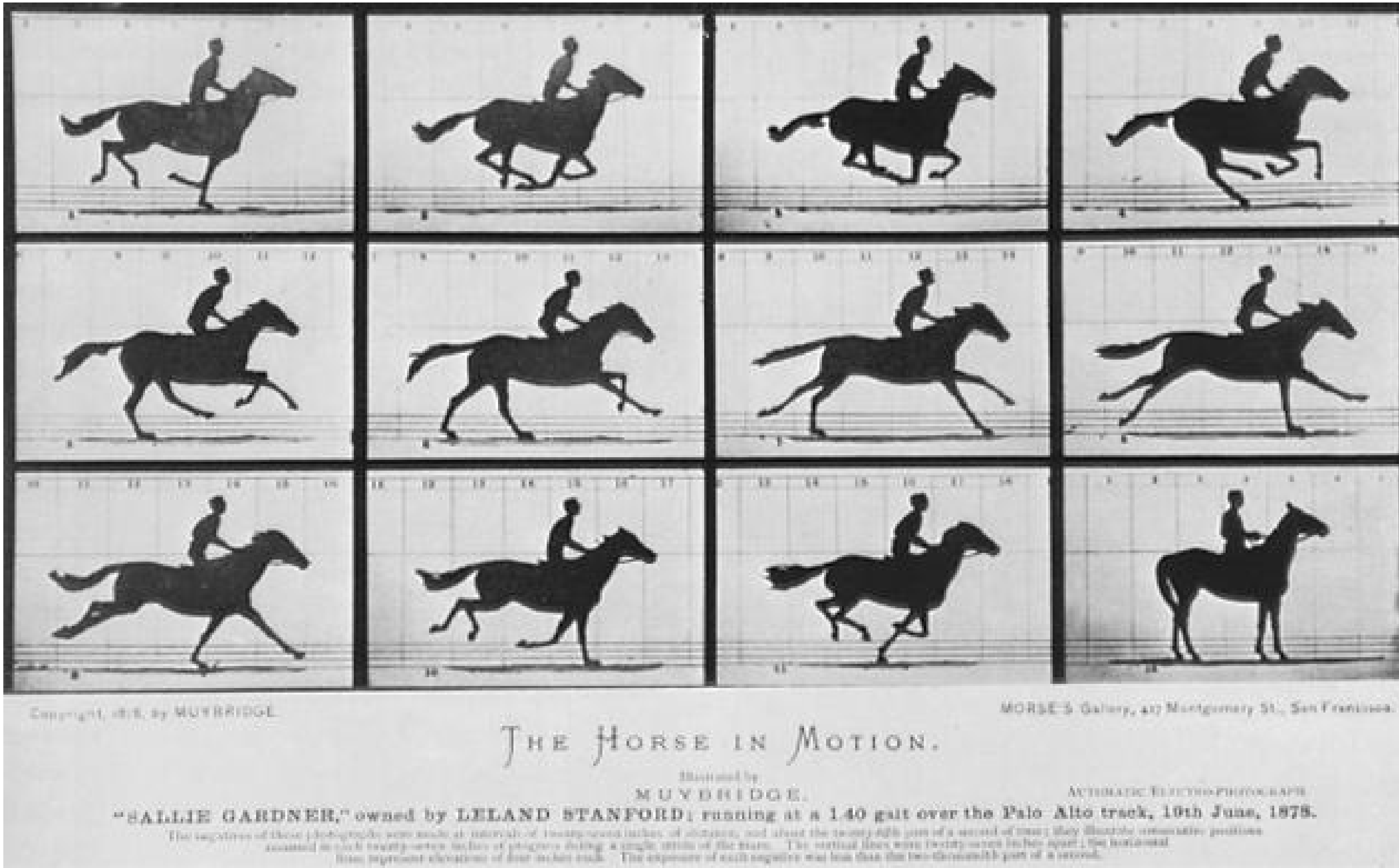
Science with the LCLS

J. B. Hastings

SLAC/SSRL/LUSI

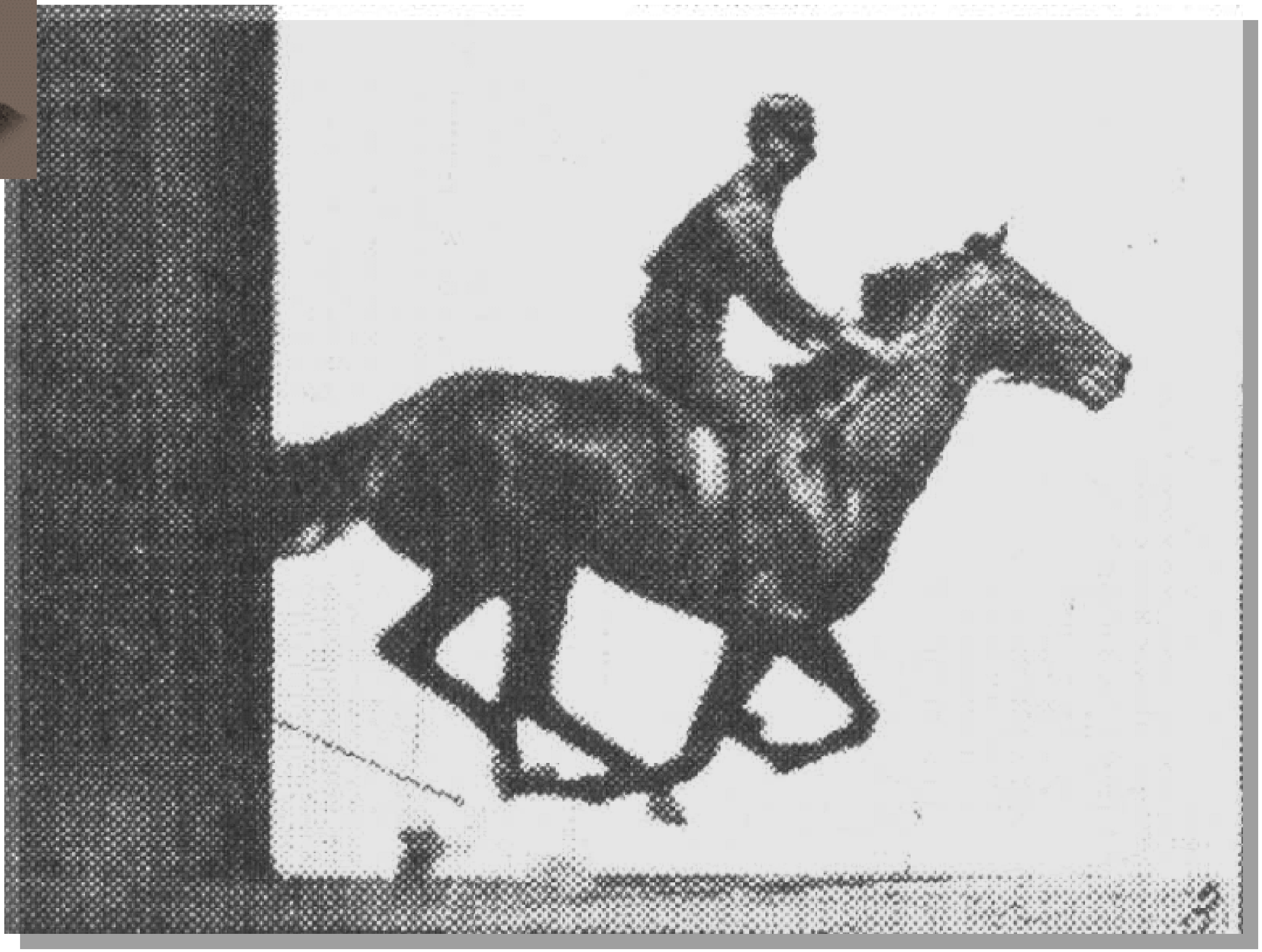


Palo Alto 1878-1879

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

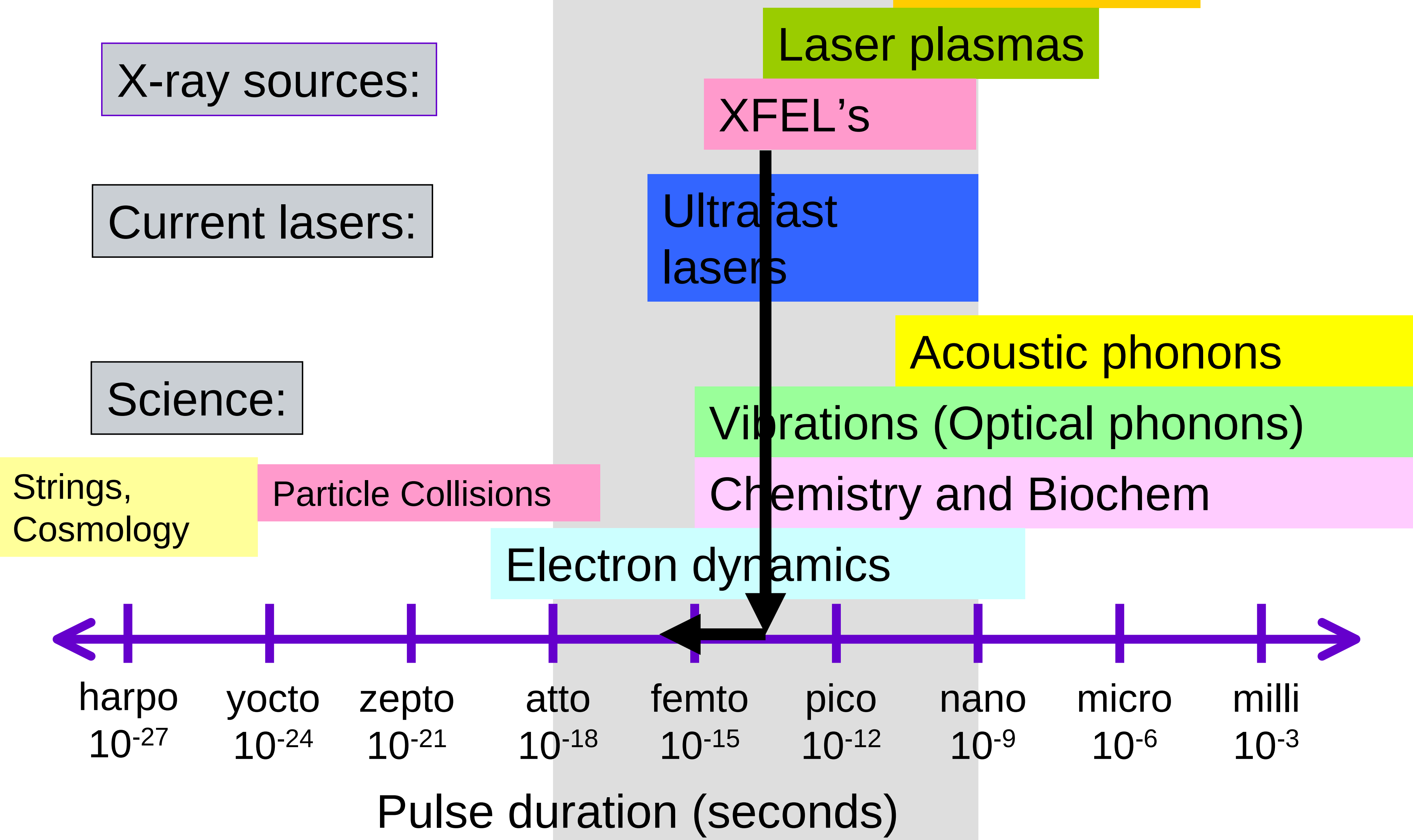
E. Muybridge



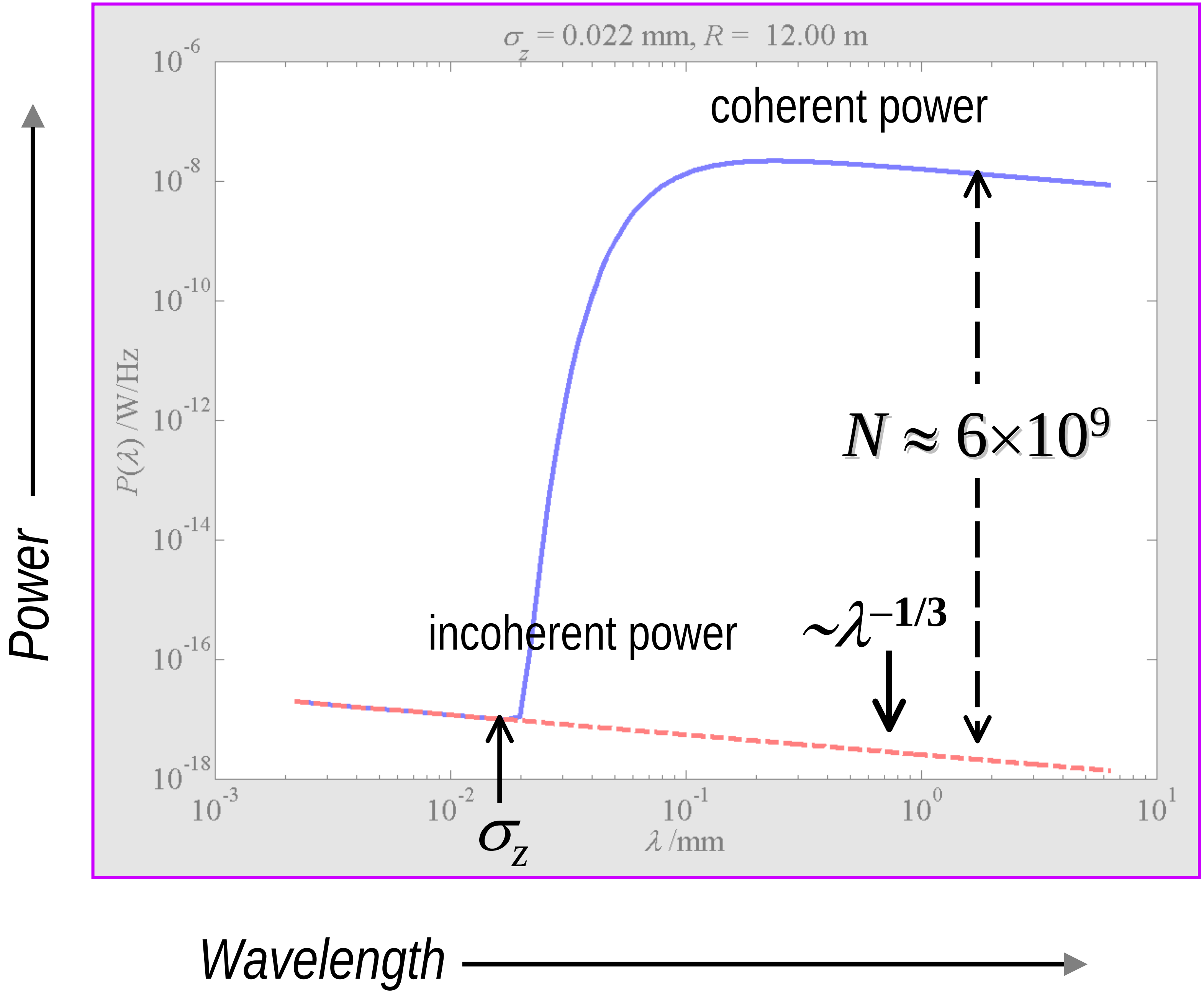
Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

Ultrafast Sources and Science



Stanford Linear Accelerator Center SSRL



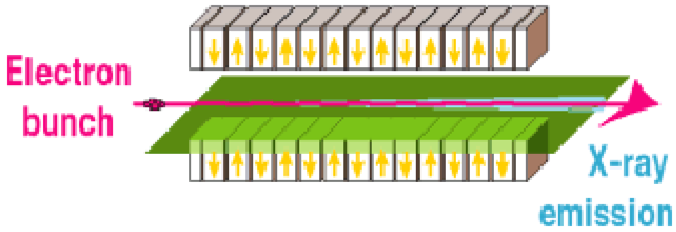
σ_z = 0.022 mm, R = 12.00 m
coherent power
$N \approx 6\times10^9$
incoherent power
$\sim\lambda^{-1/3}$
$P(\lambda)$ /W/Hz
λ /mm
σ_z
Power
Wavelength

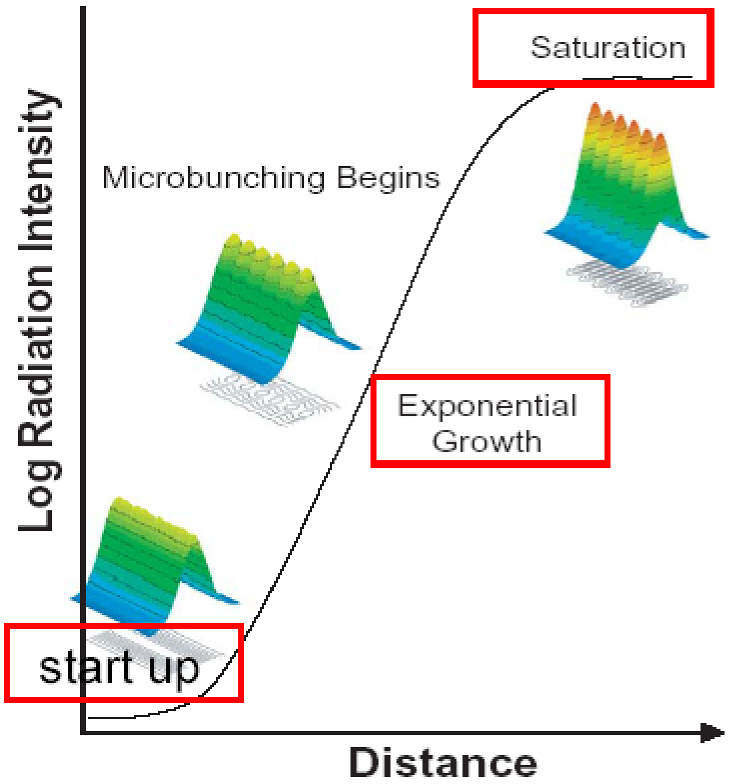
SASE FELs

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

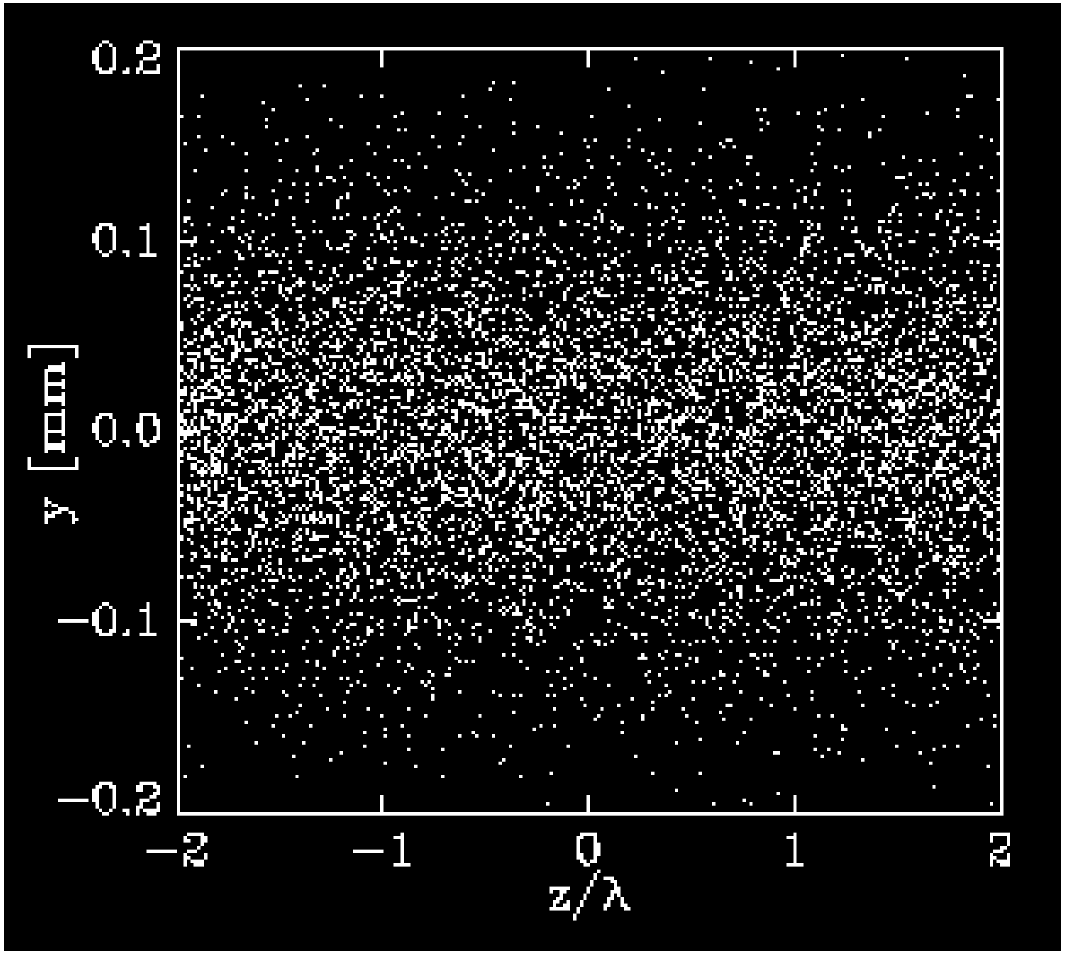
• Energy modulation ➔ density modulation at λ (microbunching) ➔ coherent radiation at λ ➔ exponential growth (L_G)

• At sufficiently high power, electrons fully microbunched with large energy spread ➔ reach saturation (P_{sat})





Microbunching through SASE Process

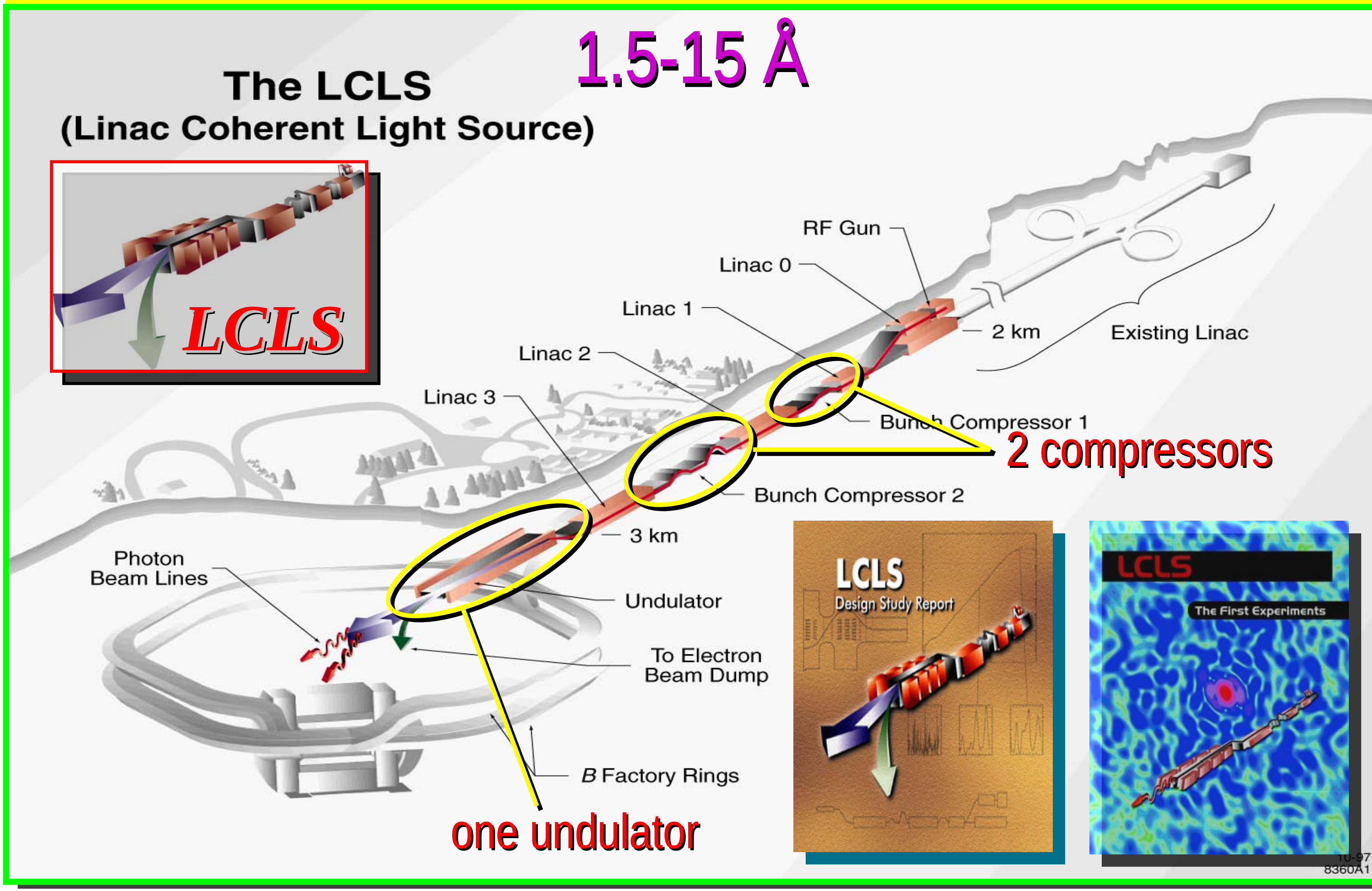


undulator entrance

half-way saturation

full saturation

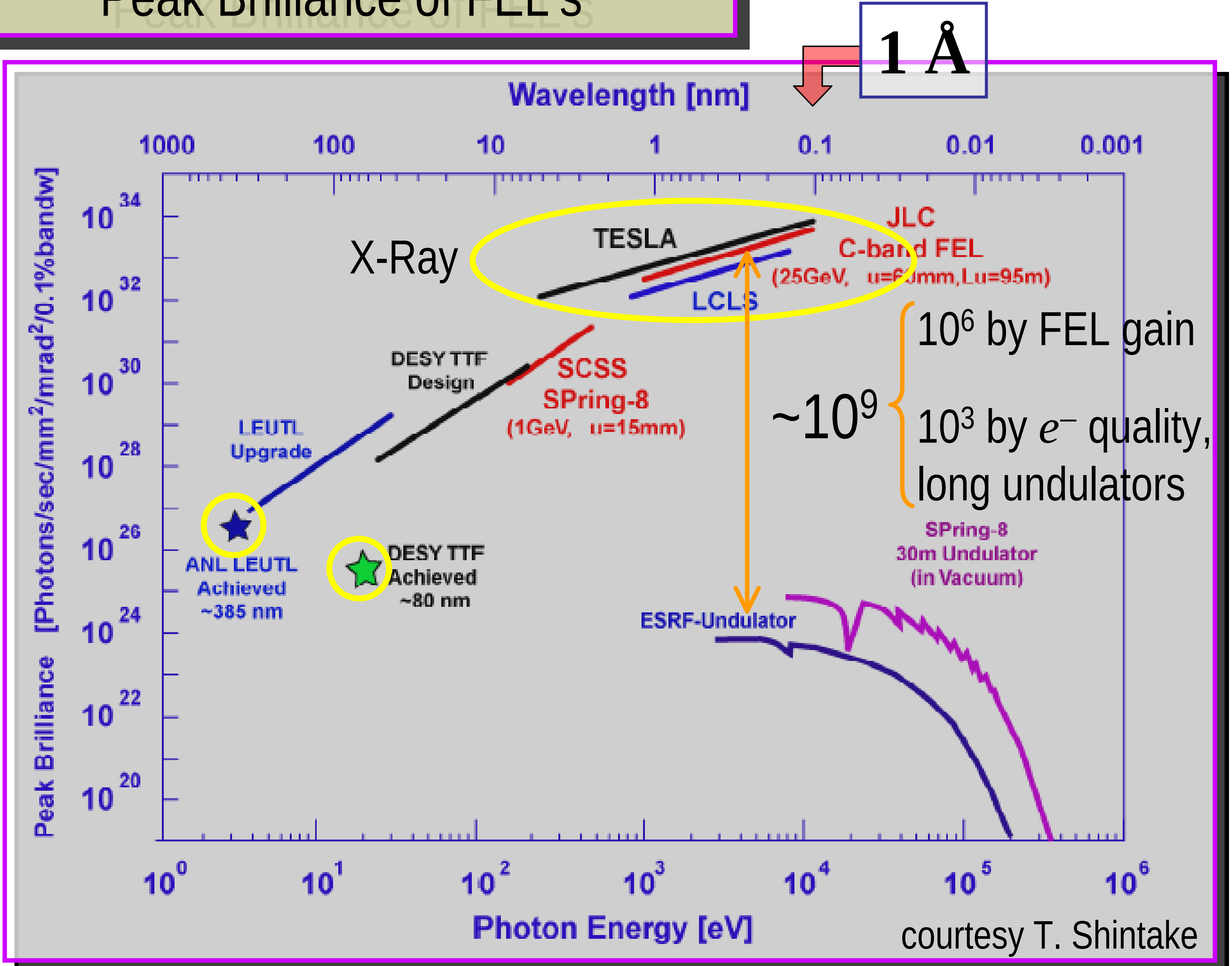
***GENESIS* - simulation for TTF parameters**
Courtesy - Sven Reiche (UCLA)



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

Peak Brilliance of FEL's

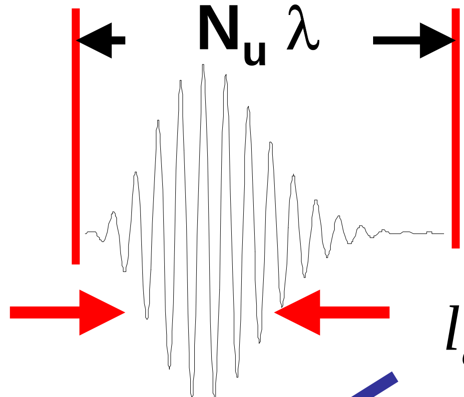
photons per phase-space volume per band-width



Temporal Characteristics

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

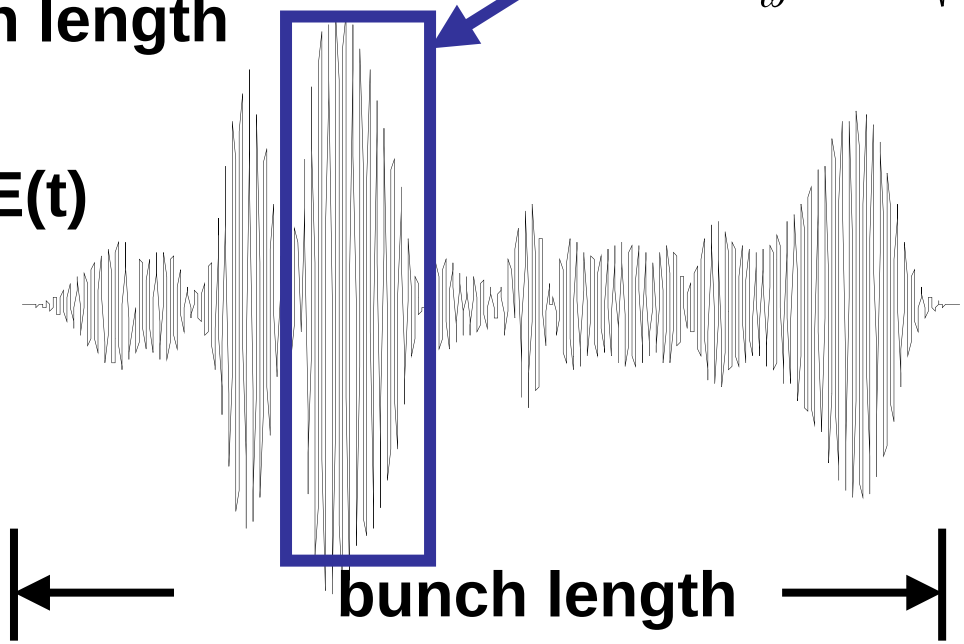
E_0: wave packet of a single e^-



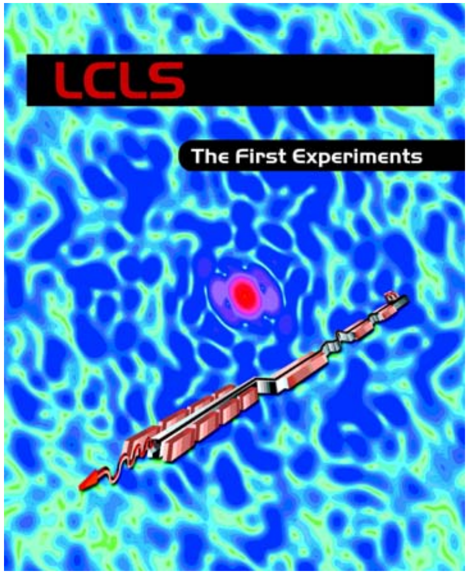
$$l_c \approx \frac{2c}{\sigma_\omega} \approx \frac{\lambda}{\pi}\sqrt{\frac{N_u}{\rho}}$$

- l_c ~ 100-1000 λ < bunch length

- Sum of all packets ➔ E(t)

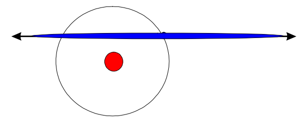


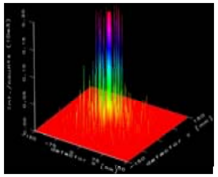
SLAC Report 611

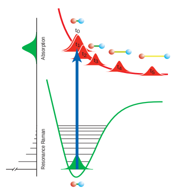


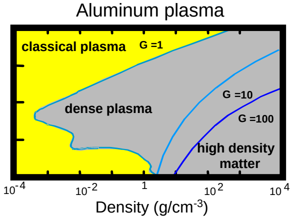
Program developed by international team of scientists working with accelerator and laser physics communities

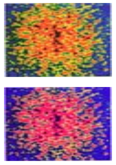
"the beginning.... not the end"











t=τ

t=0

Atomic, molecular and optical science

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

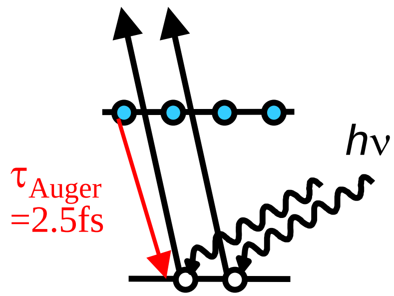
Diffraction studies of stimulated dynamics (pump-probe)

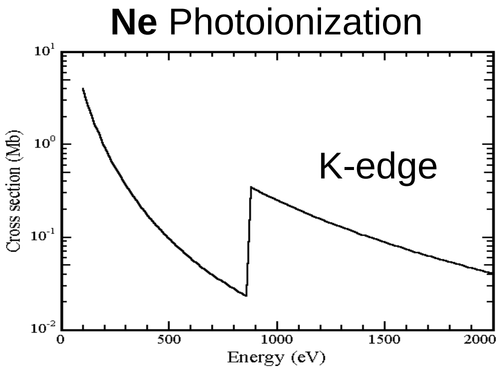
High energy density science

Coherent-scattering studies of nanoscale fluctuations

Focused beam (100nm):

Formation of Hollow Atoms:

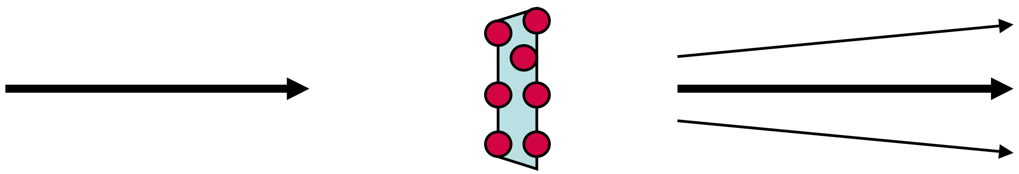


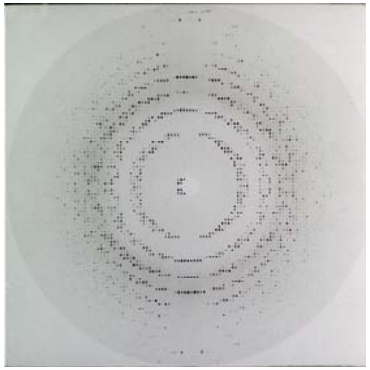


All atoms have multiple core holes per pulse (10^5 atoms)

Structural Studies on Single Particles and Biomolecules

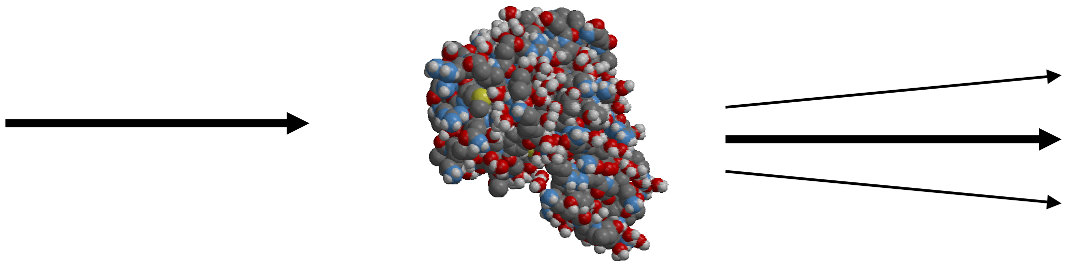
Conventional method: x-ray diffraction from crystal



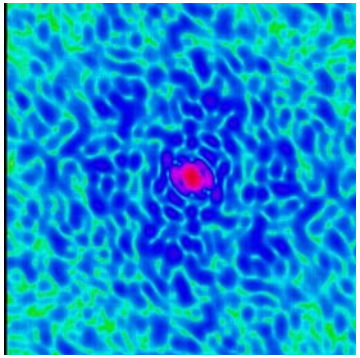


Proposed method: diffuse x-ray scattering from single protein molecule

Neutze, Wouts, van der Spoel, Weckert, Hajdu *Nature* 406, 752-757 (2000)



Lysozyme

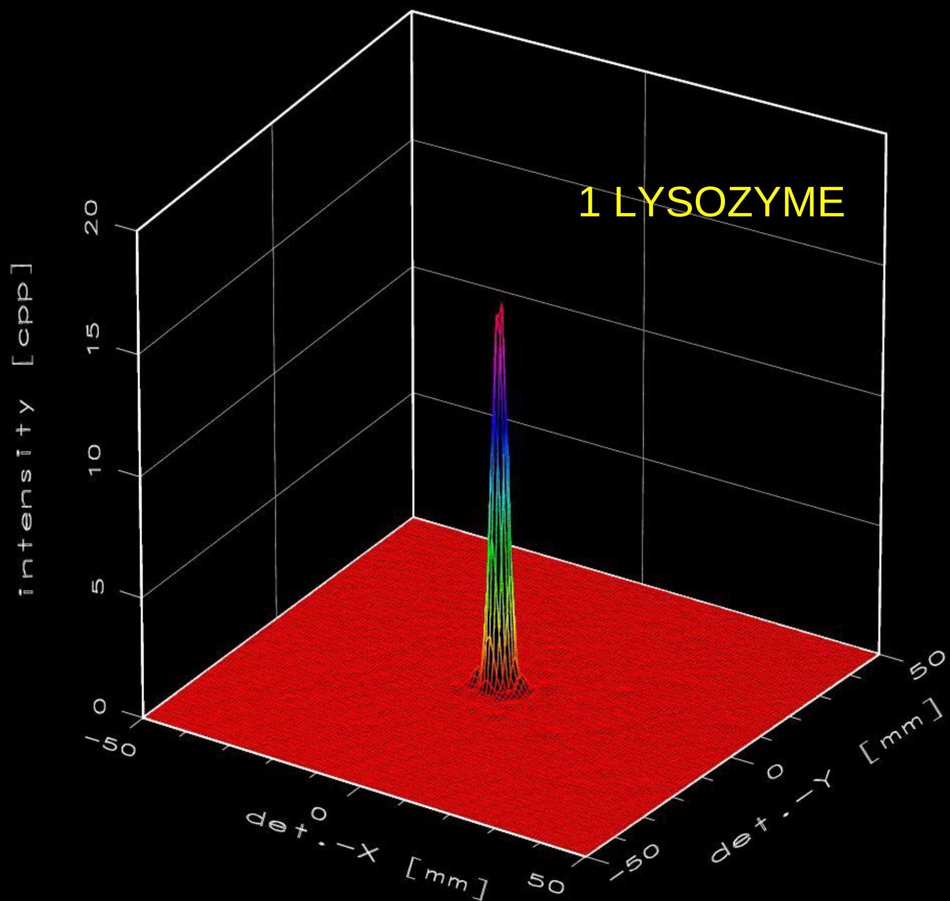


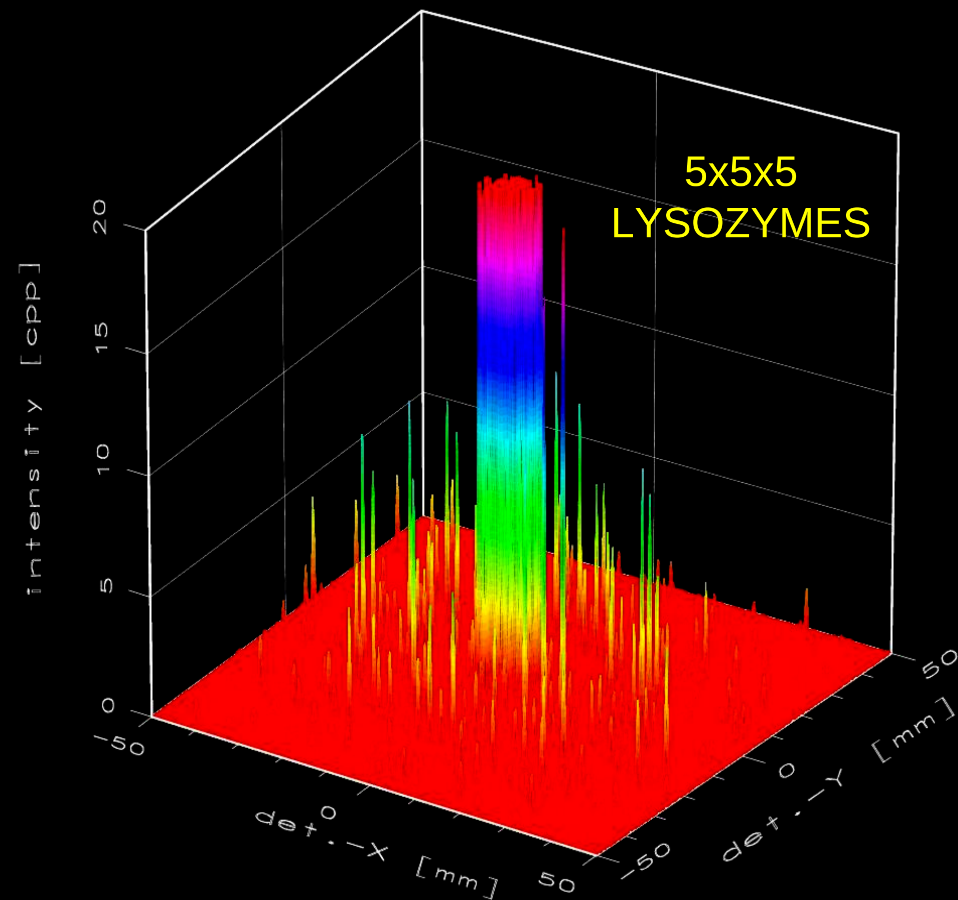
Calculated scattering pattern
from lysozyme molecule

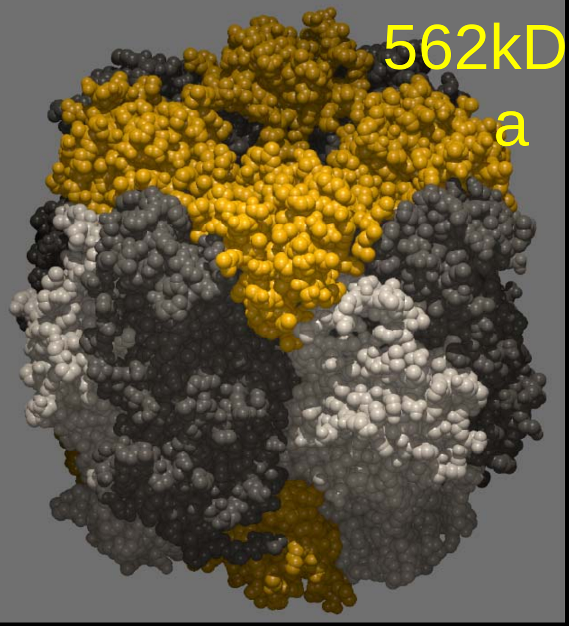
Implementation limited by radiation damage:

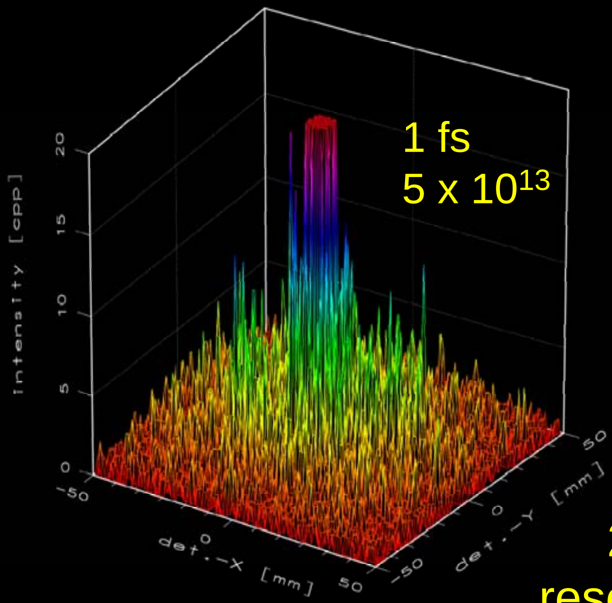
In **crystals** limit to damage tolerance is about **200 x-ray photons/Å^2**
For **single protein molecules** need about **10^{10} x-ray photons/Å^2** (for 2Å resolution)

Nanocrystal of lysozyme

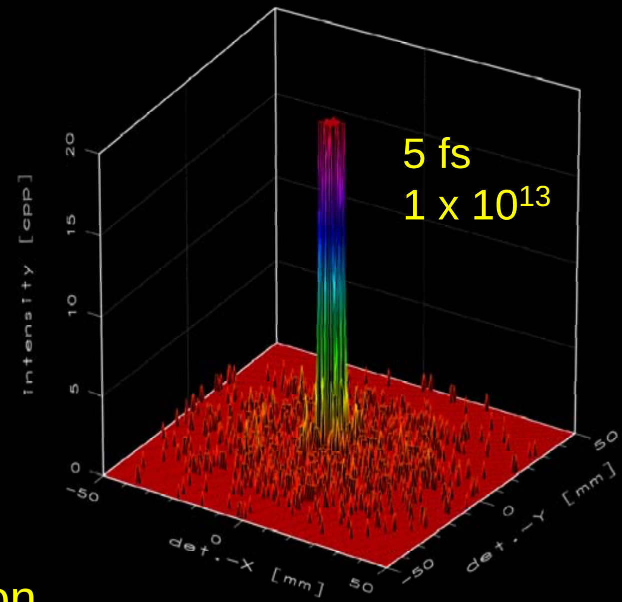




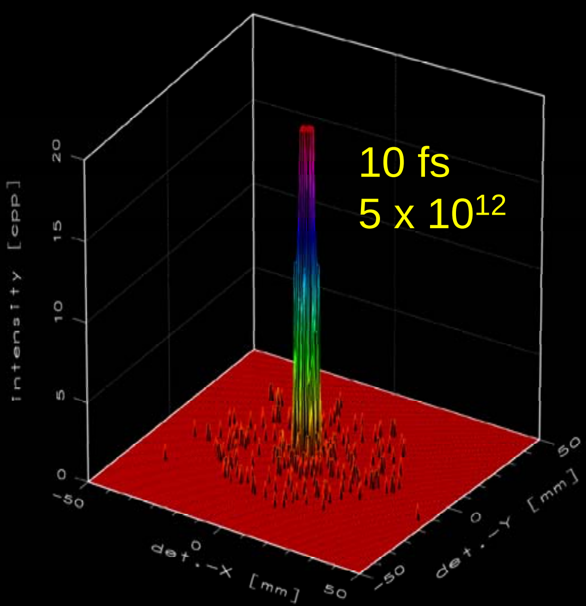


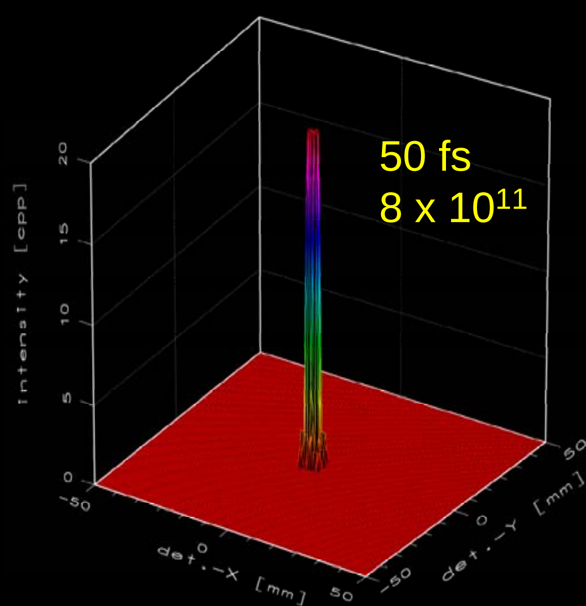


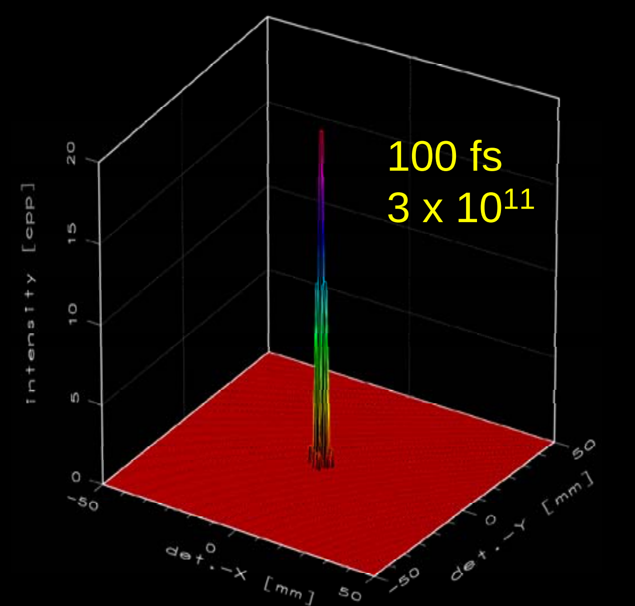
2 Å
resolution



Predicted scattering from a single RUBISCO molecule ($R_{electronic}$ = 15%)

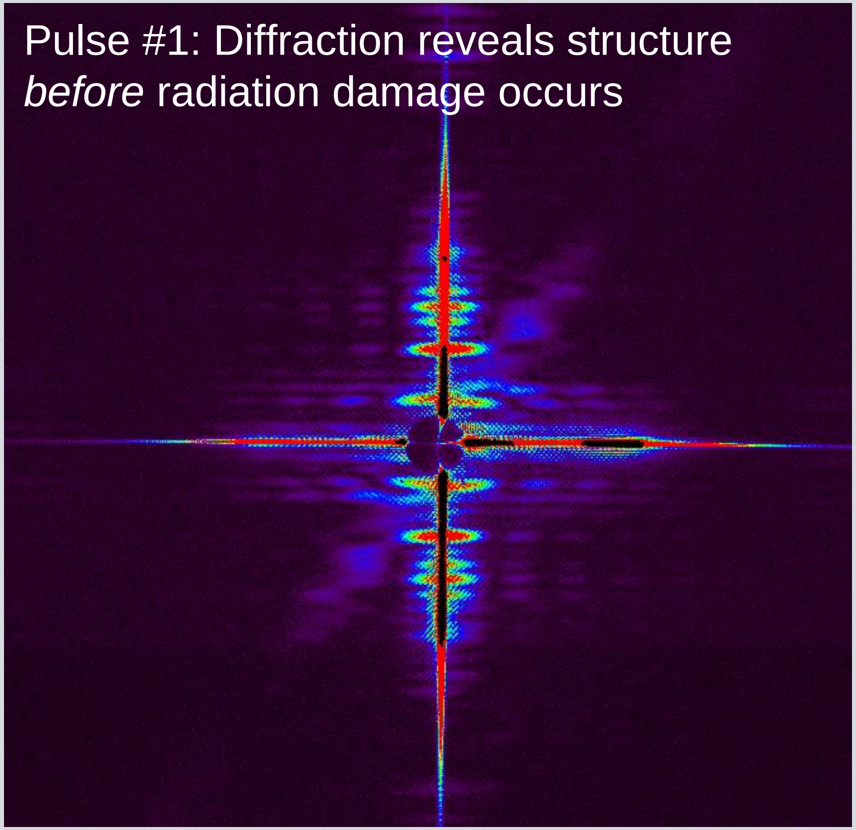


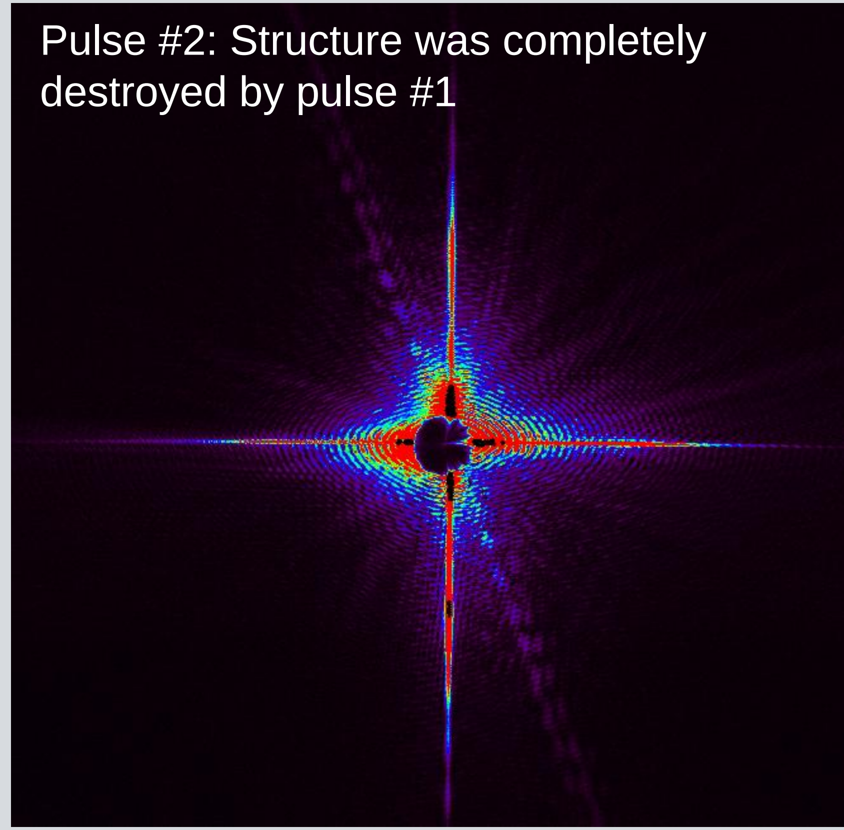




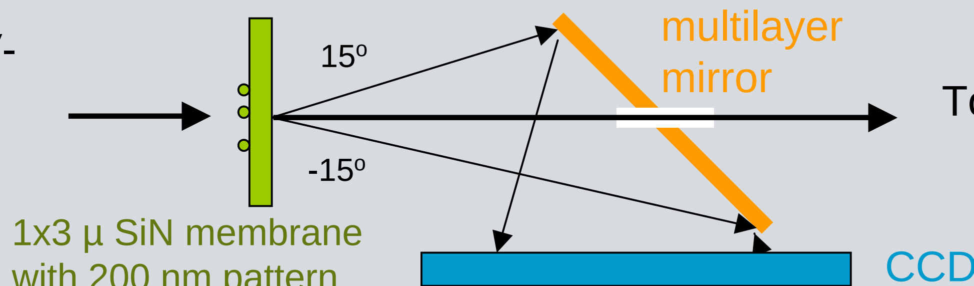
Ultrafast Coherent Single Shot X-ray Diffraction

– The First Demonstration at the VUV-FEL at DESY

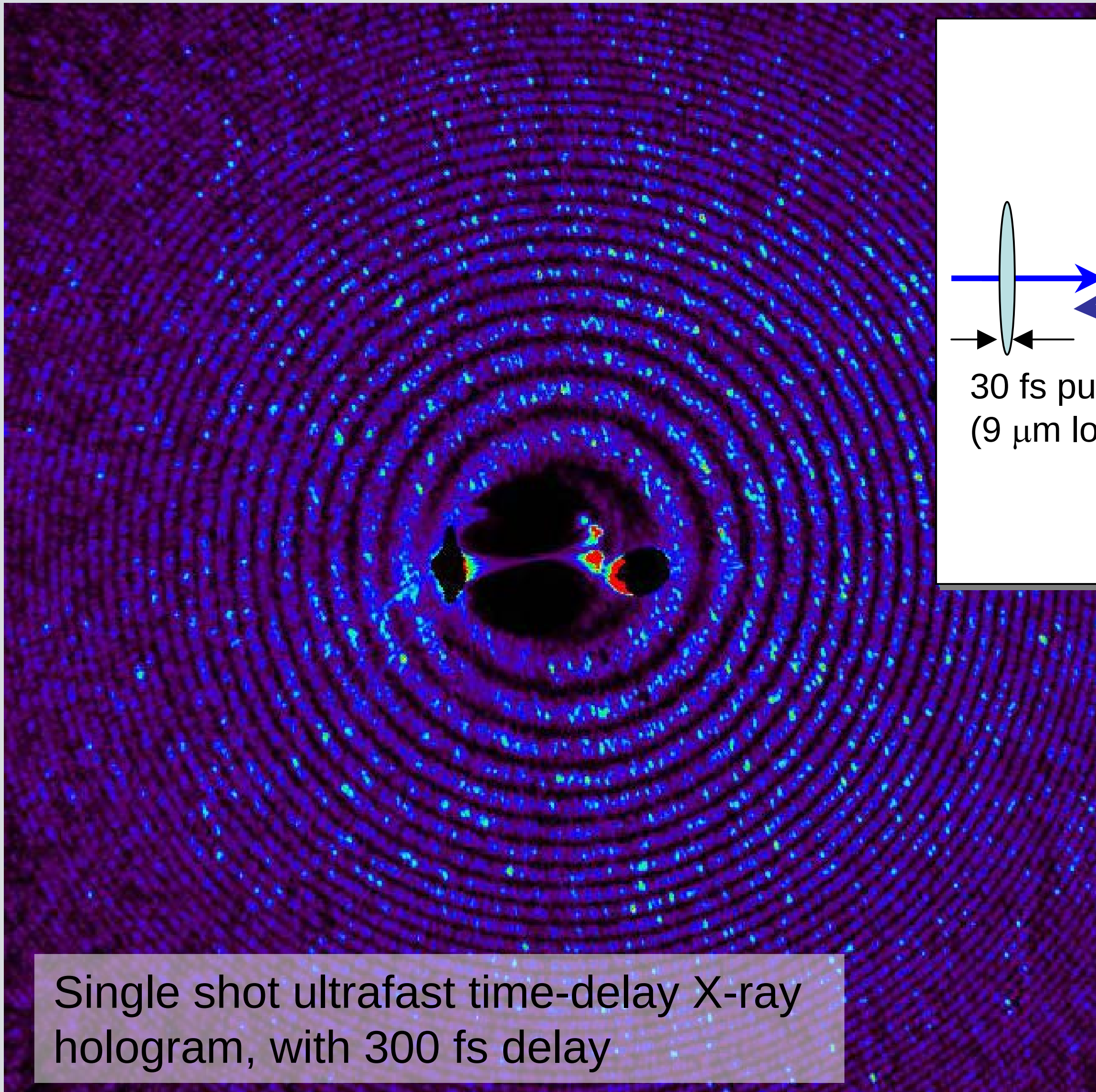




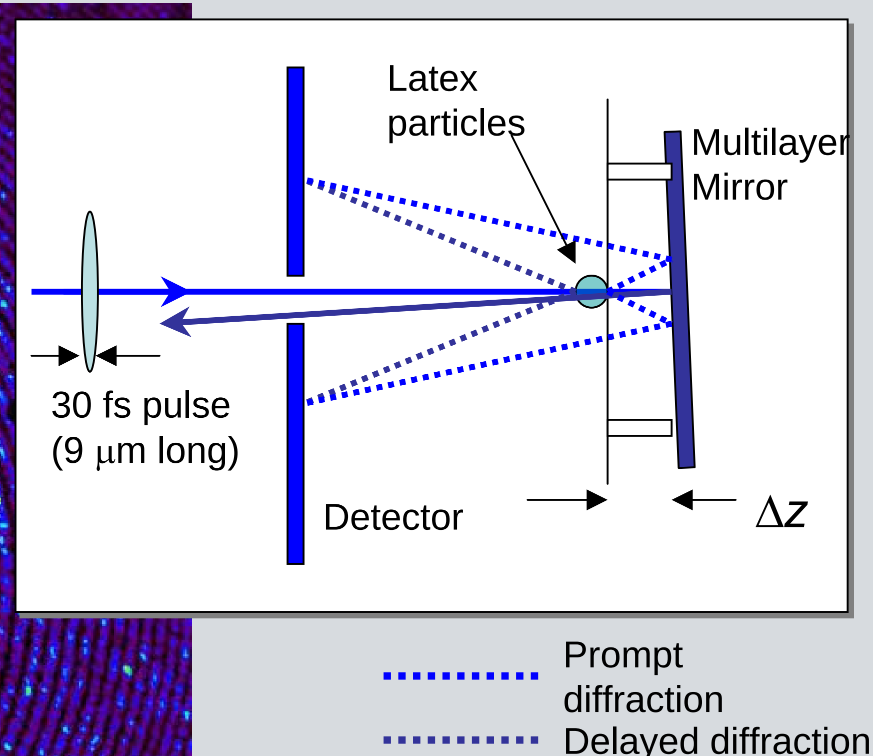
Incident VUV-FEL pulse: 30 fs, 32 nm, 3×10^{13} W cm^{-2}



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



Single shot ultrafast time-delay X-ray hologram, with 300 fs delay

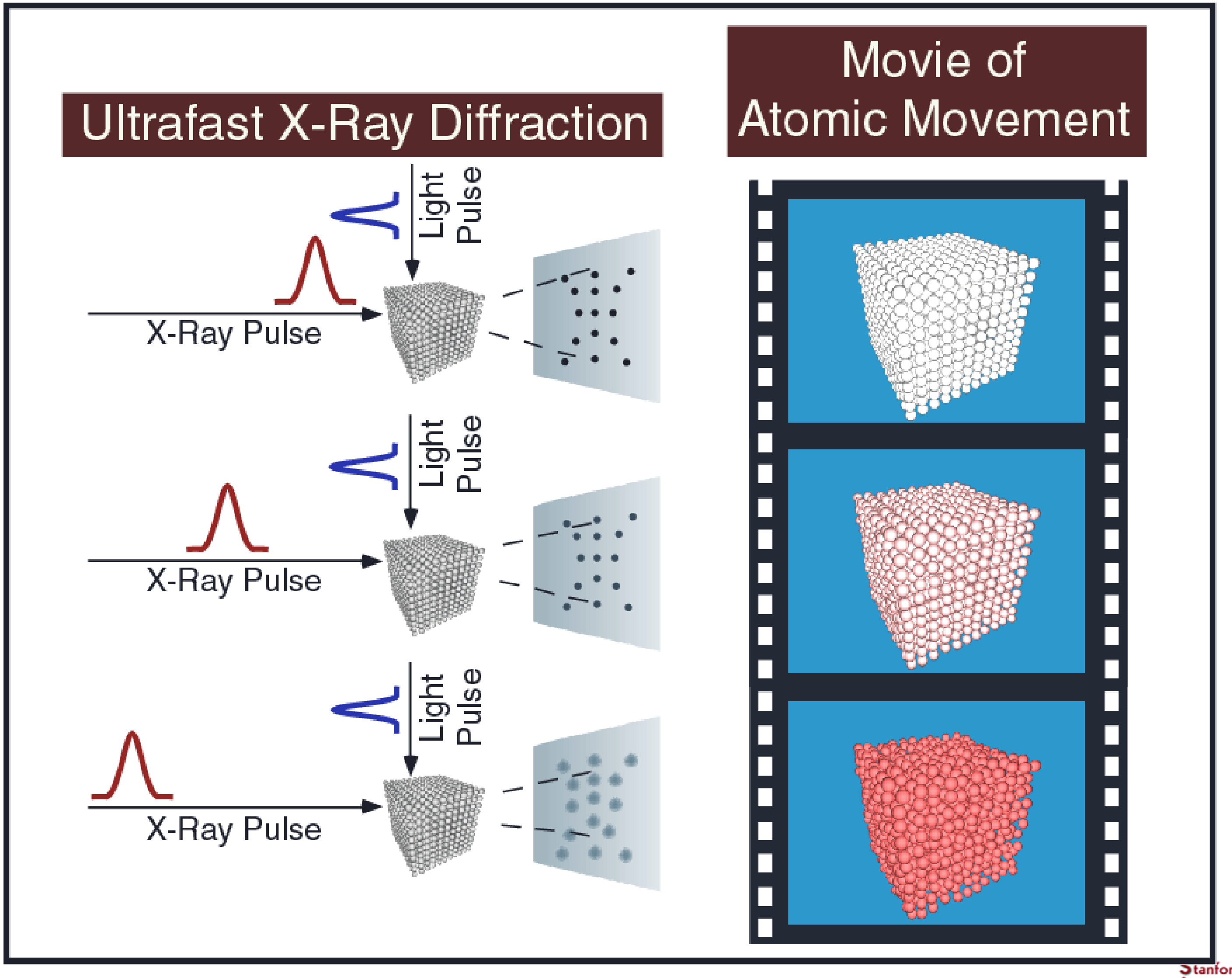


Time delay = $2\Delta z/c$

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.

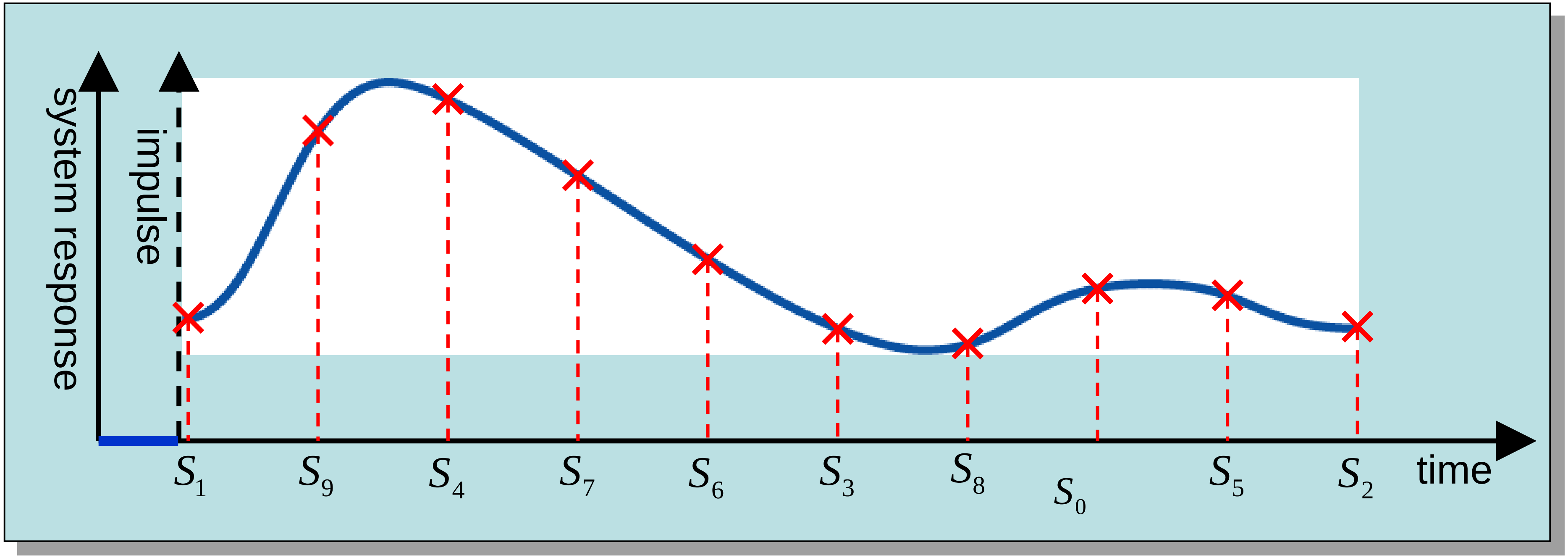
Chapman, Hajdu and collaborators

Scattering experiments



EOS and "Pump-Probe"

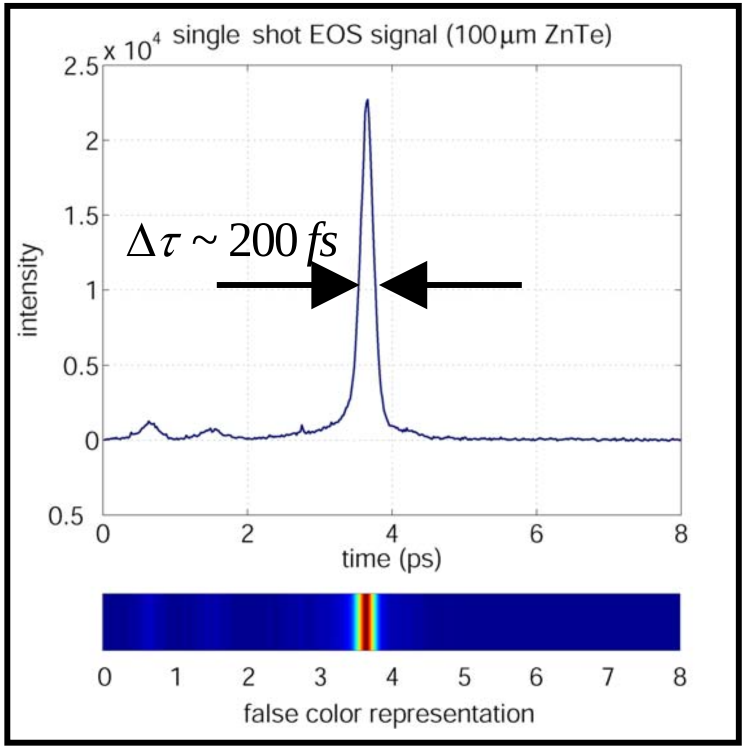
Typical time resolved experiment utilizes intrinsic synchronization between pump excitation and probe

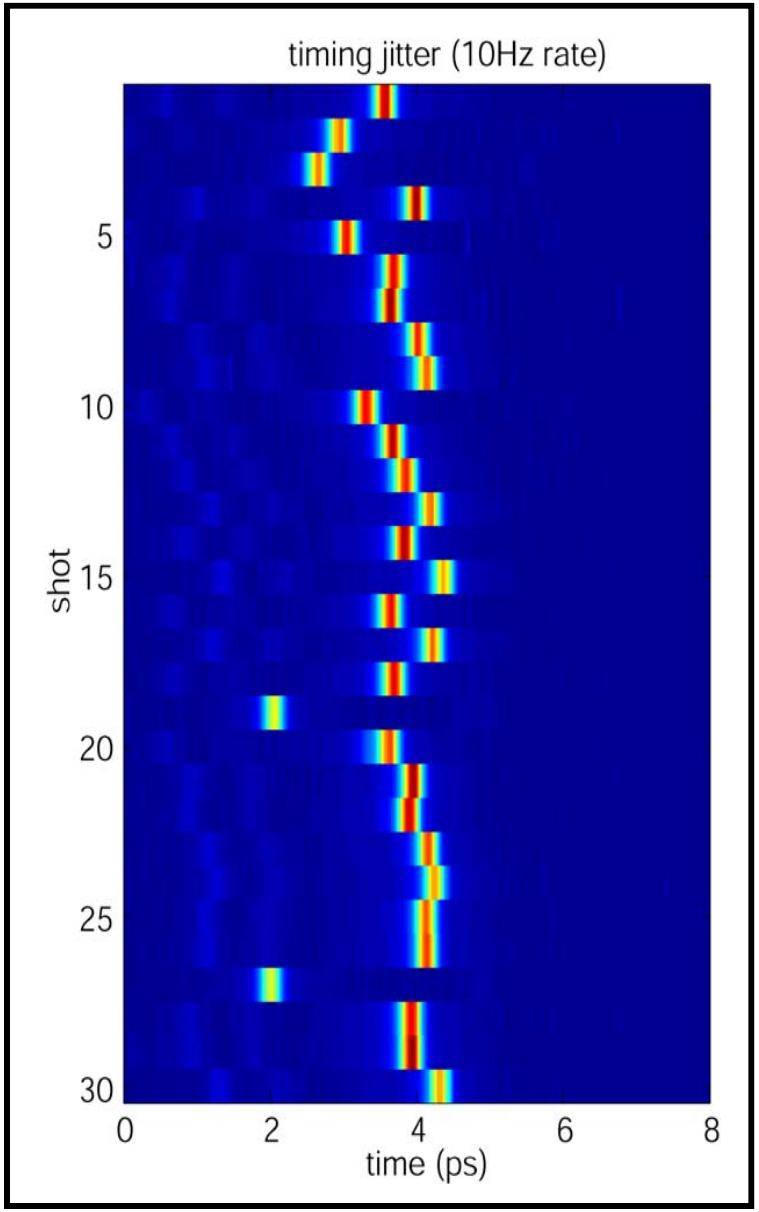


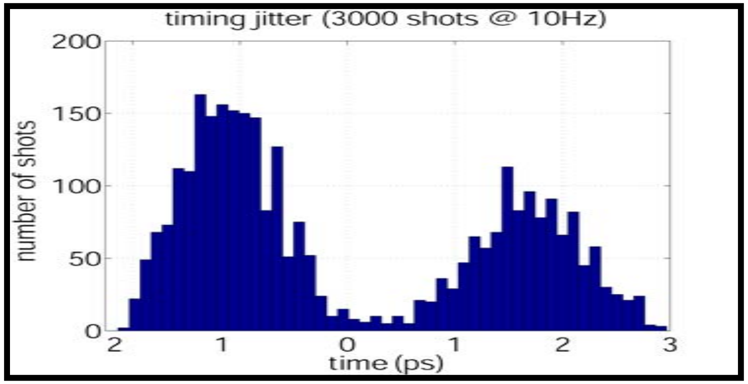
Electro-Optic Sampling (EOS) delivers arrival time to users

- Pump-Probe experiments now possible at XFELs
- Machine jitter exploited to sample time-dependent phenomena

(Typical)Single-Shot EOS Data at SPPS (100µm ZnTe)

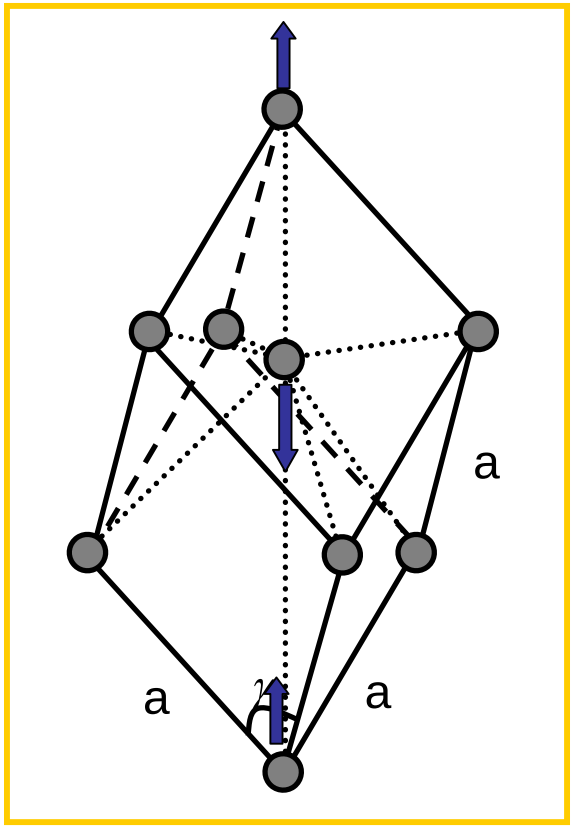






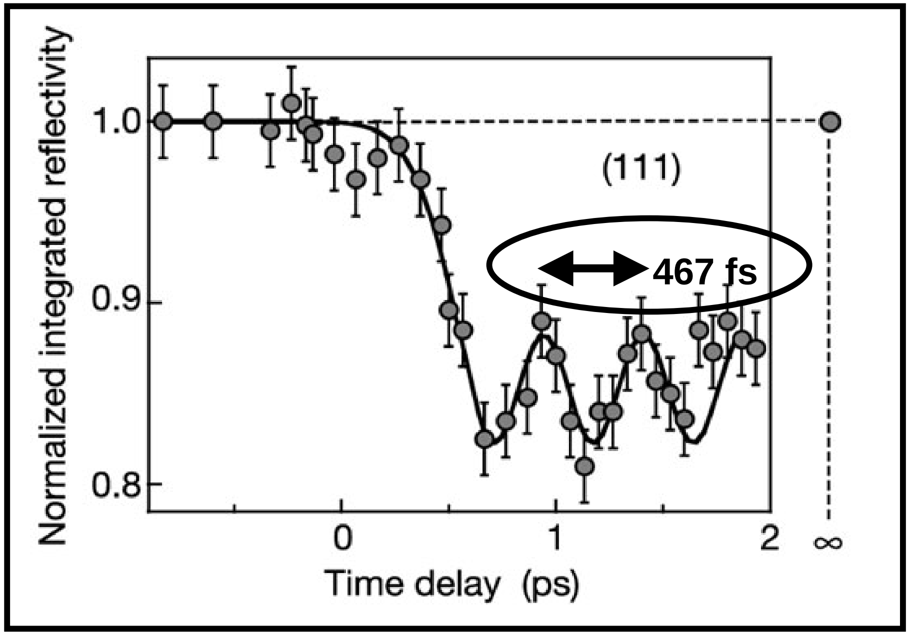
Dynamics of high amplitude coherent optical phonons

Bi structure

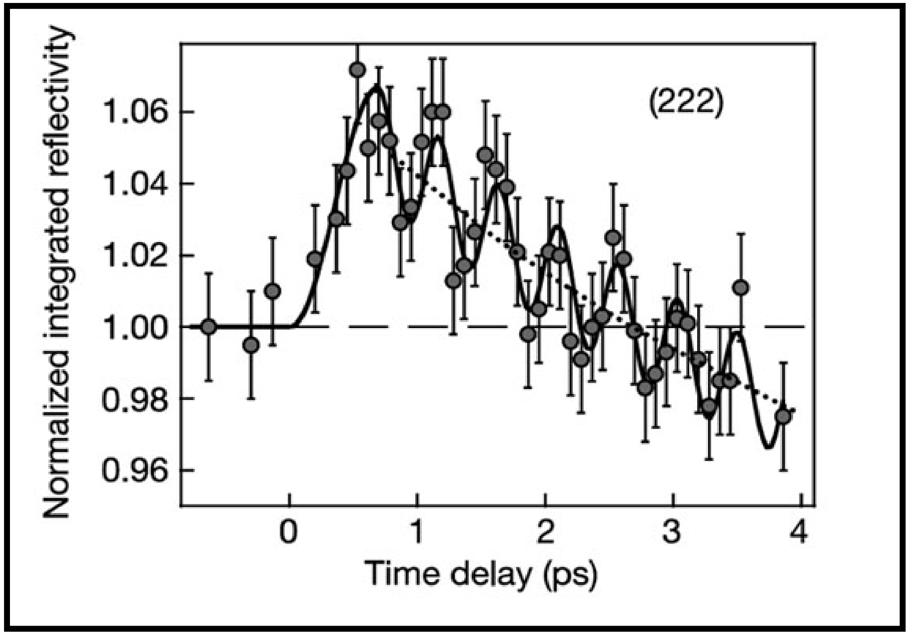


X-rays diffraction – direct probe of atomic motion

111 forbidden in simple cubic

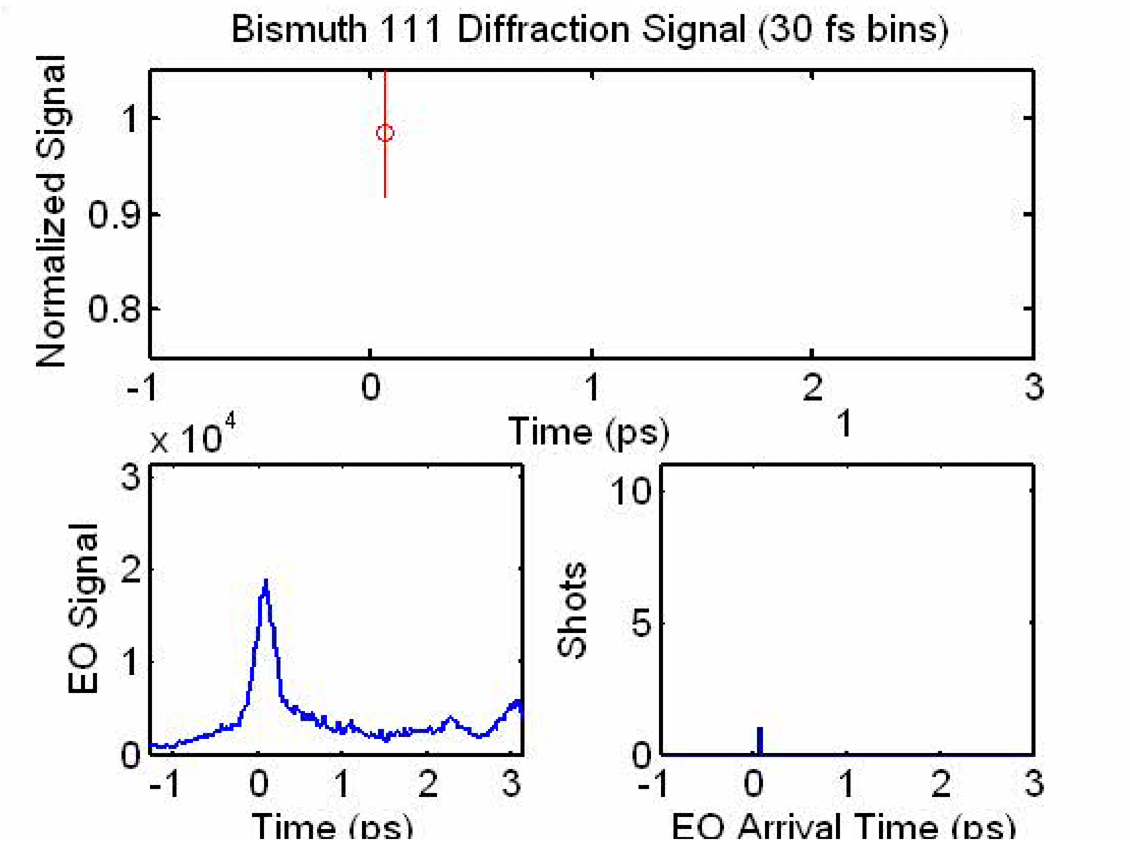


222 "perfect" in simple cubic



Sokolowski-Tinten *et al.*, Nature, 422 (2003)

Using the jitter @ SPPS for Random Sampling



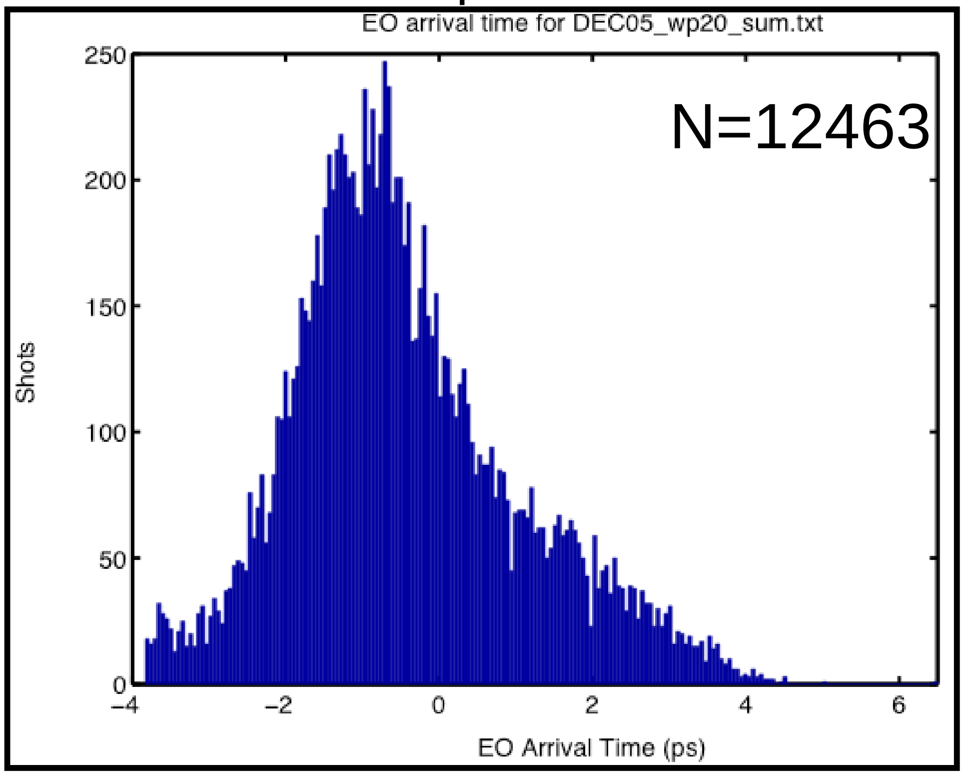
D. M. Fritz *et al.* unpublished

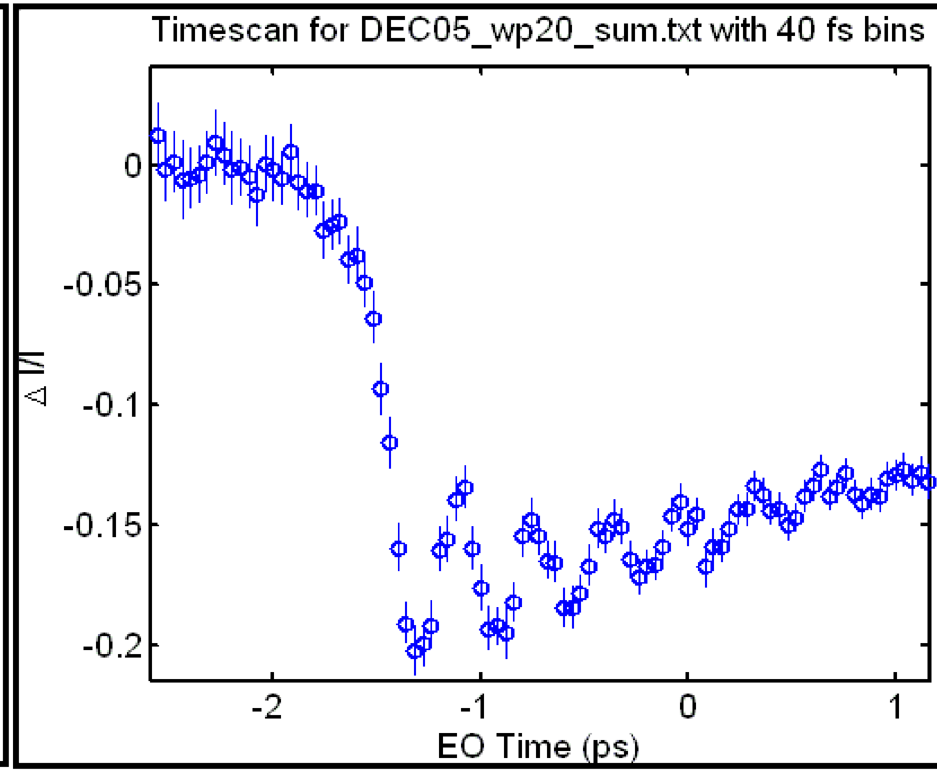
Stanford Linear Accelerator Center SSRL

Using the jitter @ SPPS for Random Sampling

1.74 mJ/cm^2 (absorbed), <n>~1%   f =2.5 THz*   A = 0.92 pm

< x> = 5pm





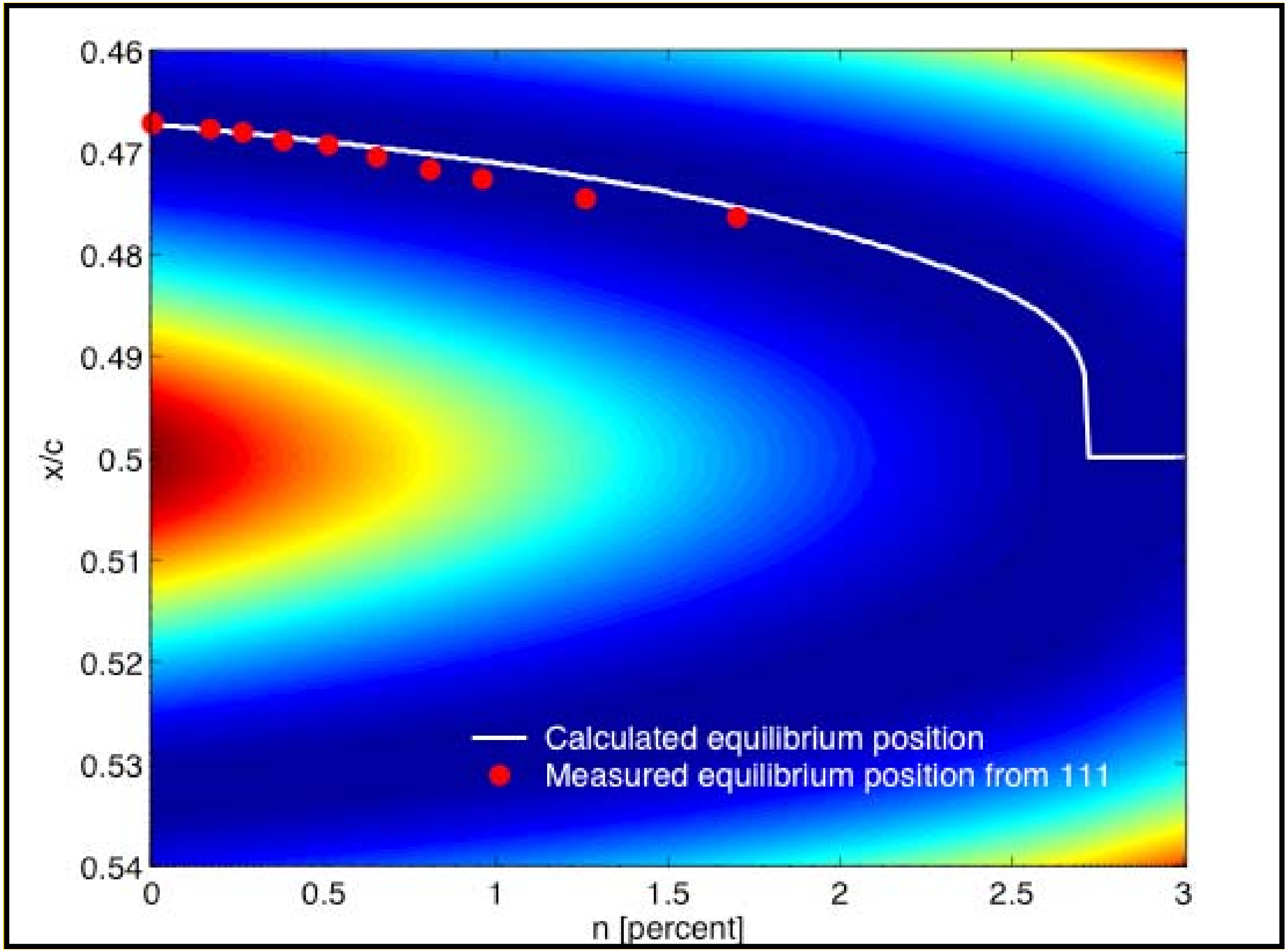
Arrival time distribution   Sorted normalized data

D. M. Fritz *et al.* unpublished

*precise time calibration still in progress

Stanford Linear Accelerator Center SSRL

Measured (Mean) Equilibrium Position



D. M. Fritz *et al. unpublished*

Exciting science with the baseline LCLS

Atomic physics in a new regime

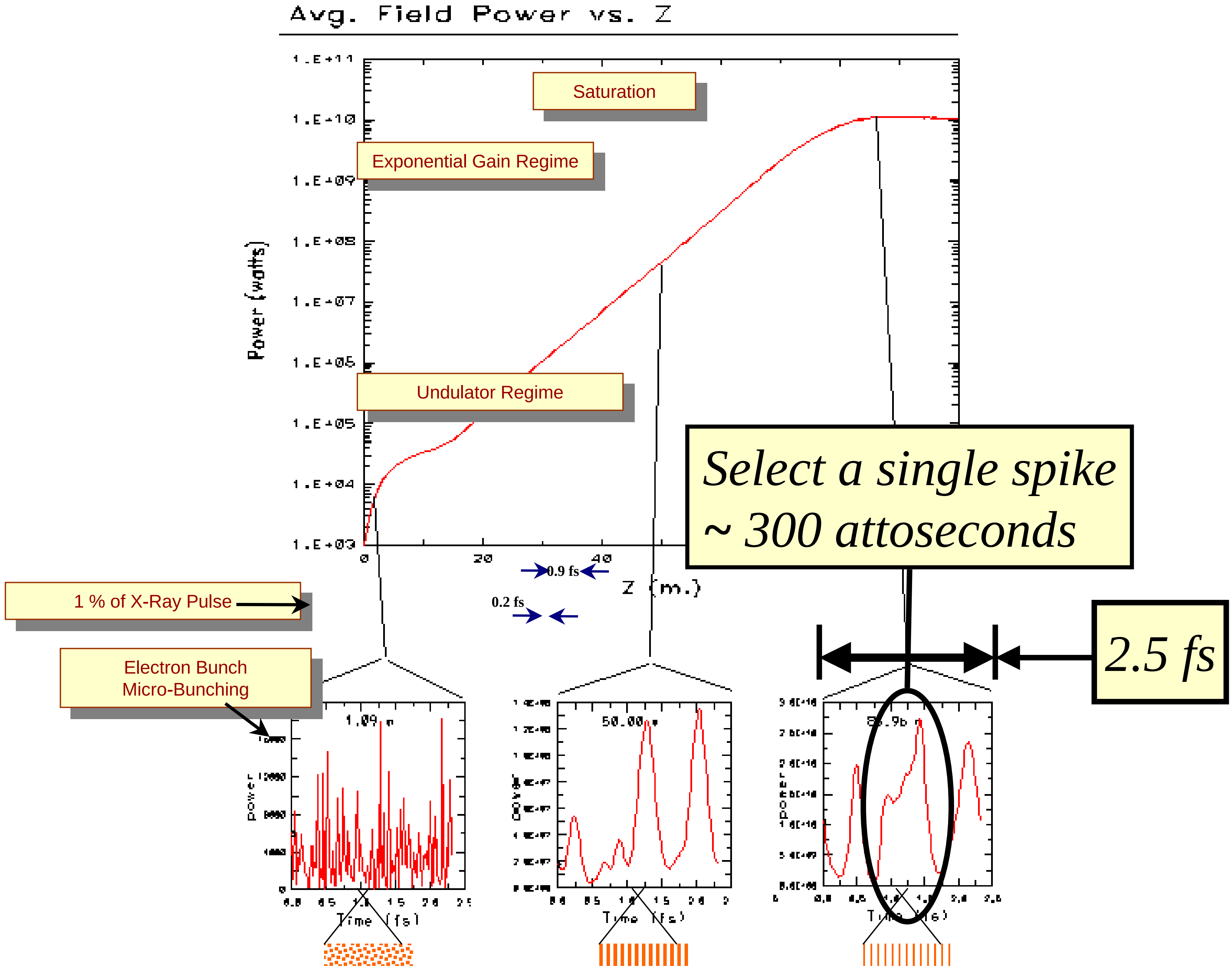
Potential to collect and invert diffraction patterns from ‘single molecules’ providing atomic resolution

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

And MUCH more

Looking to the future:

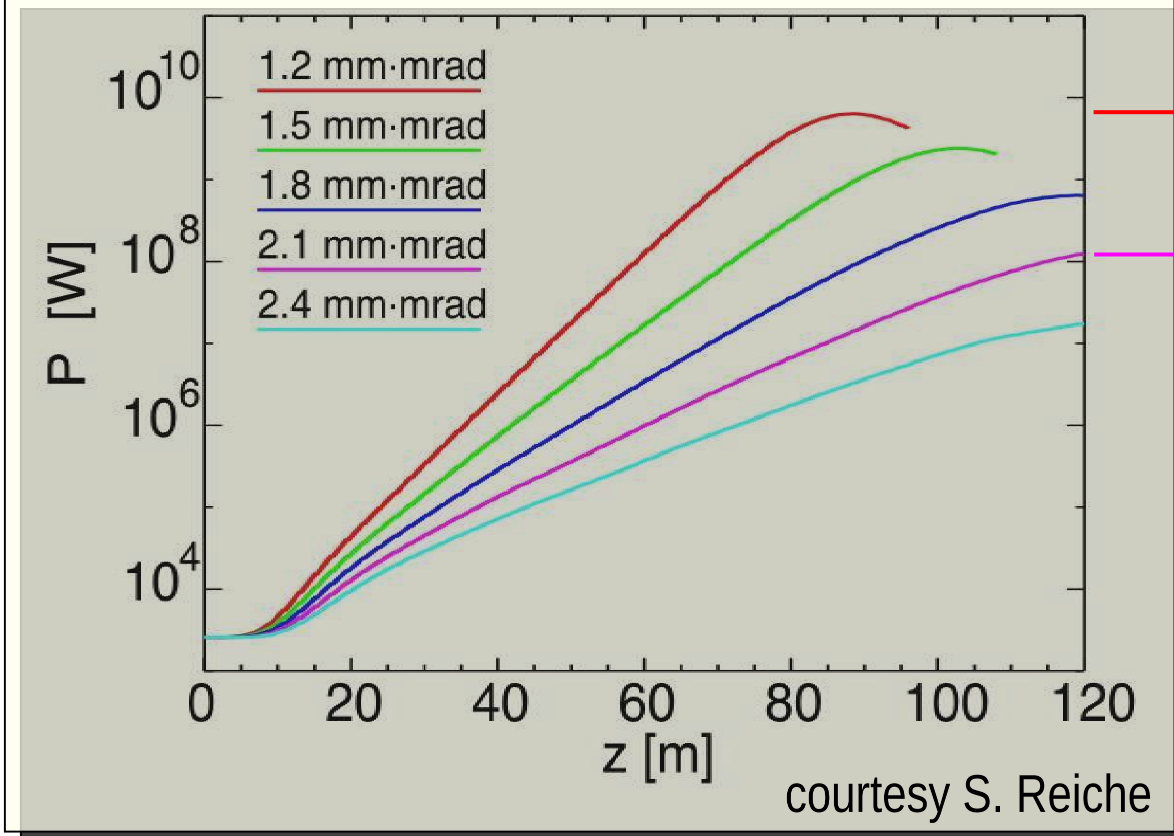
Can we get attosecond pulses ??


Avg. Field Power vs. Z
Saturation
Exponential Gain Regime
Undulator Regime
Power (watts)
Z (m.)
0.9 fs
0.2 fs
Select a single spike
~ 300 attoseconds
2.5 fs
1 % of X-Ray Pulse
Electron Bunch
Micro-Bunching
1.09 m
50.00 m
Time (fs)

Transverse Emittance is Critical for X-ray FEL

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}$$

< 1 μm at 1 Å, 15 GeV



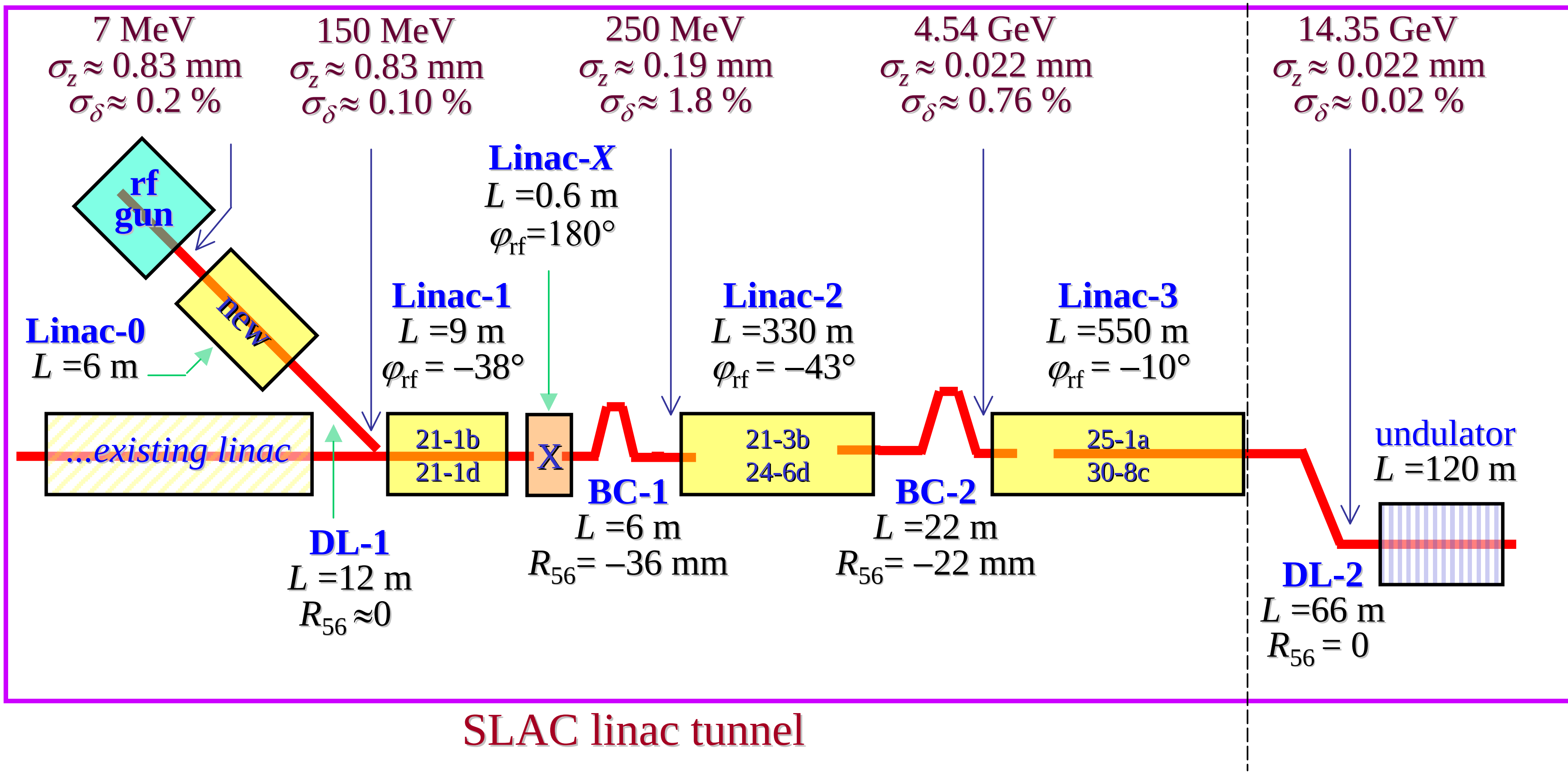
$\varepsilon_N = 1.2\ \mu$m → $P = P_0$

$\varepsilon_N = 2.0\ \mu$m → $P = P_0/100$

Can we spoil most of the e^- bunch and leave 1-fs to lase?

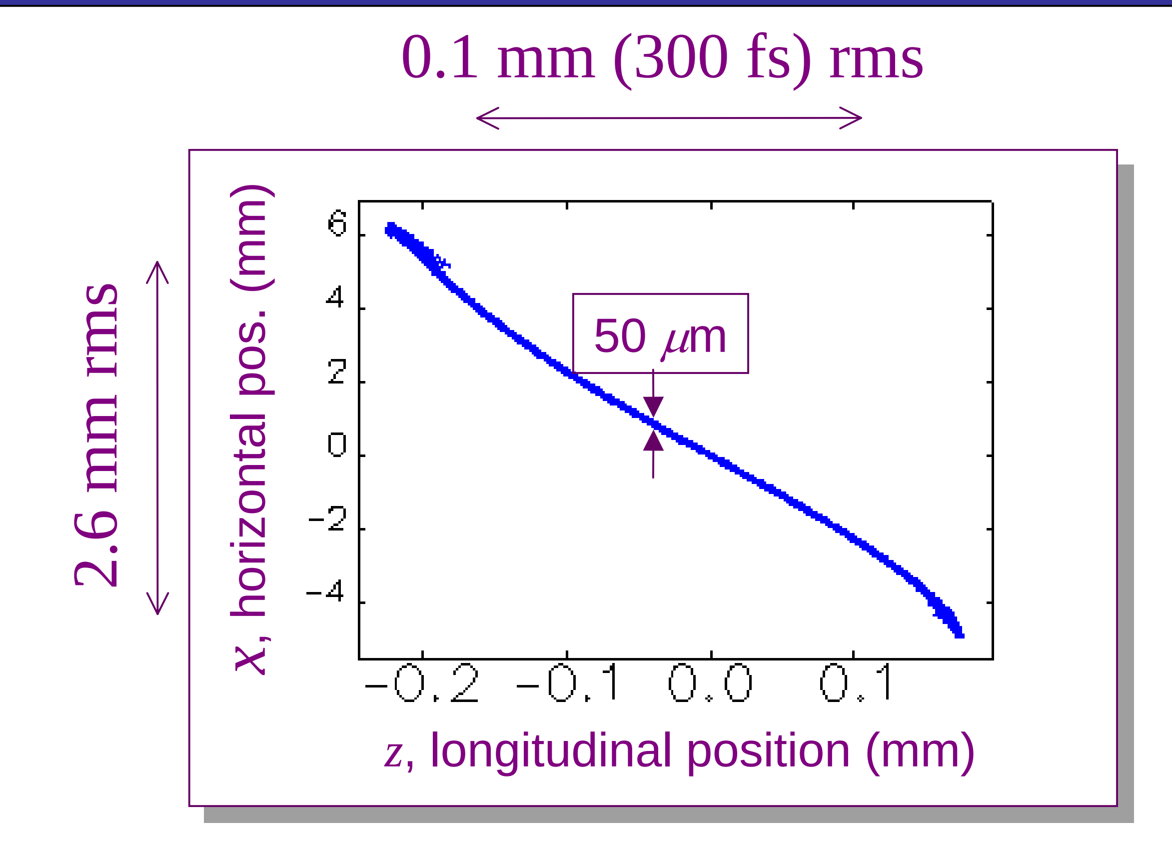
Stanford Linear Accelerator Center SSRL

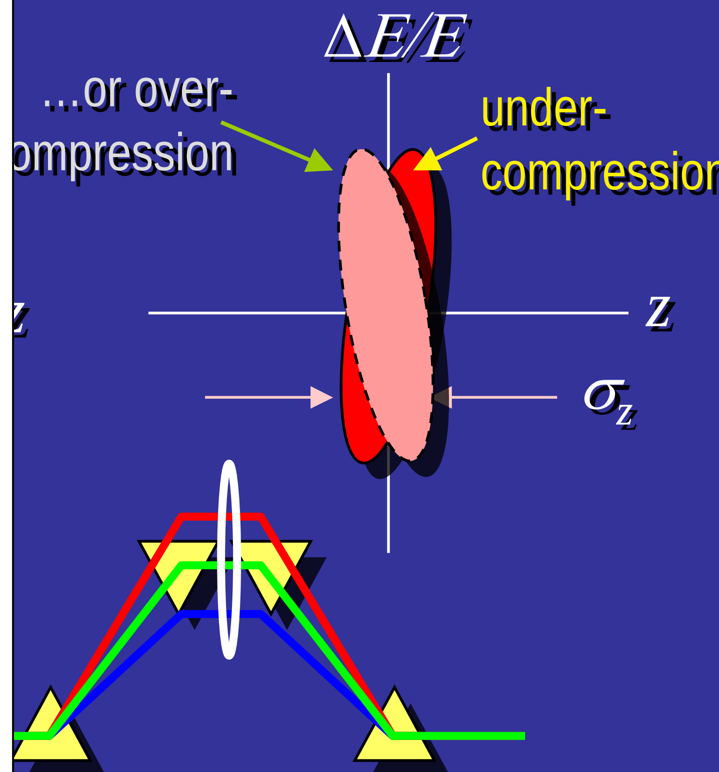
single bunch, 1-nC, 120-Hz



SLAC linac tunnel

Magnetic Bunch Compression





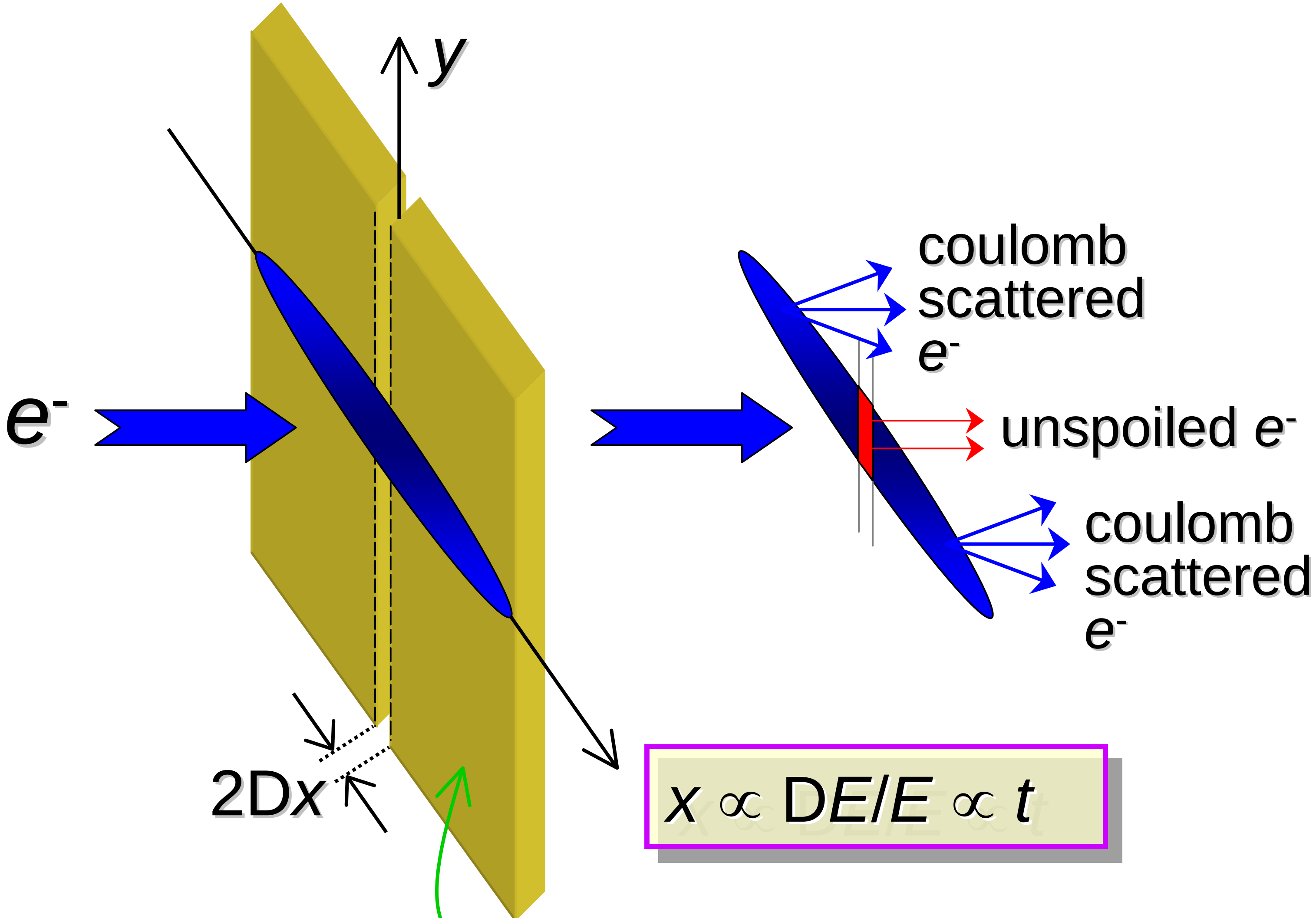
$$V = V_0 \sin(\omega\tau)$$

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

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

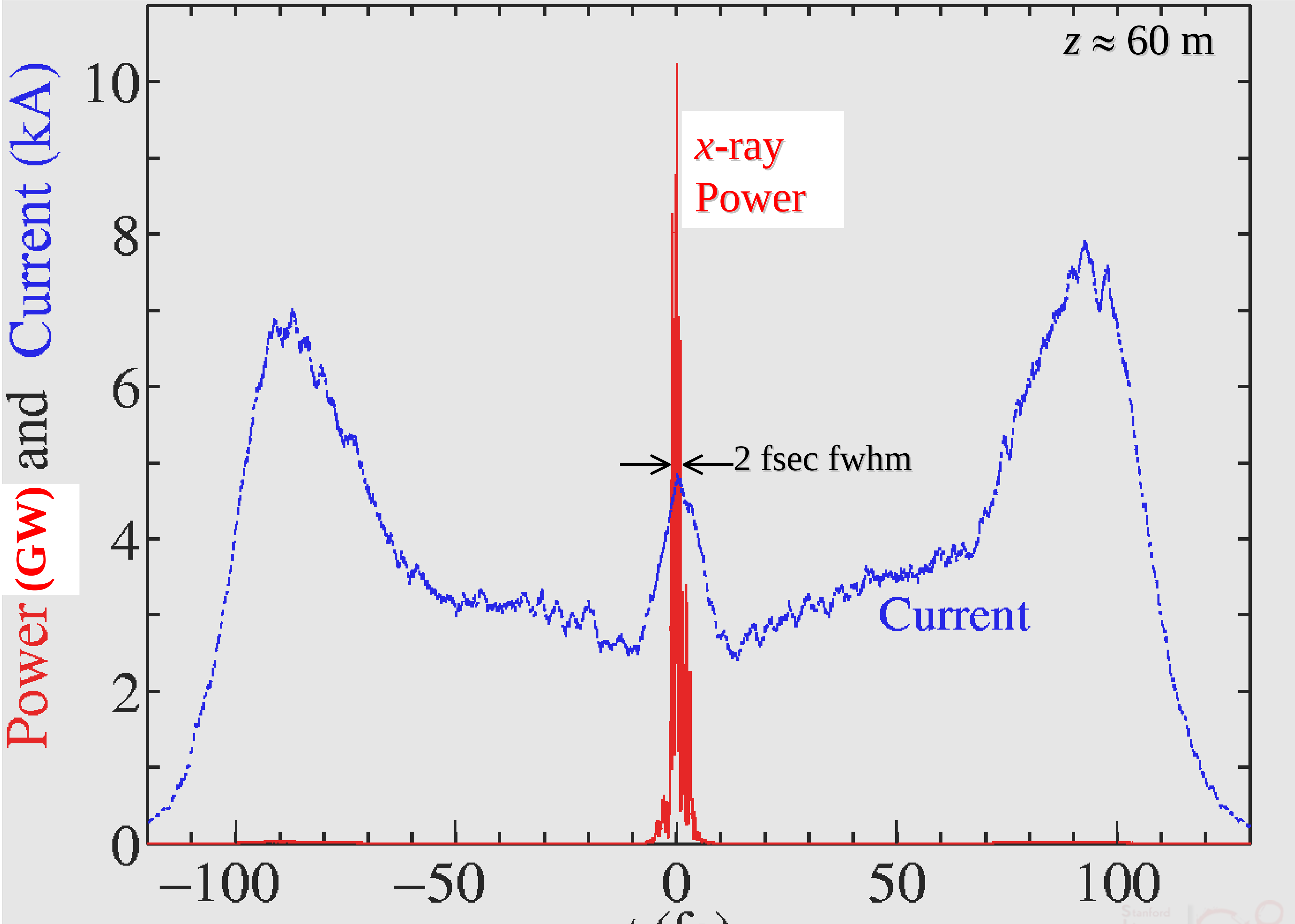
Add thin slotted foil in center of chicane



x ∝ D*E*/*E* ∝ *t*

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

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



z ≈ 60 m
x-ray
Power
2 fsec fwhm
Current
Power (GW) and Current (kA)
t (fs)
0
2
4
6
8
10
−100
−50
0
50
100

Summary

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