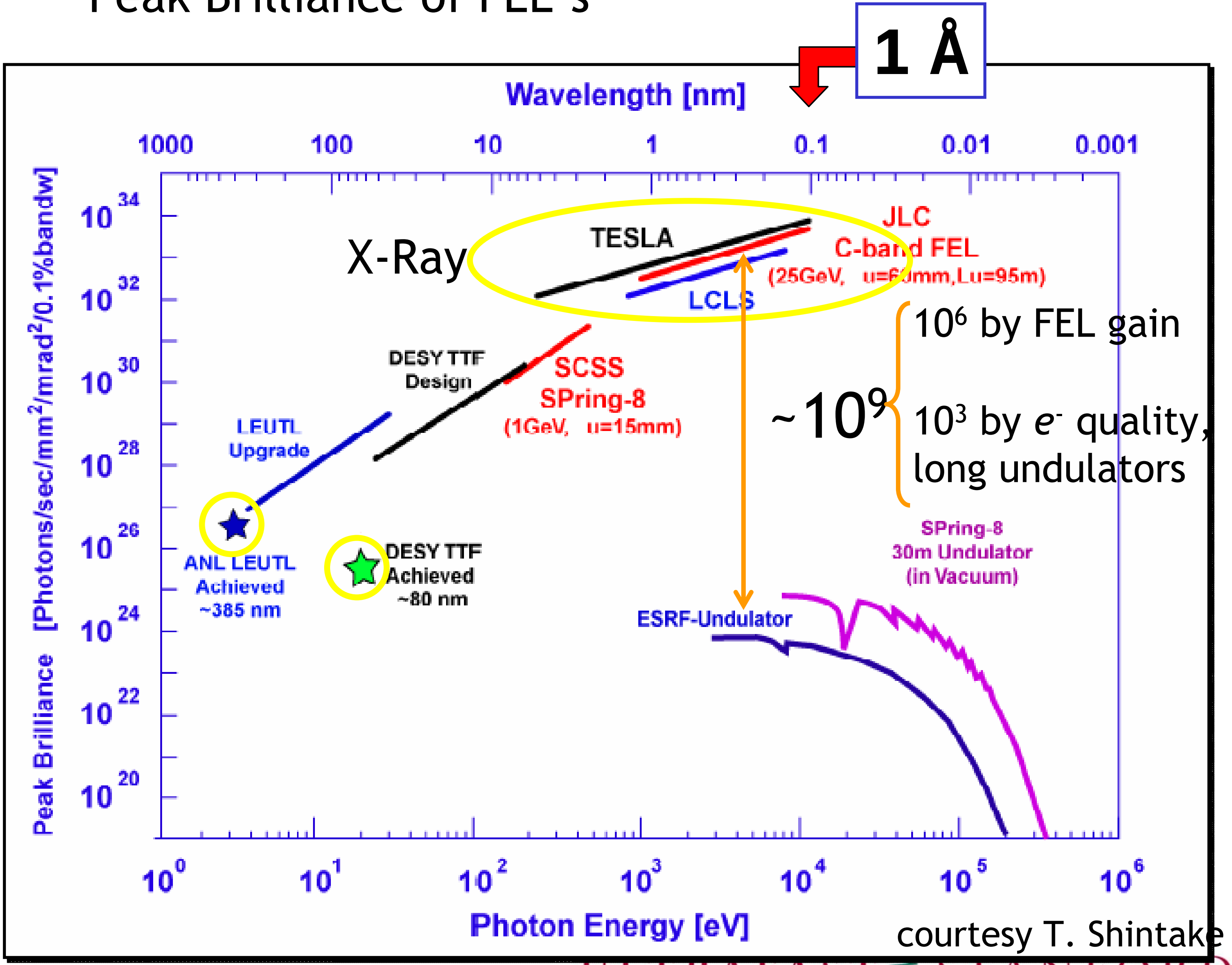
FFTB hall

(RF phase: $\phi_{rf} = 0$ at accelerating crest)

Two stages of bunch compression

Peak Brilliance of FEL's

photons per phase-space volume per band-width



1 Å

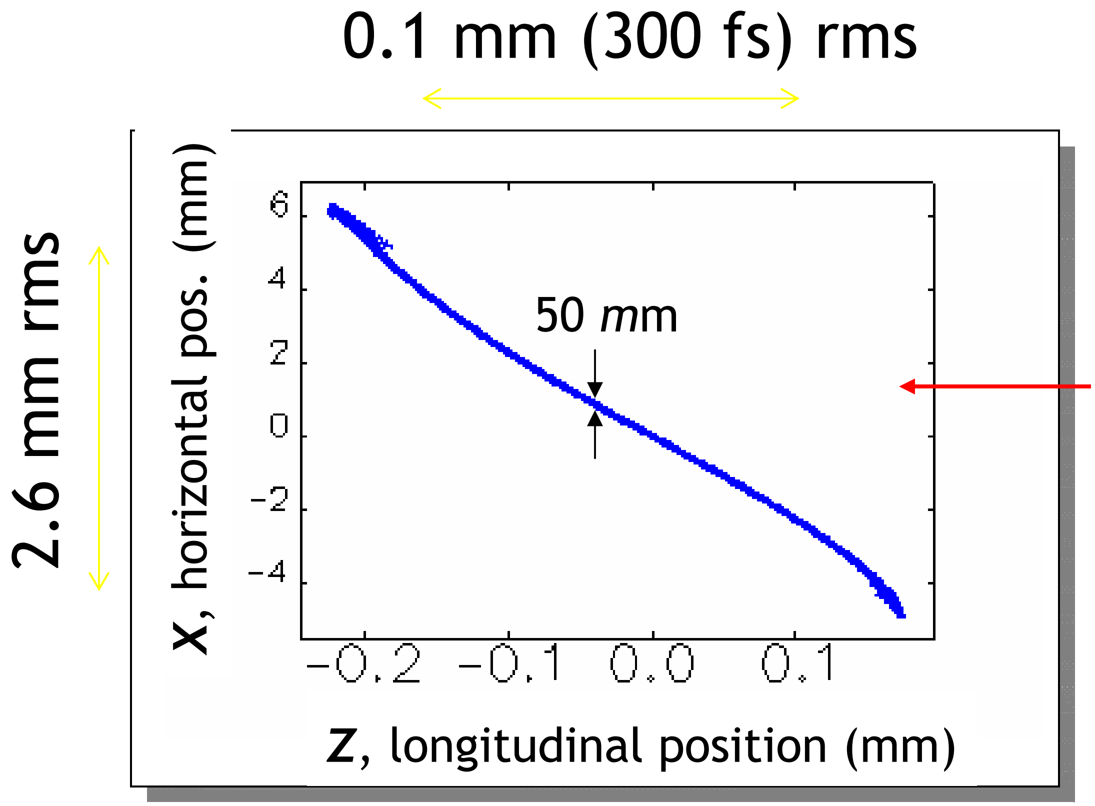
X-Ray

~10^9

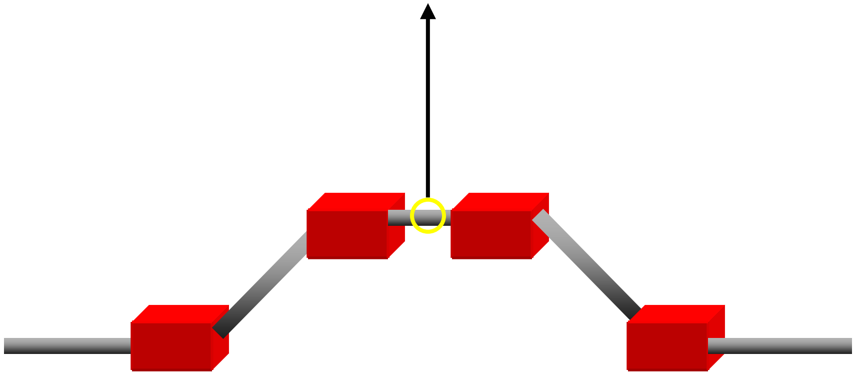
10^6 by FEL gain

10^3 by e^- quality, long undulators

courtesy T. Shintake

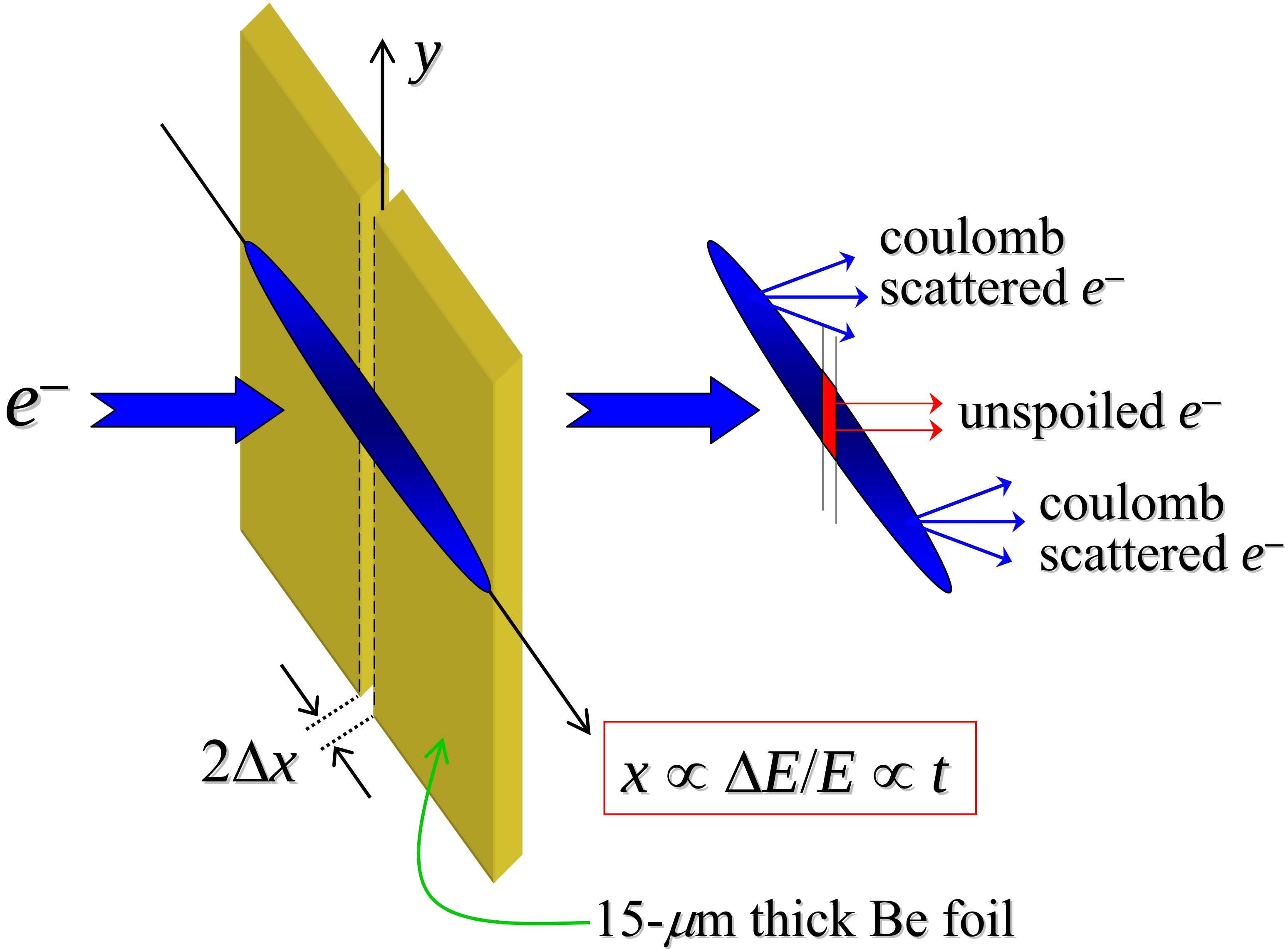


Easy access to *time* coordinate along bunch



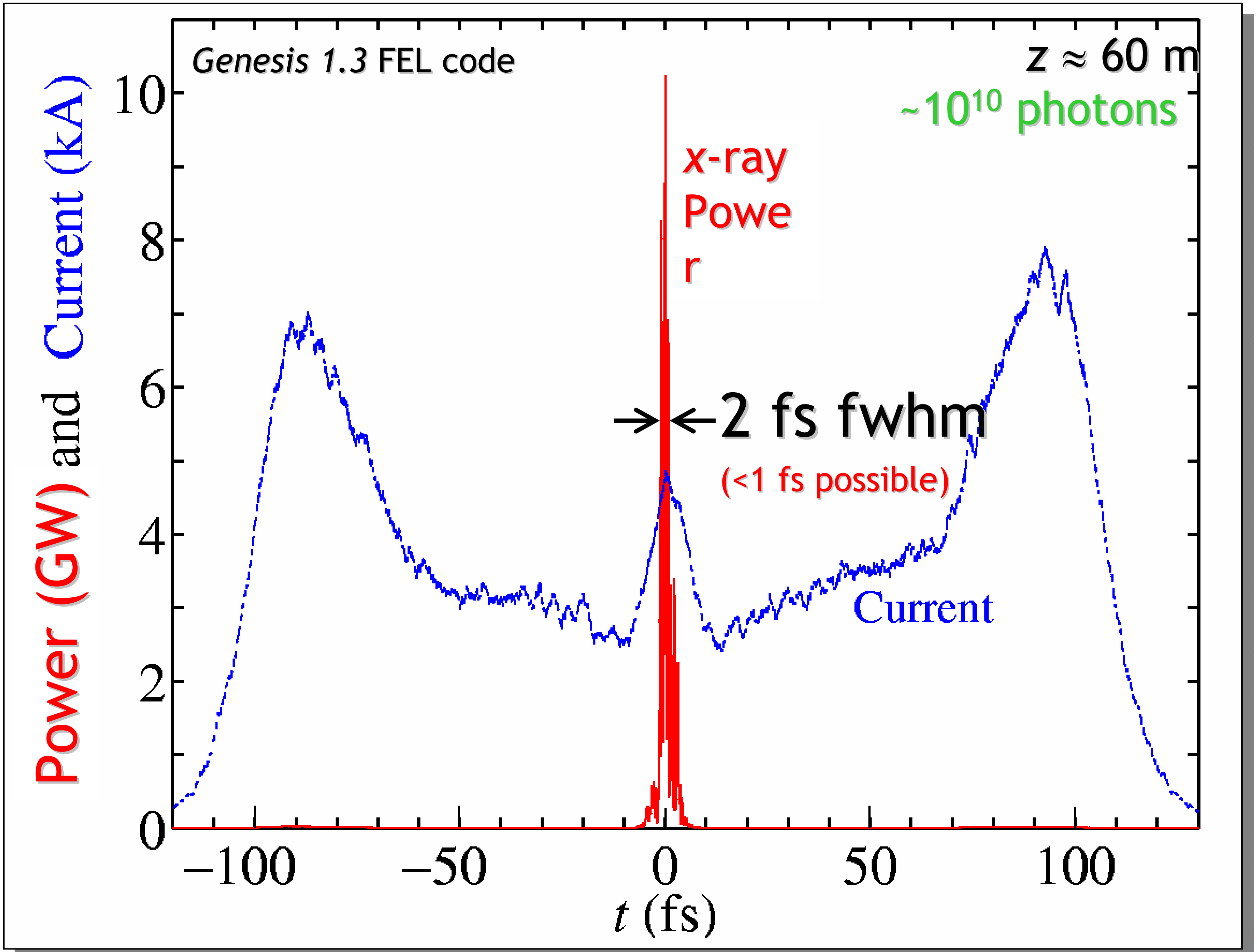
LCLS BC2 bunch compressor chicane
(similar in other machines)

Add thin slotted foil in center of chicane

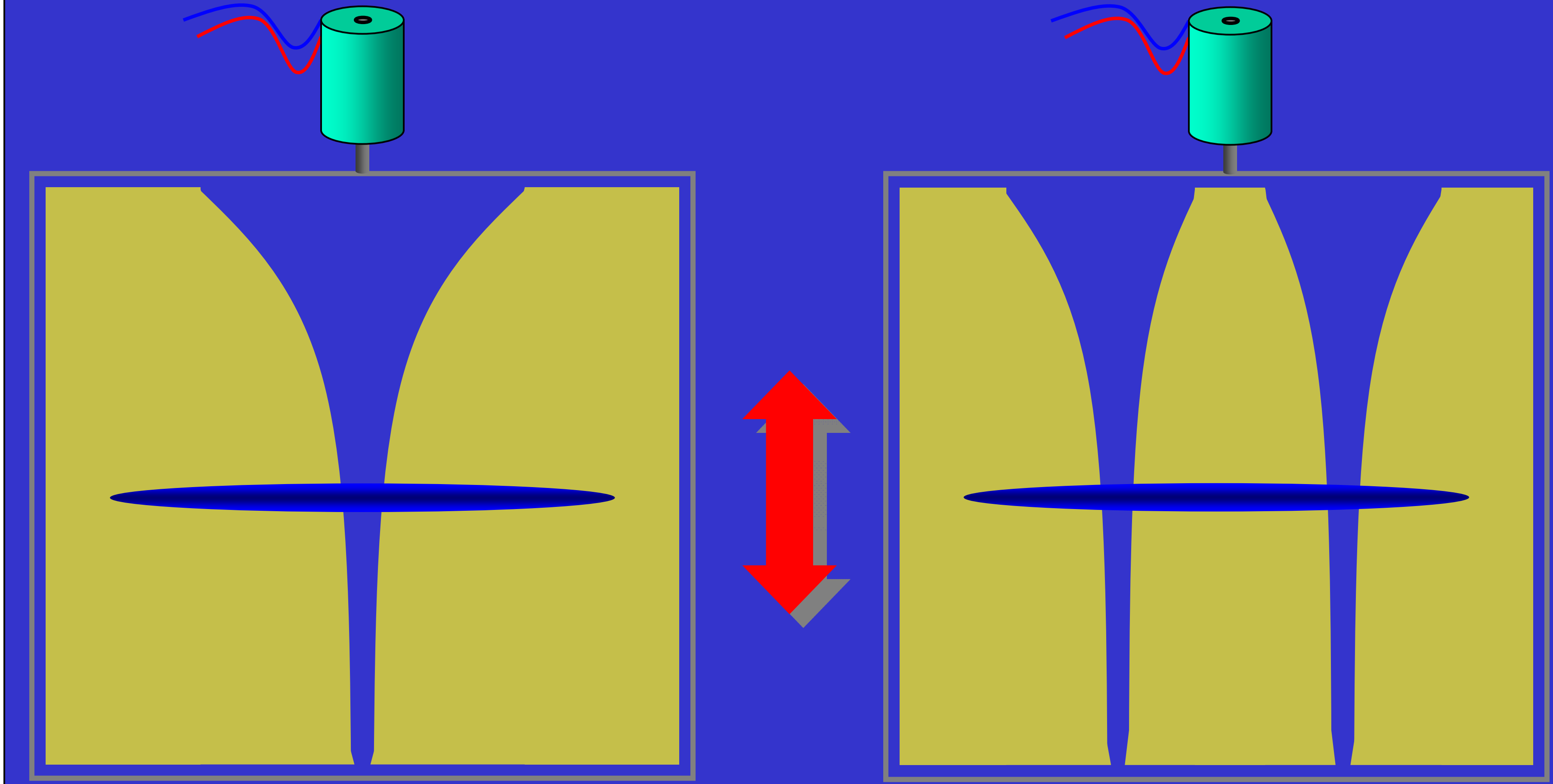


PRL **92**, 074801 (2004).

P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)


Genesis 1.3 FEL code
z ≈ 60 m
~10^10 photons
x-ray Power
2 fs fwhm
(<1 fs possible)
Current
Power (GW) and Current (kA)
0
2
4
6
8
10
−100
−50
0
50
100
t (fs)

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

Unique aspects

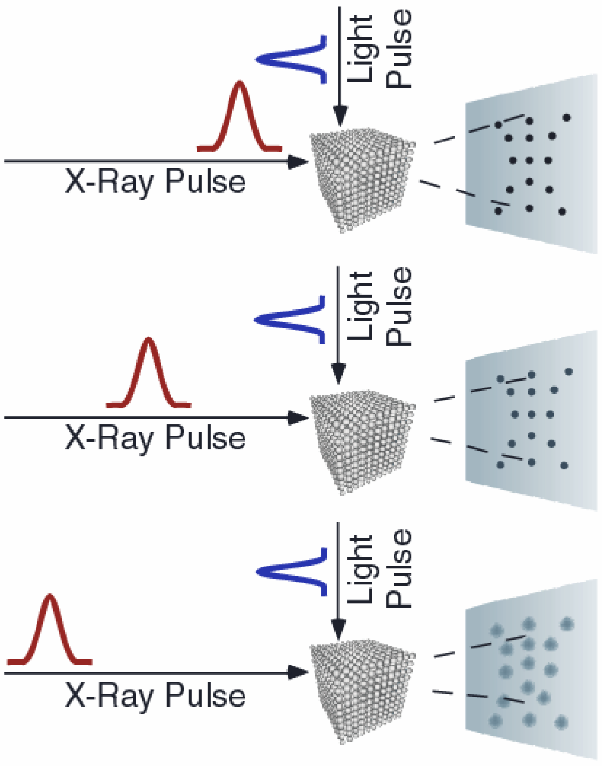
- High peak power
- High coherence
- Short pulse duration

Challenges

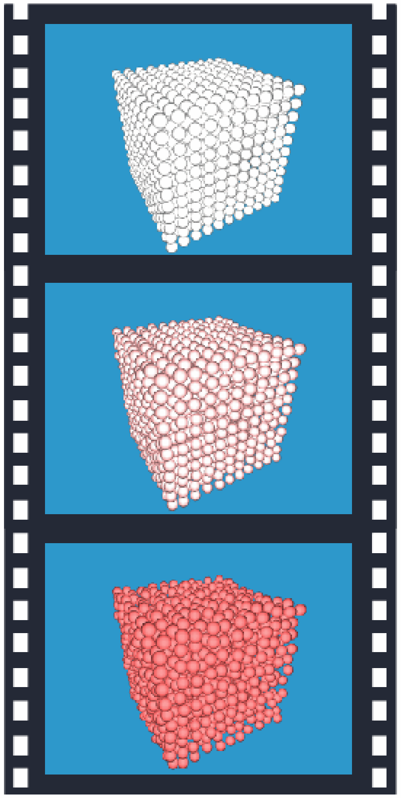
- Synchronization to femtoseconds
- Handling high intensity x-rays
- Large fluctuations

Synchronization is essential for viewing femtosecond dynamics: Pump-Probe Spectroscopy

Pump-probe experiments require good synchronization

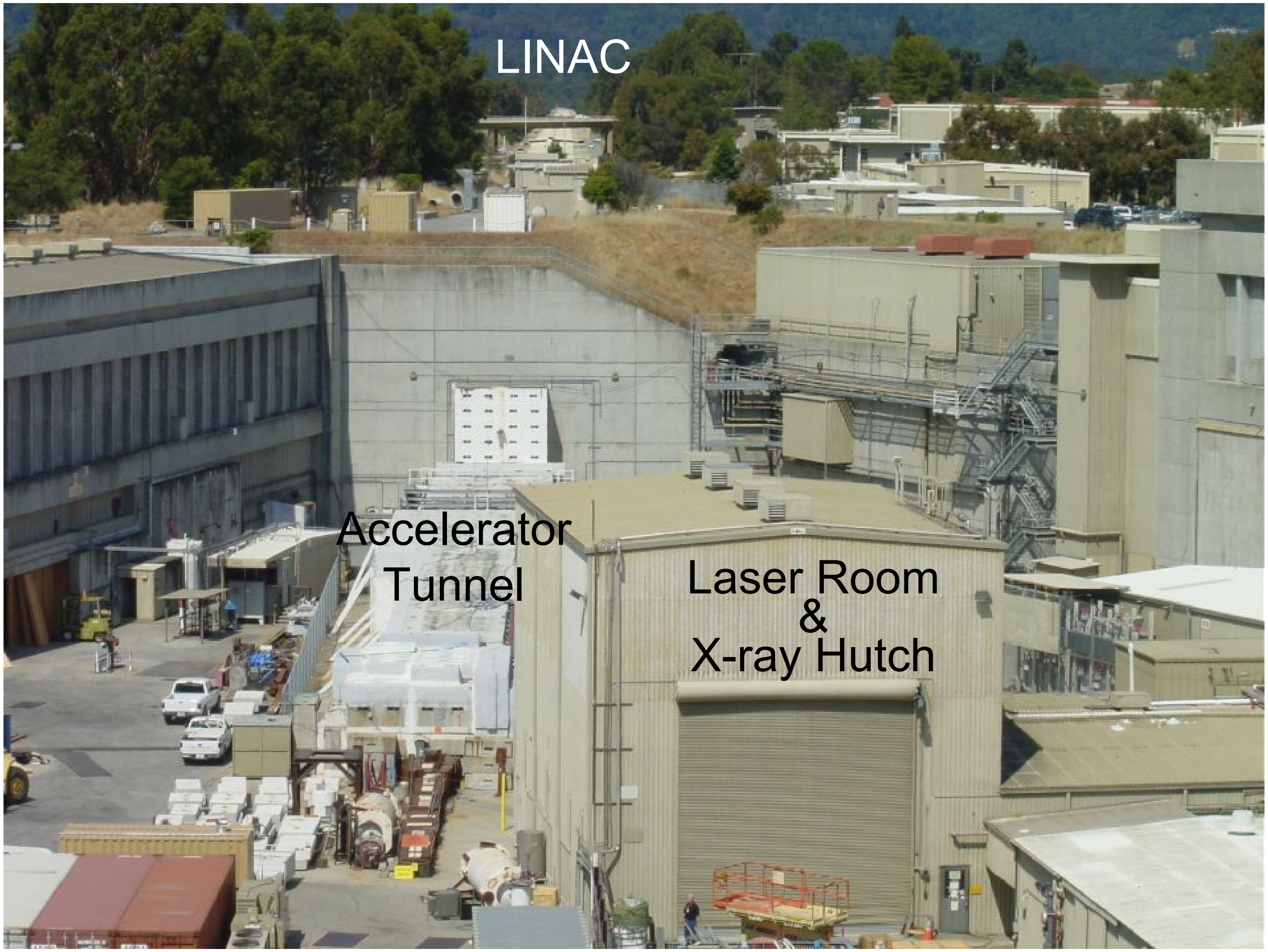


Movie of Atomic Movement



Stuff moves
in
0.01-10 ps

SPPS Facility



100 fs synchronization is equivalent to controlling the arrival of the electron bunch to 1 part in 100 million of its total travel.

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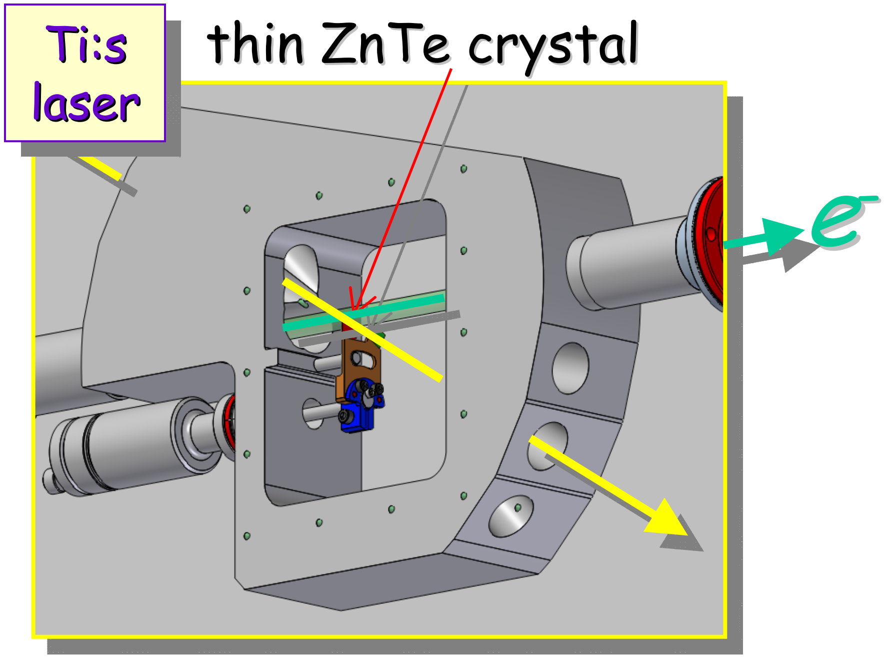
Electro-optic measurement of the compressed pulse



Ti:s laser

thin ZnTe crystal

e^-

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

A. Cavalieri, et al., PRL in press

Undulator,
View upstream

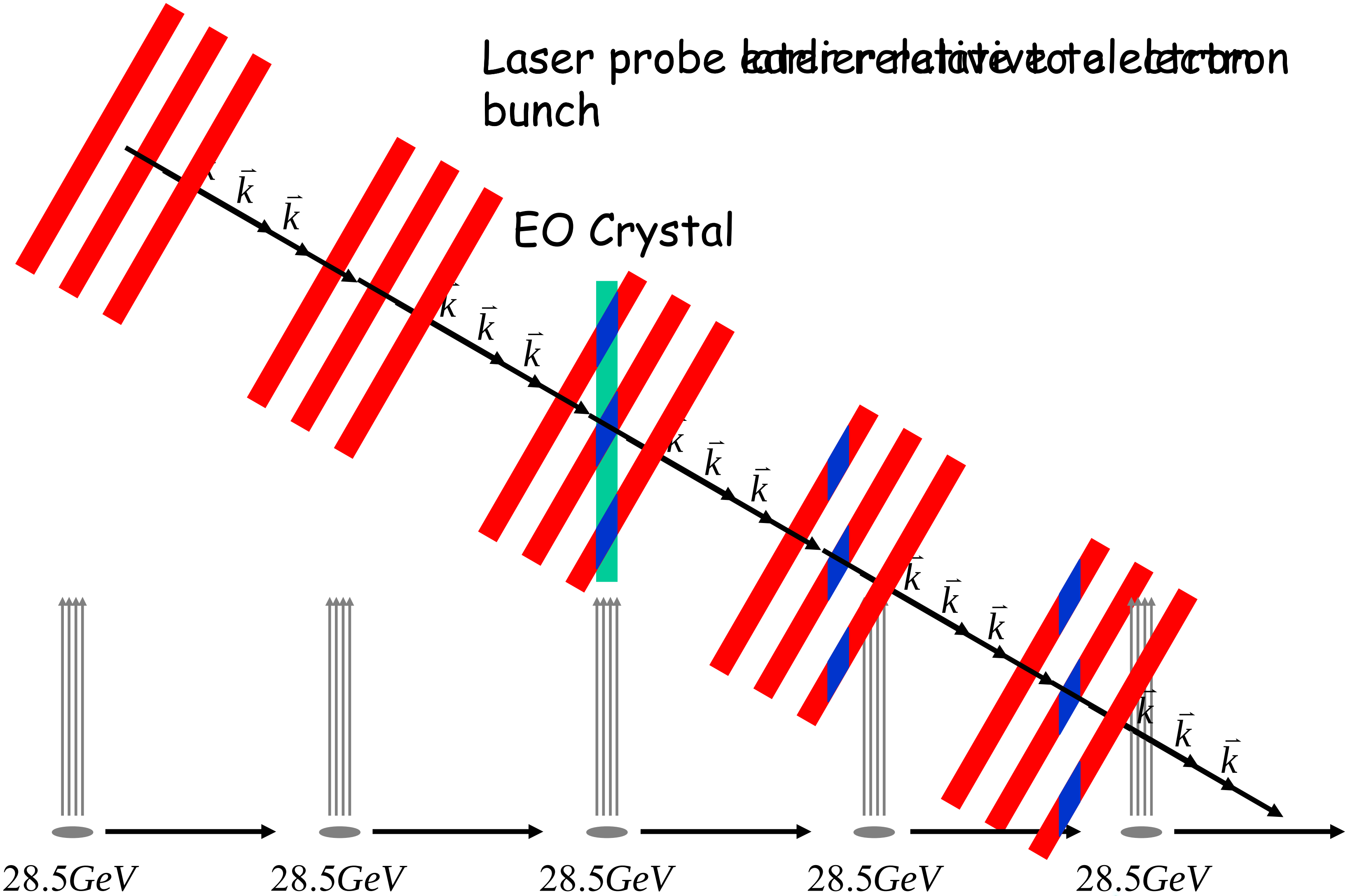
Dave Fritz, Soo Lee, David Reis

The Movie:

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

Adrian Cavalieri, et al.

Spatially Resolved Electro-Optic Sampling (EOS)

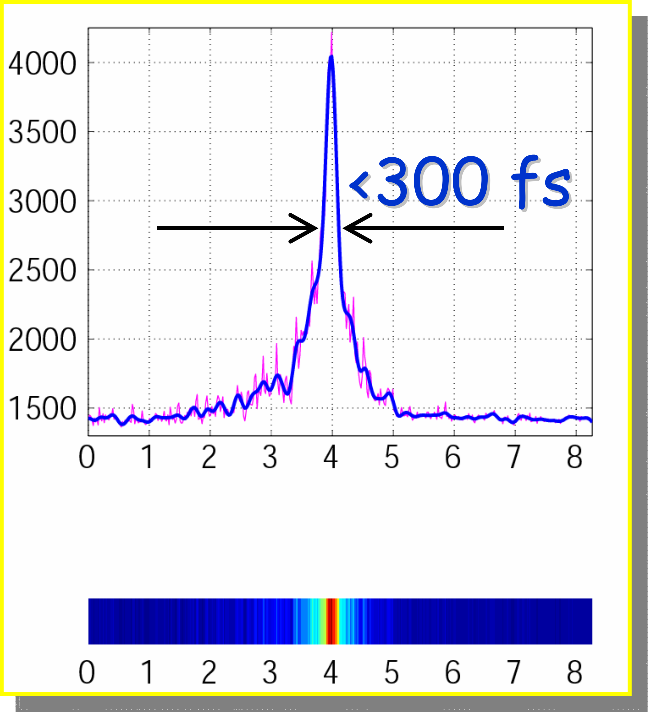


Laser probe earlier relative to electron bunch

later relative to electron

Measurements of the electron bunch

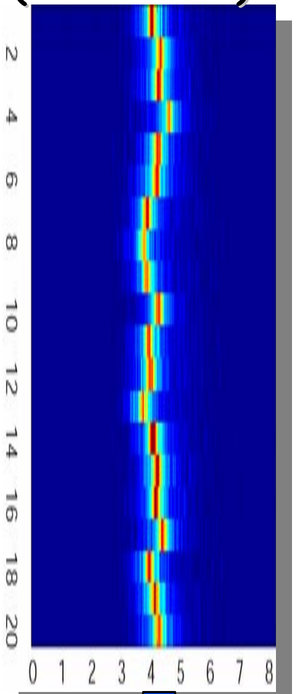
Single-Shot

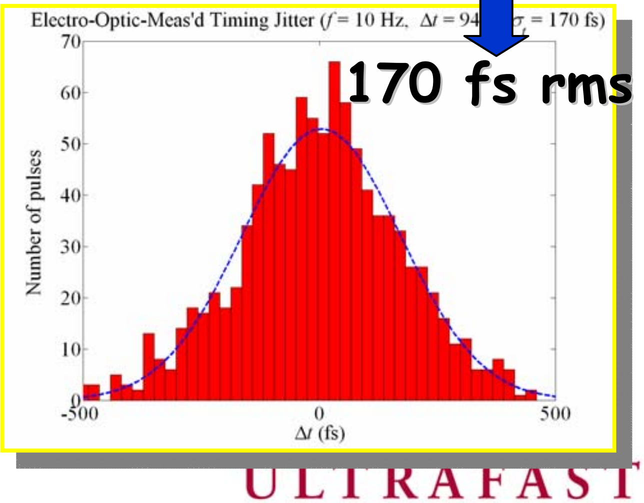


<300 fs

Timing Jitter

(20 Shots)

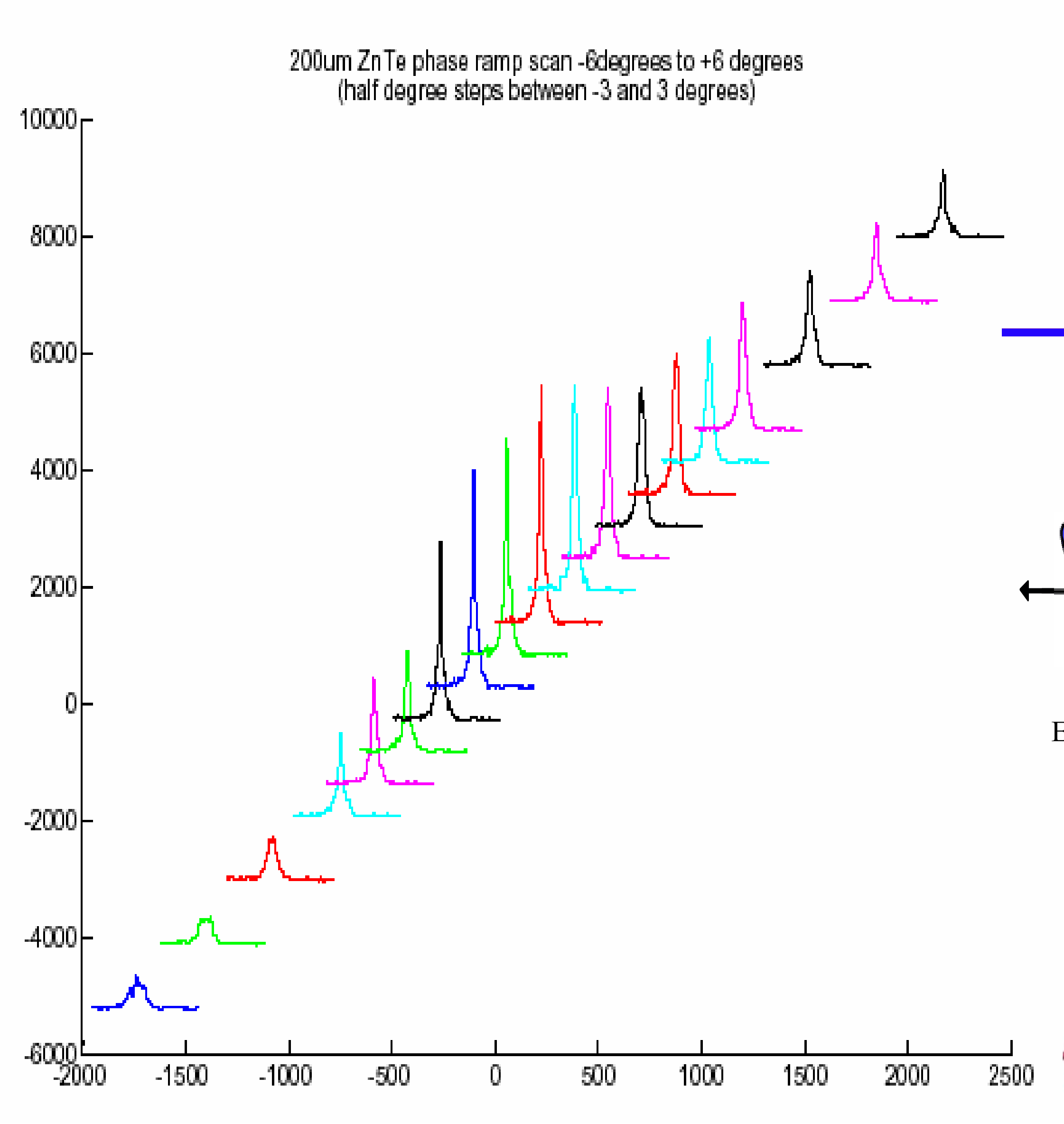




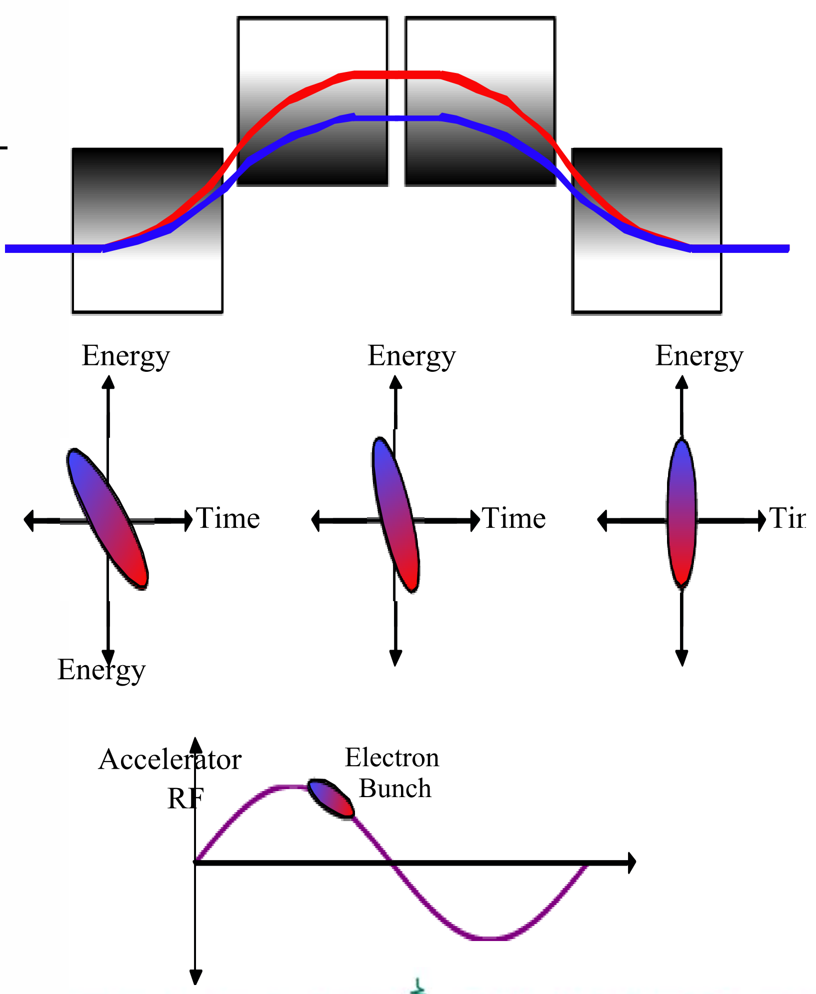
170 fs rms

A. Cavalieri et al.,
Phys. Rev. Lett. (2005)

Pulse broadening off optimum phase in compressor



Magnetic Chicane



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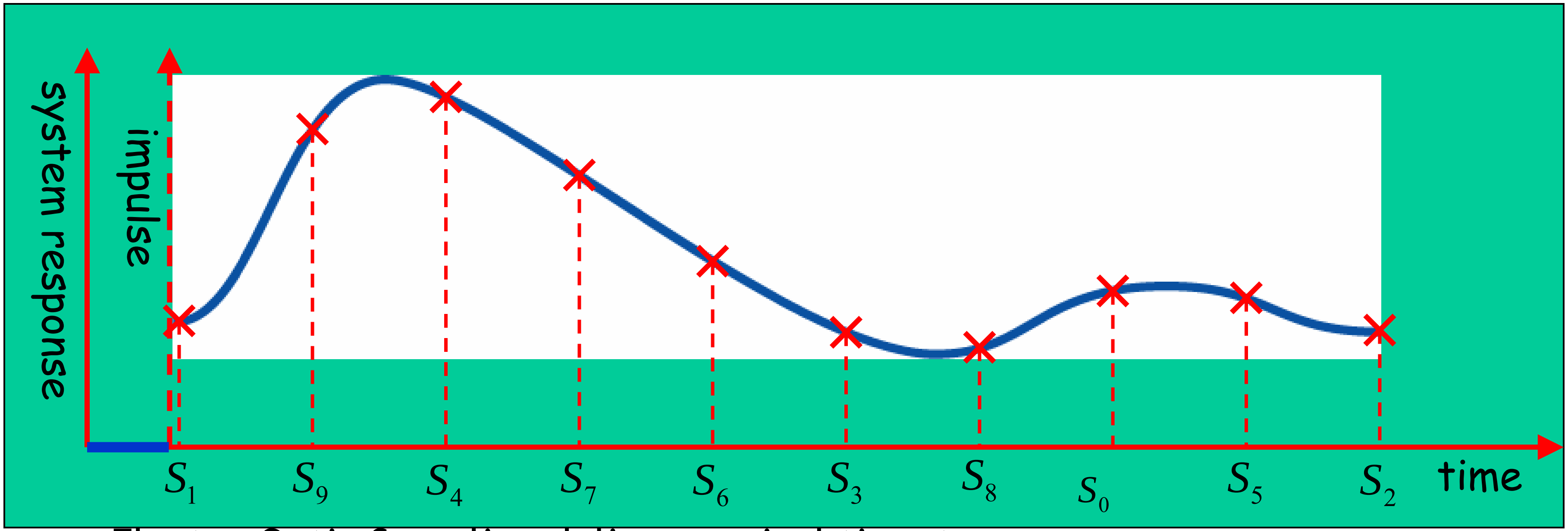
Synchronization: Use sampling method:

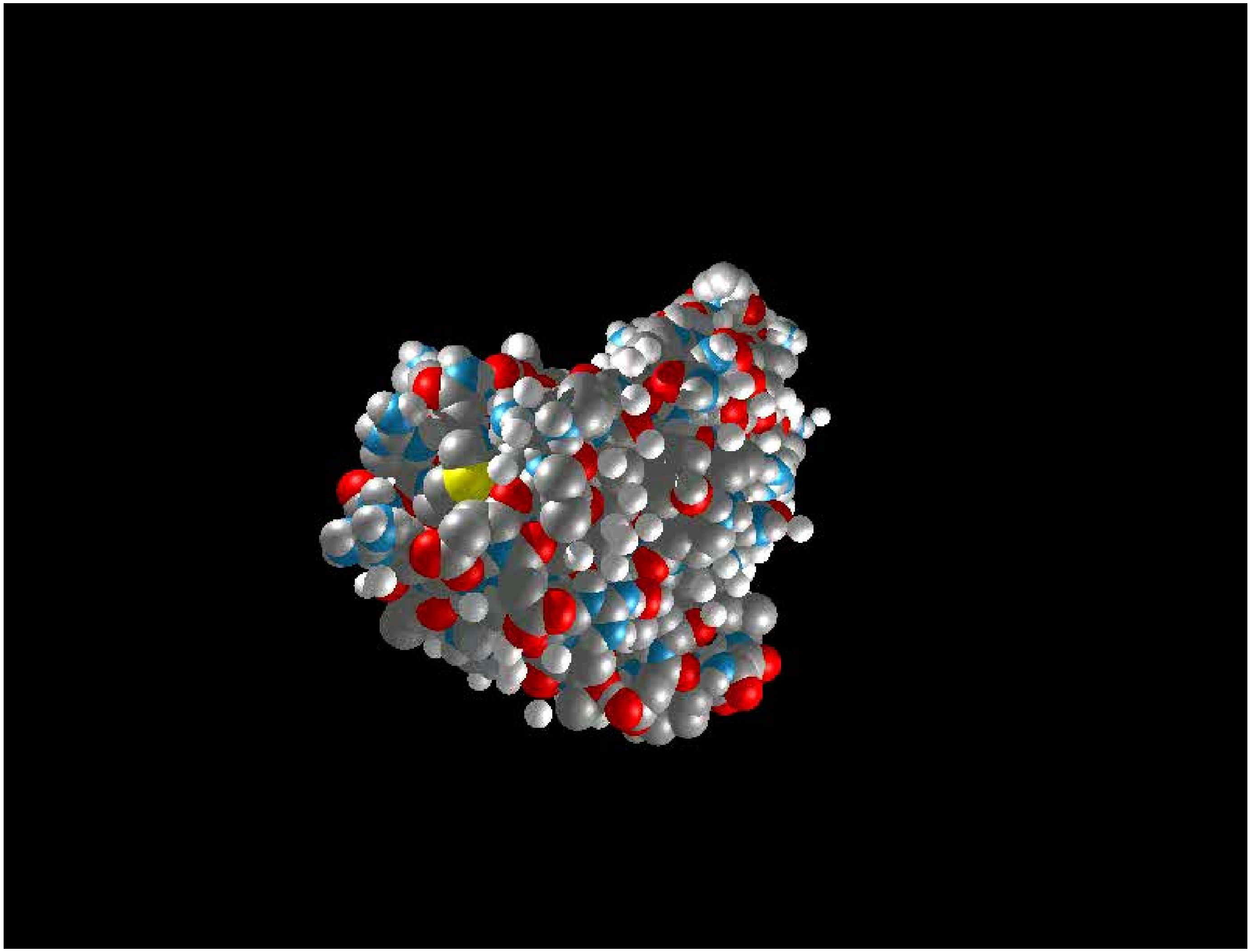
Typical time resolved experiment utilizes intrinsic synchronization between pump excitation and probe



- Electro-Optic Sampling delivers arrival time to users
  - Pump-Probe experiments now possible
  - Machine jitter exploited to sample time-dependent phenomena

ULTRAFAST STANFORD

High power simulation of exploding T4 Lysozyme

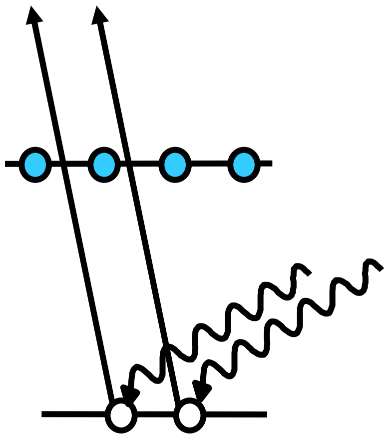


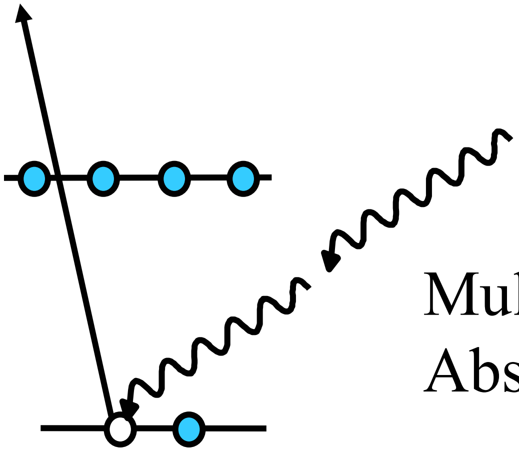
1×10^{11}W/cm^2 irradiation for 200 fs by LCLS pulse in 1mm spot (unfocused)

ULTRAFAST STANFORD

New fundamental processes observable at LCLS

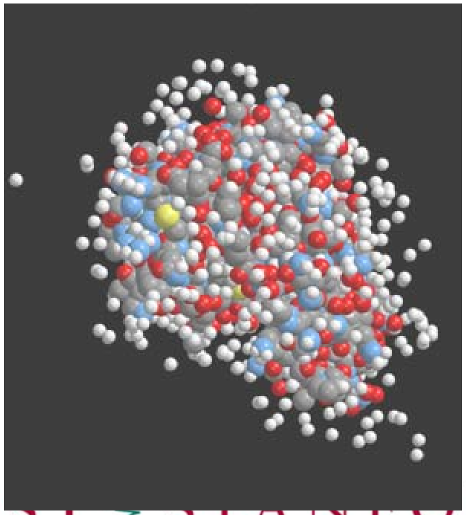
Multiple ionization beats relaxation:
Hollow atoms





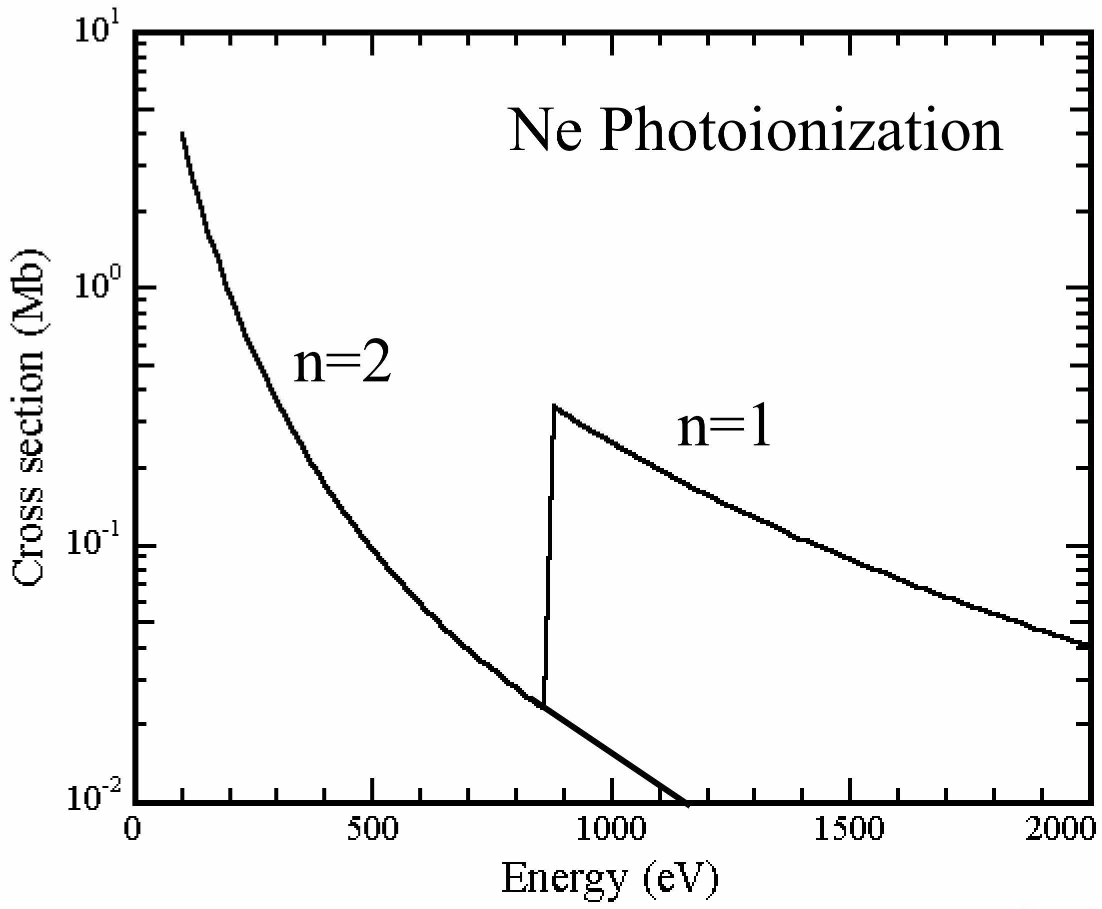
Multiphoton ionization:
Absorption below the edge

Giant Coulomb explosions
of clusters

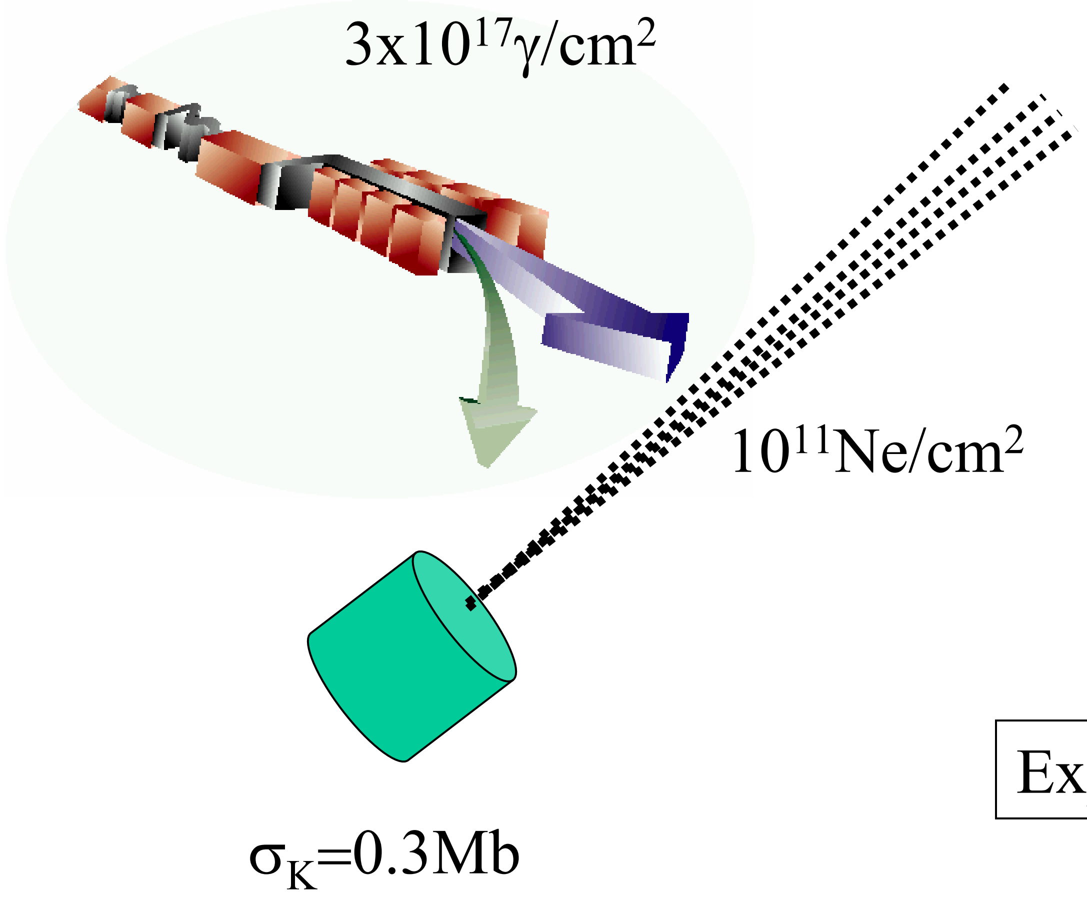


Experiment 1: Multiple Core Vacancy Formation (MCVF)

Inner shell ionization dominates.



Model Parameters

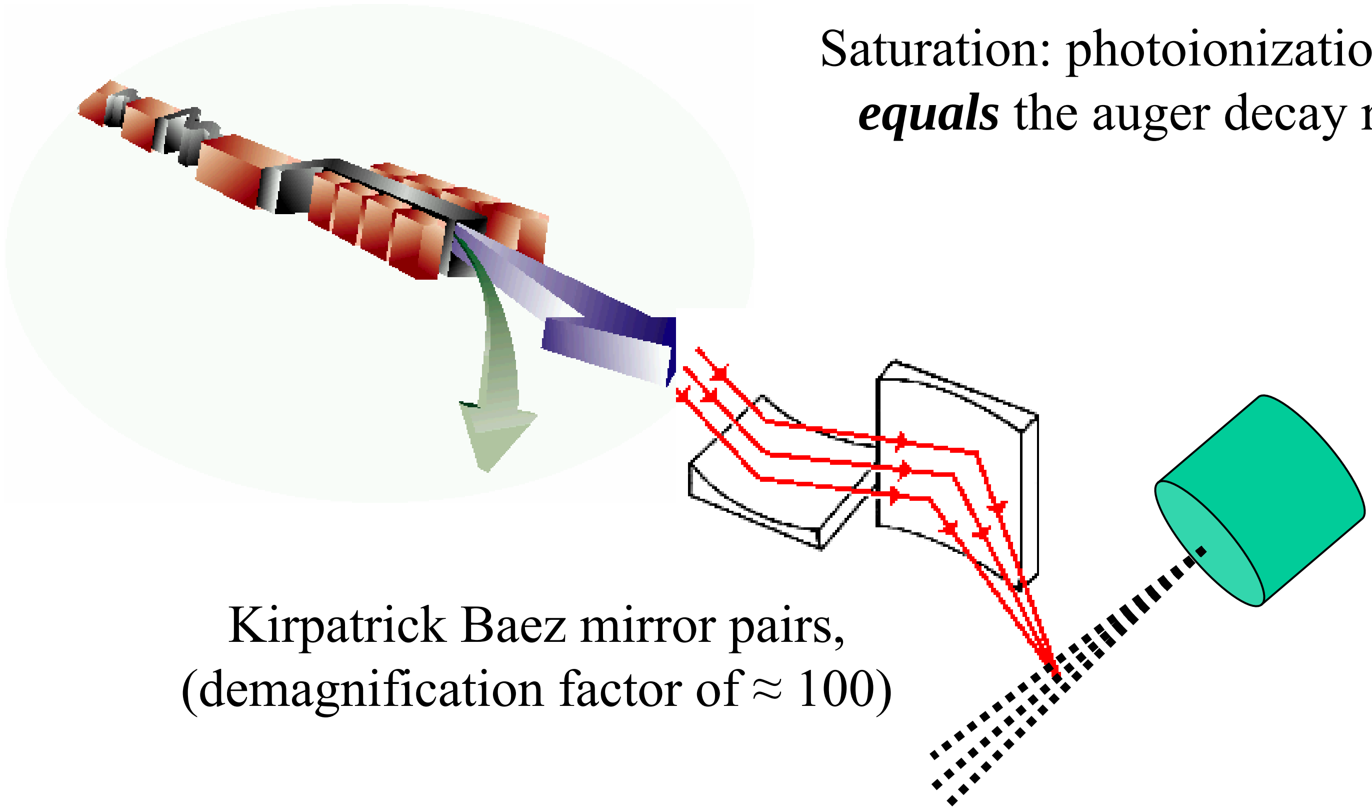


Ionization: $\Gamma = 10^{12} s^{-1}$

Auger: $\Gamma = 4 \times 10^{14} s^{-1}$

Expect: 75 MCVF/pulse

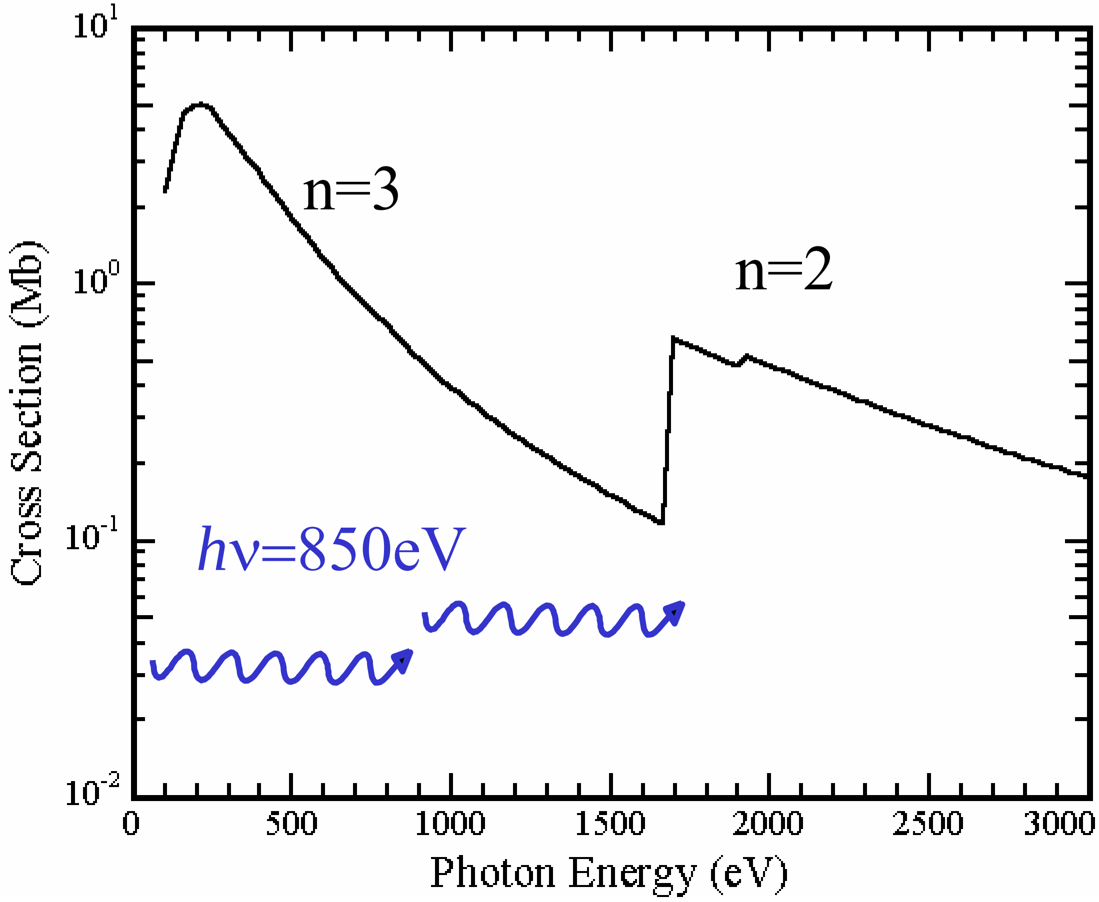
Focused Beam Experiments



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

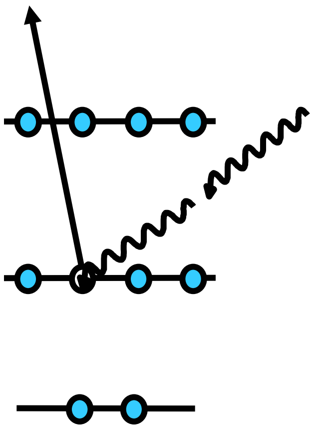
Kirpatrick Baez mirror pairs,
(demagnification factor of ≈ 100)

2-photon absorption in Kr



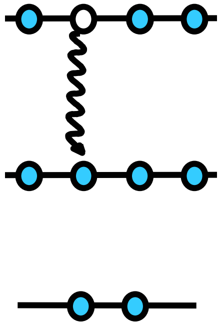
2-Photon Absorption-- Detecting Events:

$Kr + 2\gamma(>850eV)$
$\rightarrow Kr^{+*}(L) + e$

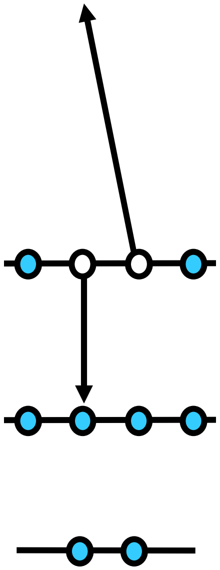


Clean detection signature: 1.5keV particles

$\rightarrow Kr^{+*}(M)$
$+\gamma(1.5\text{keV})$



$\rightarrow Kr^{+*}(MM)$
$+ \text{e}(1.5\text{keV})$



2-Photon Rate (unfocused)

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

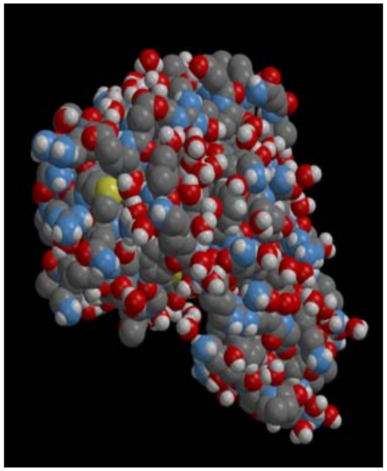
$\Gamma_{2\gamma} = \sigma_{2\gamma} I^{2} = (10^{-53}\mathrm{cm}^{4}\mathrm{s})(10^{31}\gamma/\mathrm{cm}^{2}\mathrm{s})^{2} = 10^{8}\mathrm{s}^{-1}$

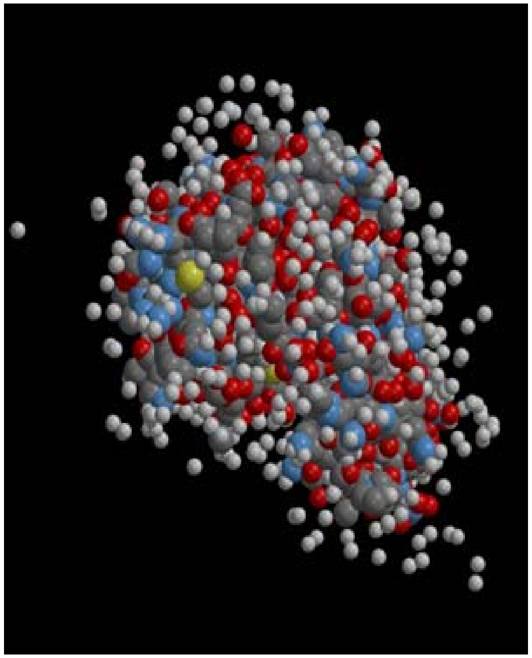
$2\mathrm{x}10^{-5}$ two-photon absorptions per atom

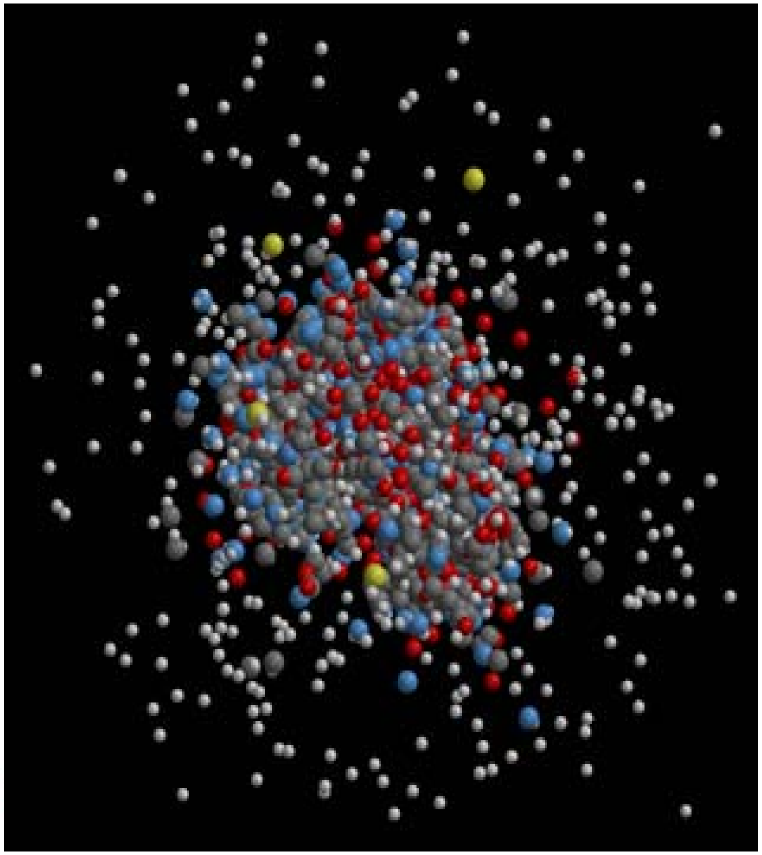
$2\mathrm{x}10^{6}$ events per pulse

Event rate could be a good beam intensity diagnostic

Experiment 3: Giant Coulomb Explosions







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.

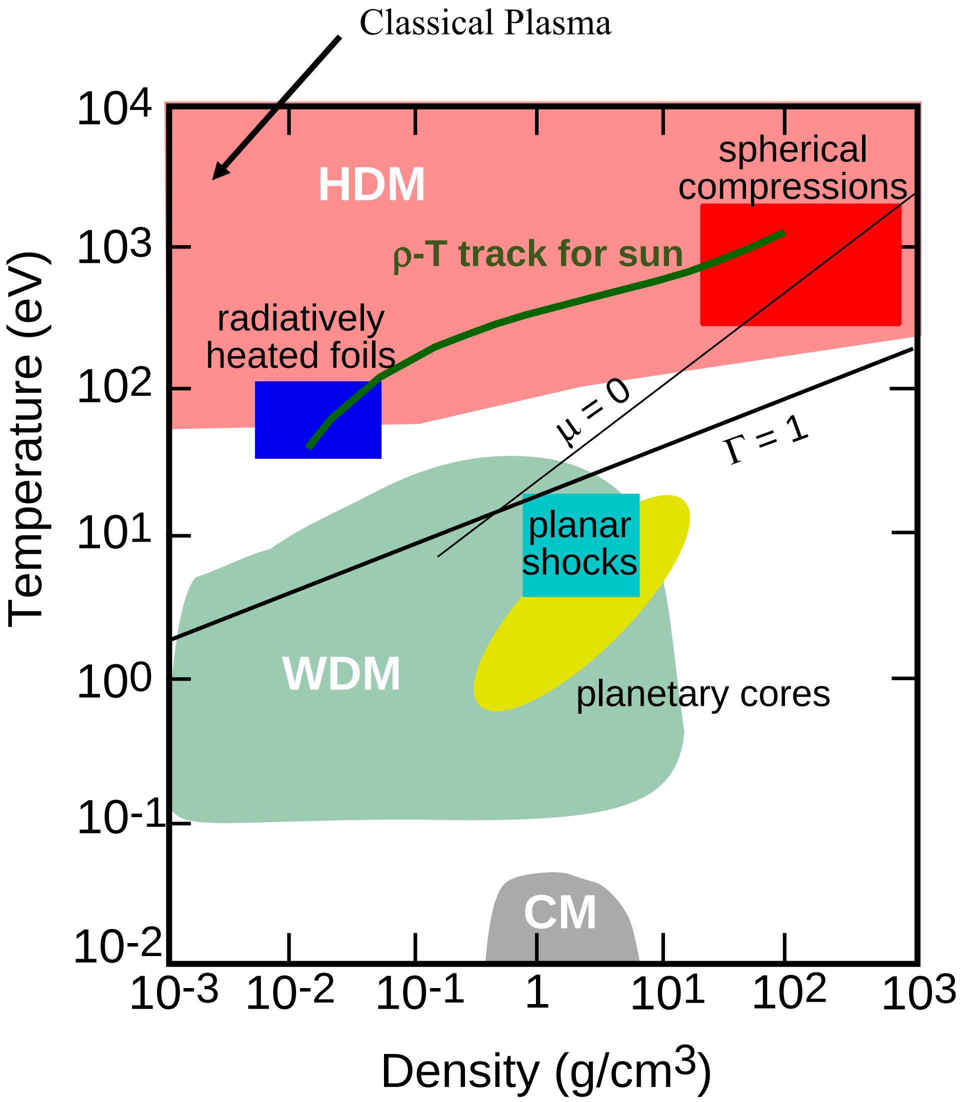
Focused explosions

- 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).

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



WDM and HDM are emerging, largely unchartered fields

Why so difficult to calculate make and probe?

Few theories even capable of making predictions

- Interaction energy between particles is greater than thermal energy
- Regime is too dense and cold for plasma theories
- Regime is too warm for condensed matter theories

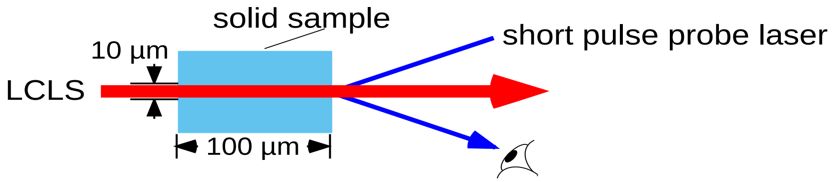
Experiments difficult due to rapid time evolution and spatial gradients

Laser based experiments limited by lack of plasma penetration

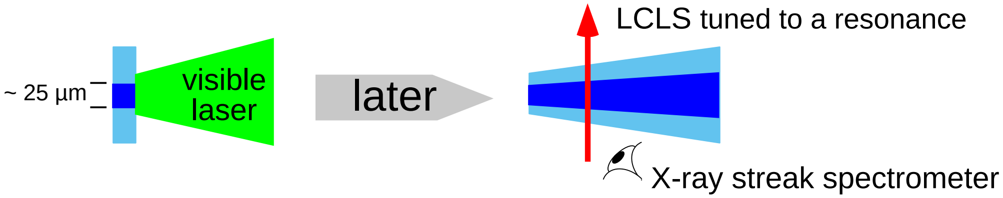
- Use unique properties of LCLS to overcome difficulties

Highlight of Three Experiments with LCLS

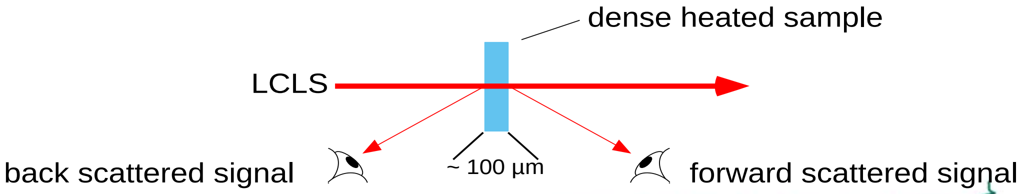
- **Creating WDM**
  - **Generate ≤10 eV solid density matter**
  - **Measure the fundamental nature of the matter via equation of state**



- **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**



ULTRAFAST STANFORD

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

Free Electron Lasers and Other Advanced Sources of Light:
Scientific Research Opportunities
National Research Council (1994)
http://www.nap.edu/catalog/9182.html

Status of FEL Physics Research Worldwide
Claudio Pellegrini, UCLA April 23, 2002.
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April_2002_Talk_Finals/Pellegrini_Physics_15-Apr-2002.ppt