Instantaneous photography: The LCLS and instruments to exploit it.

J. B. Hastings

Stanford Linear Accelerator Center

Feb 8, 2007

Remarks of Prof. J. Etchemendy, Stanford University Provost, at the LCLS Groundbreaking, Oct. 20, 2006.

Quoting from Tom Hankins and Robert Silverstein in *Instruments and the Imagination*

"Instruments have a life of their own. They do not merely follow theory; often they determine theory, because instruments determine what is possible, and what is possible determines to a large extent what can be thought."

The telescope, the microscope; the chronograph, the photograph: all gave rise to a blossoming of theoretical understanding not possible before their invention.

How Short?

…defined by New York Traffic Commissioner T.T. Wiley in 1950 as:

"…the time between the light turning green and the guy behind you honking."

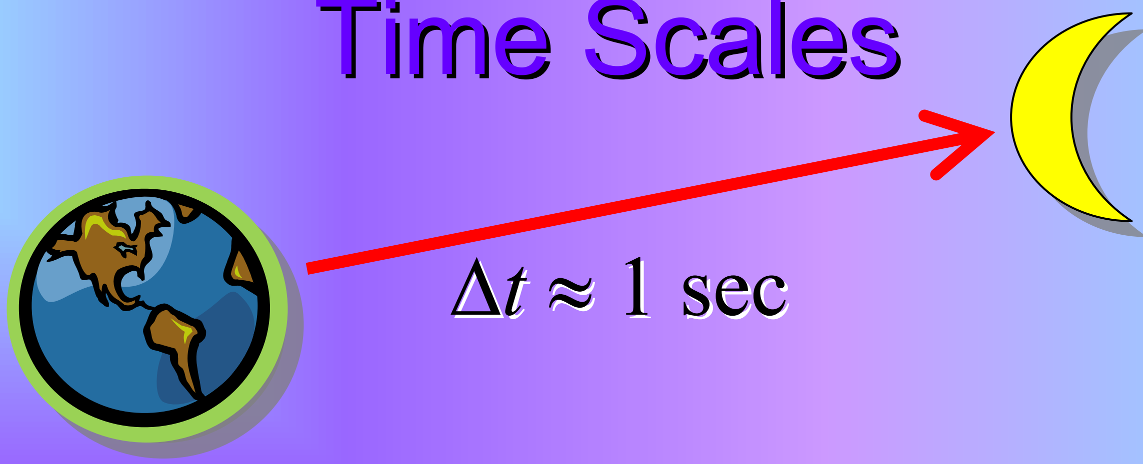
-W. Safire, *NY Times*, March 7, 2004

Several FEL proposals go beyond even this:

- **sub-femtosecond pulses**
- **1-Å radiation**
- **GW power levels**
- **unprecedented brightness**

why so short…

Time Scales

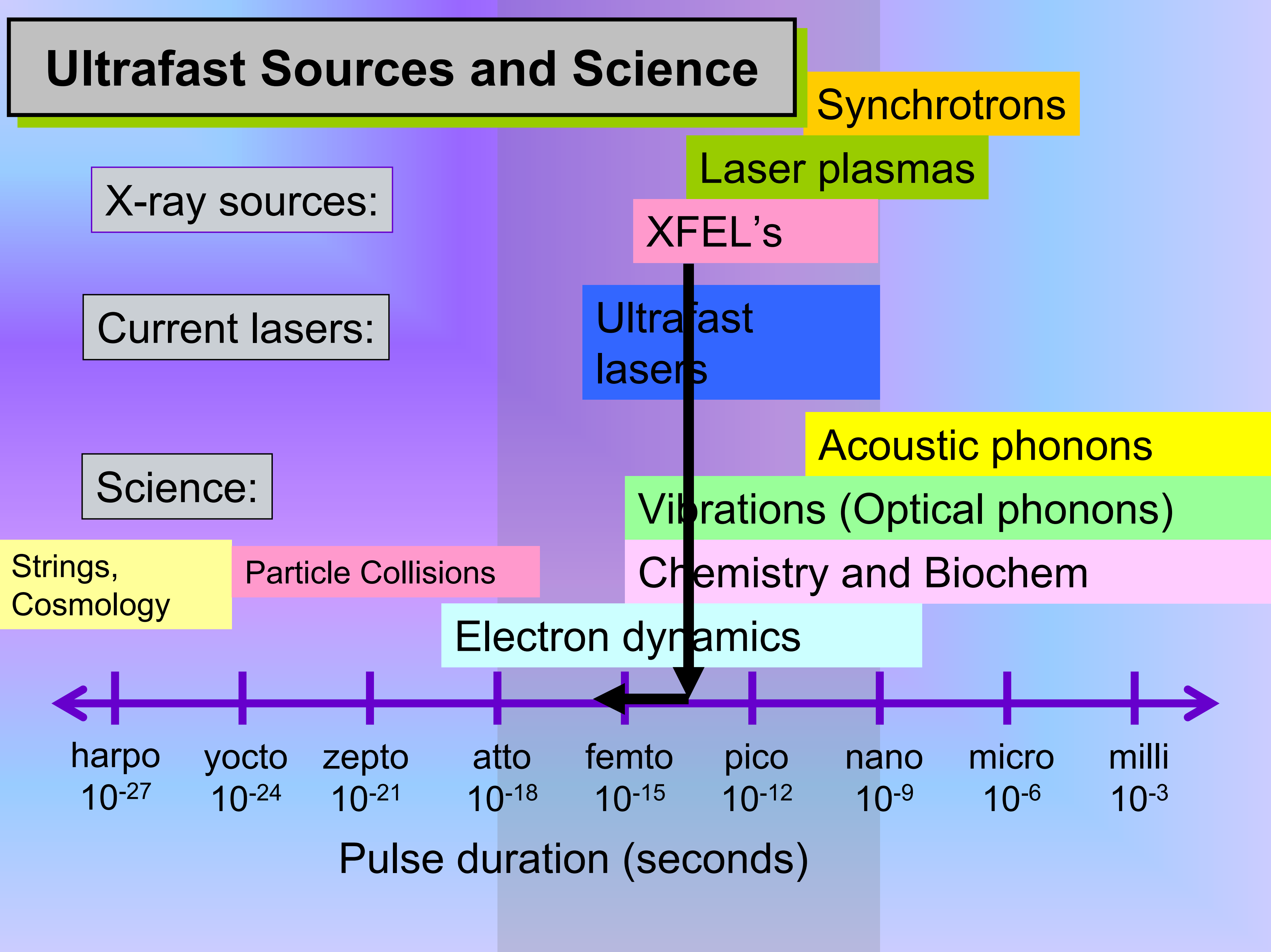


1 **femto**-second (fs) = 10^{-15} sec ⇒ 0.3 μm

1 **atto**-second (as) = 10^{-18} sec ⇒ 0.3 nm

…then yakto, zepto, and… Harpo?

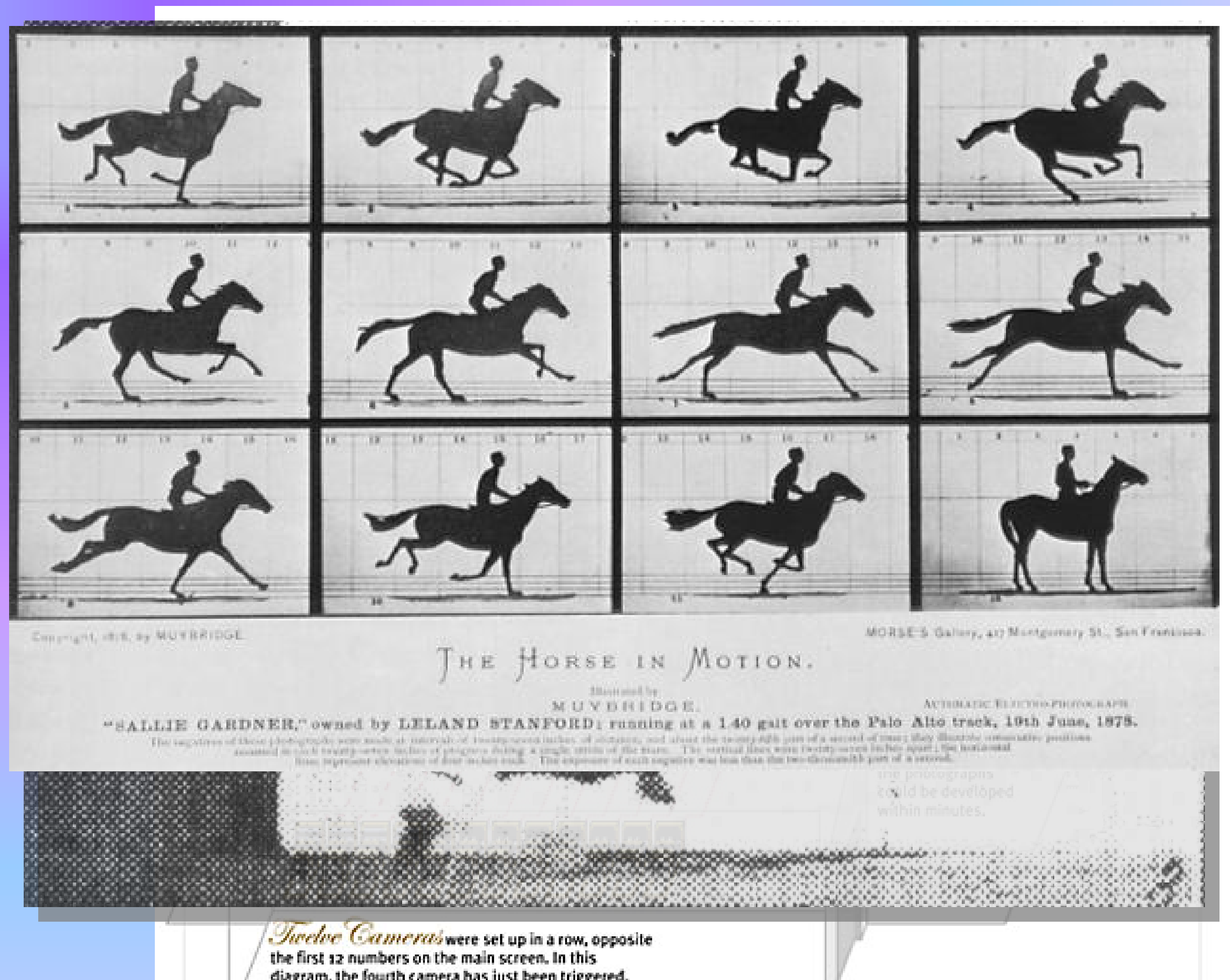
In Neils Bohr’s 1913 model of the Hydrogen atom it takes about **150 as** for an electron to orbit the proton.
– *Nature*, 2004


Ultrafast Sources and Science
X-ray sources:
Synchrotrons
Laser plasmas
XFEL's
Current lasers:
Ultrafast lasers
Science:
Acoustic phonons
Vibrations (Optical phonons)
Chemistry and Biochem
Strings, Cosmology
Particle Collisions
Electron dynamics
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}
Pulse duration (seconds)

E. Muybridge at L. Stanford in **1878**

disagree whether all feet leave the ground during gallop…

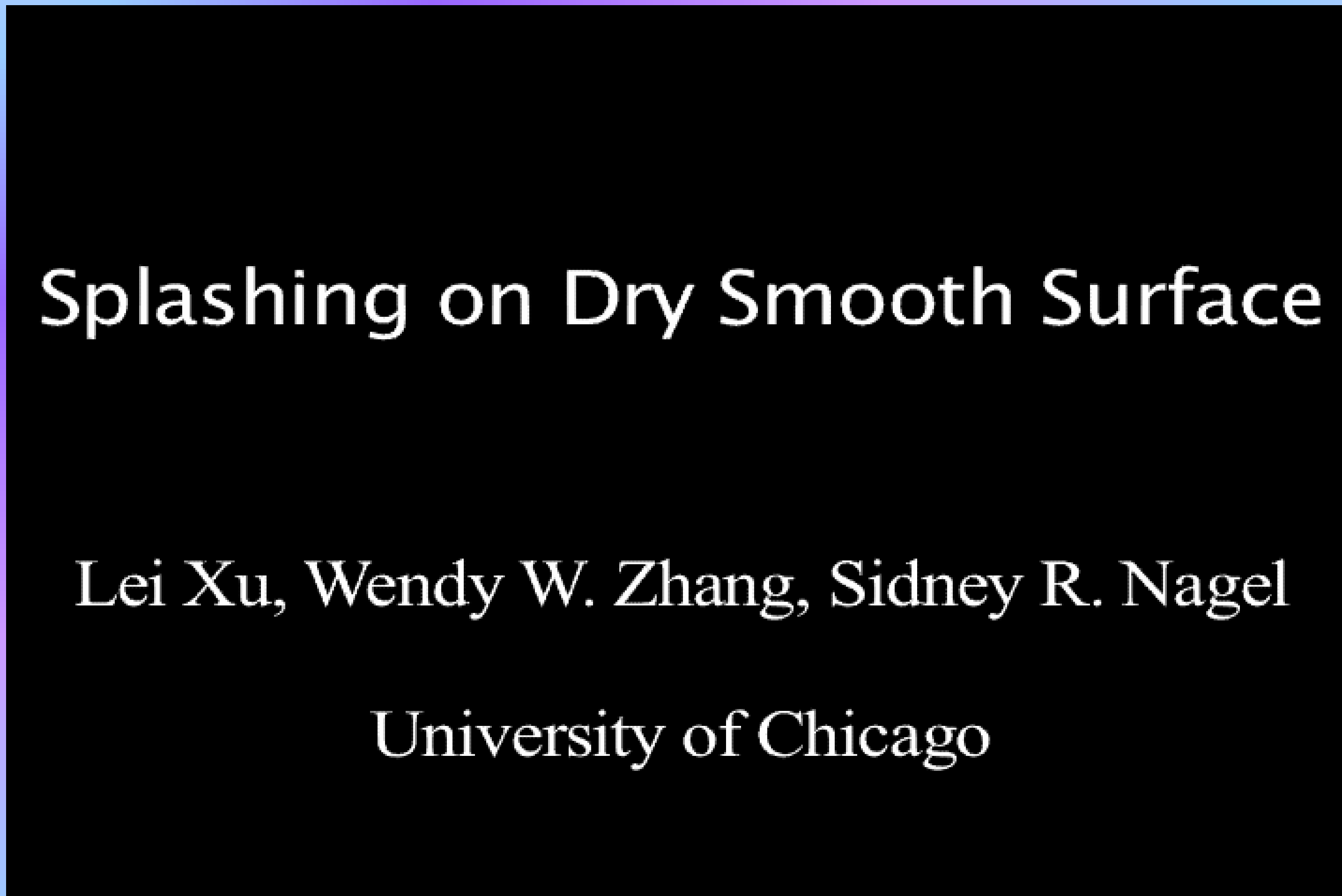
E. Muybridge



used spark photography to freeze this 'ultra-fast' process

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

Drop Spalshing on a Dry Smooth Surface

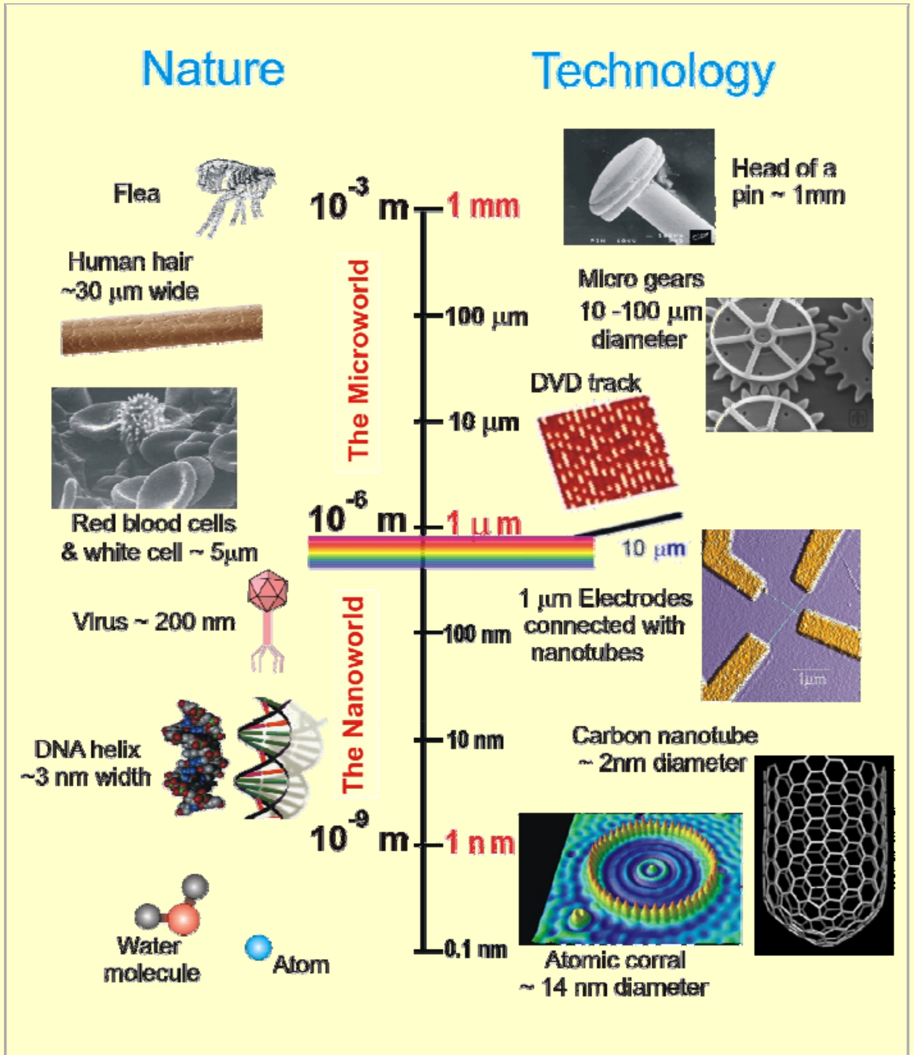


47000 fps

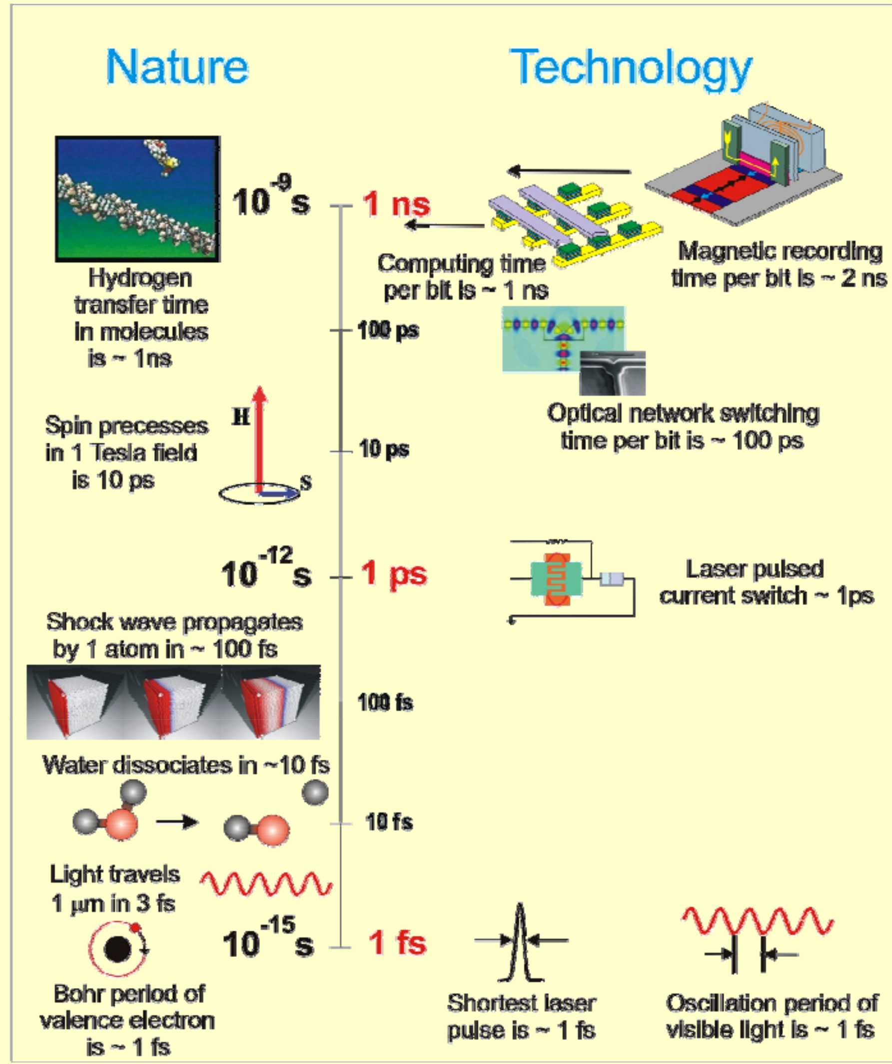
Lei Xu, Wendy W. Zhang, Sidney R. Nagel, PRL **94,** 184505 (2005)

X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

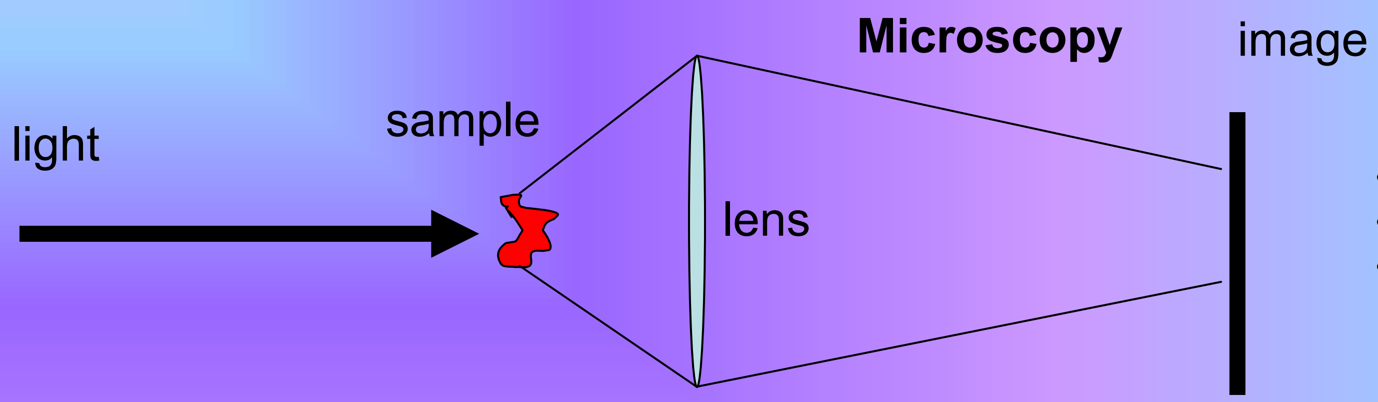
Ultra-Small



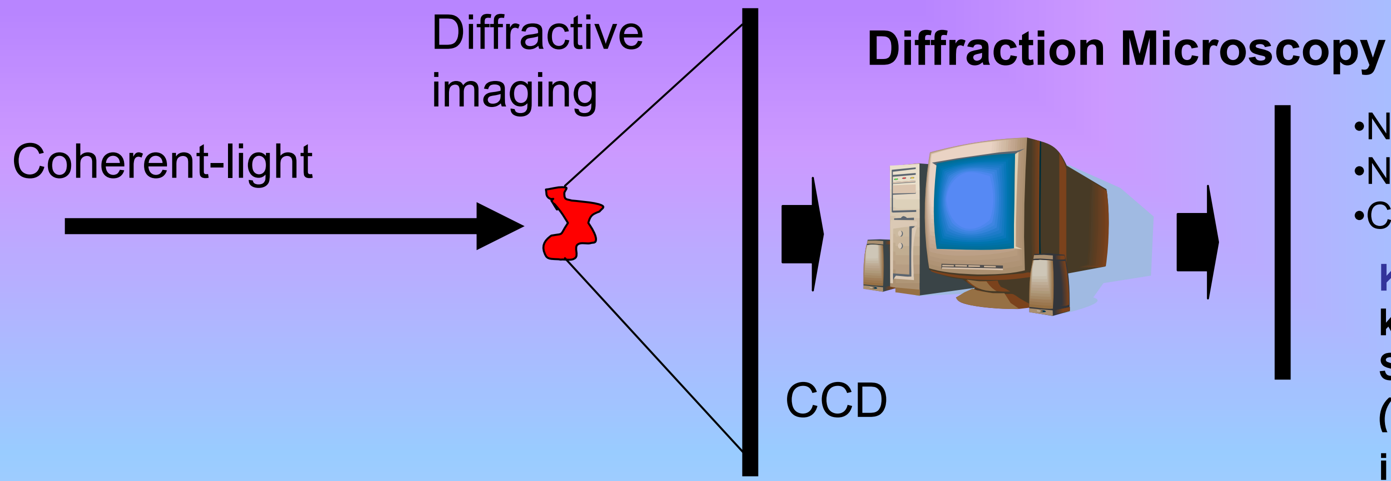
Ultra-Fast



Instant Photography with coherent x-rays

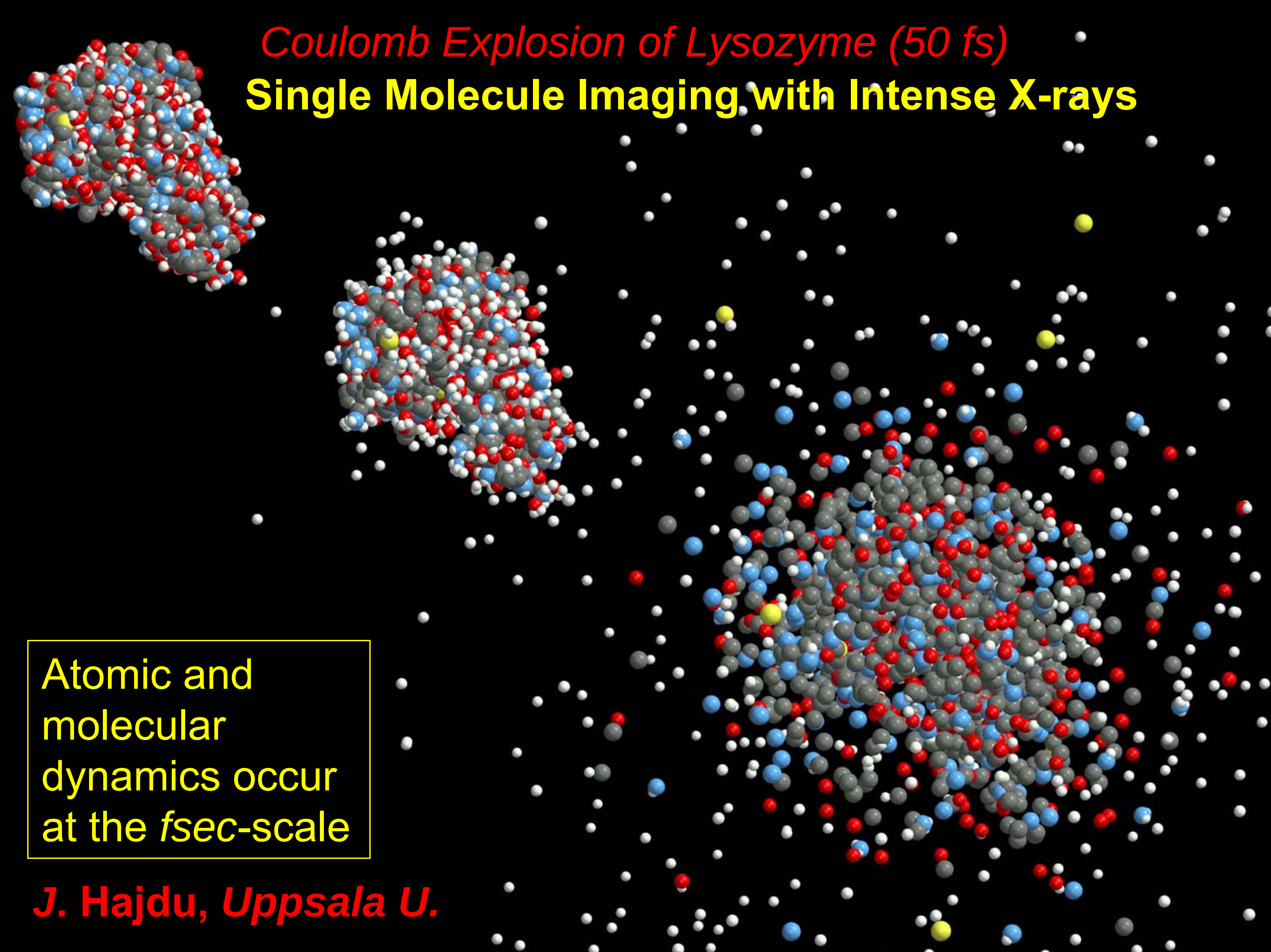


•depth of field limit
•lens-limited
•direct



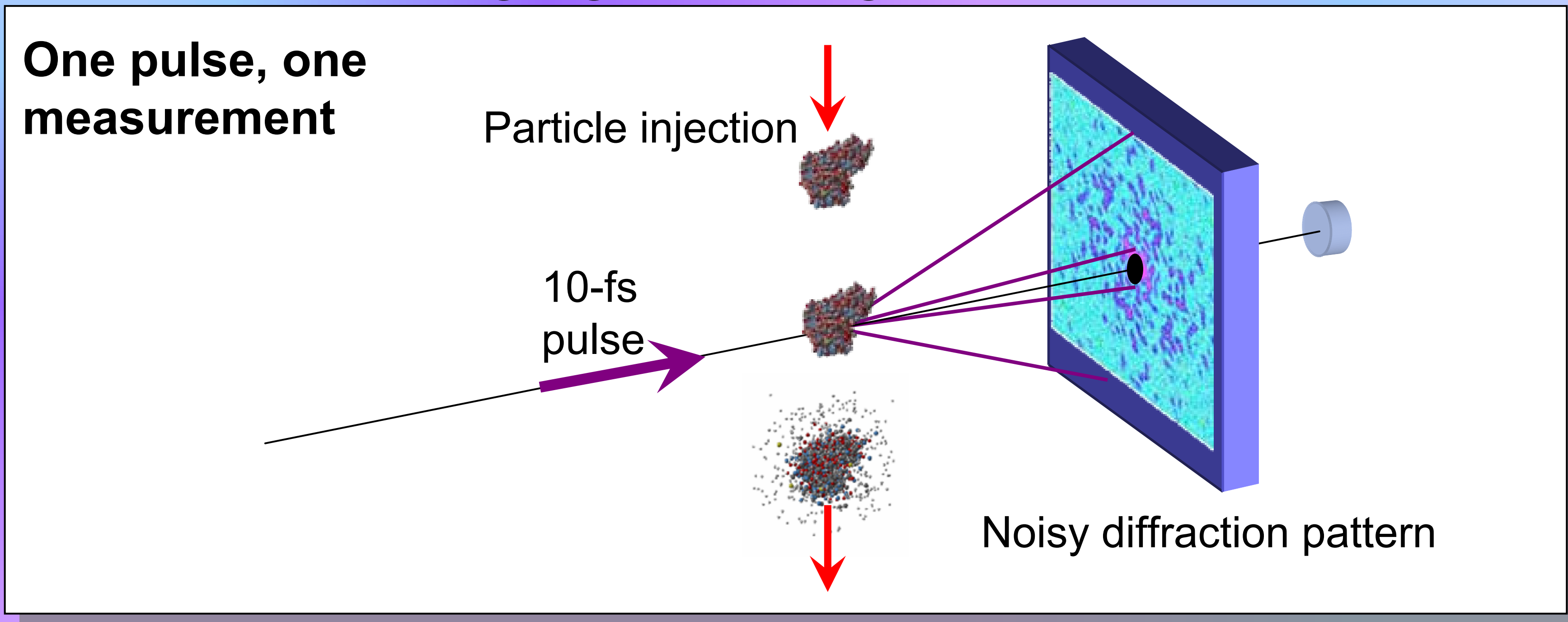
•No depth of field limit
•No lens-limited
•Computer-limited

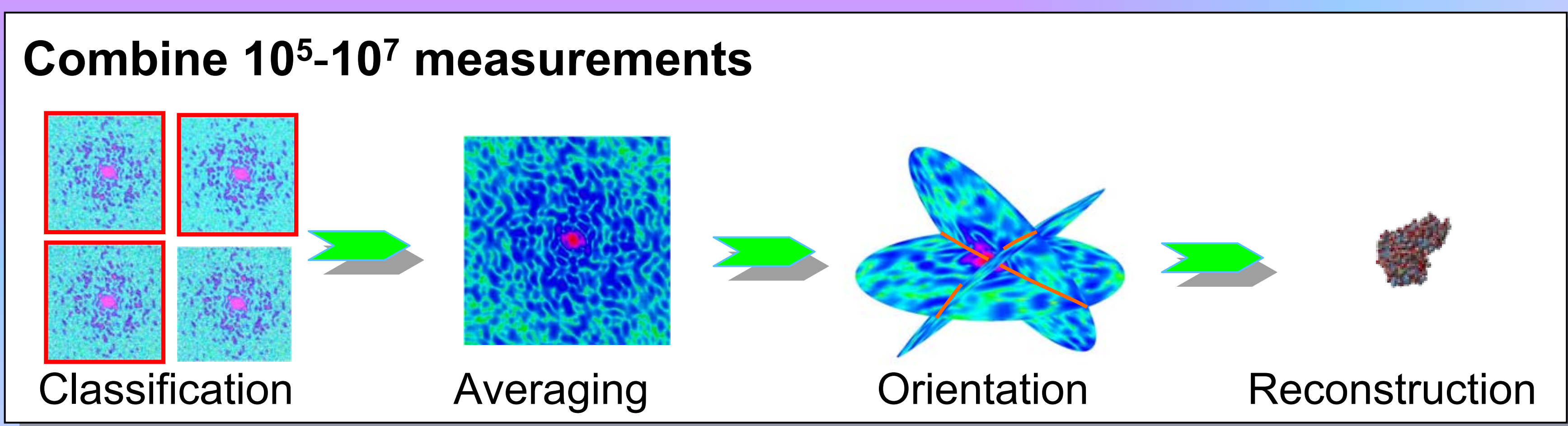
Known:
k-space amplitude: I
Support
(outline of the object)
in real space S



Coulomb Explosion of Lysozyme (50 fs)
Single Molecule Imaging with Intense X-rays
Atomic and molecular dynamics occur at the fsec-scale
J. Hajdu, Uppsala U.

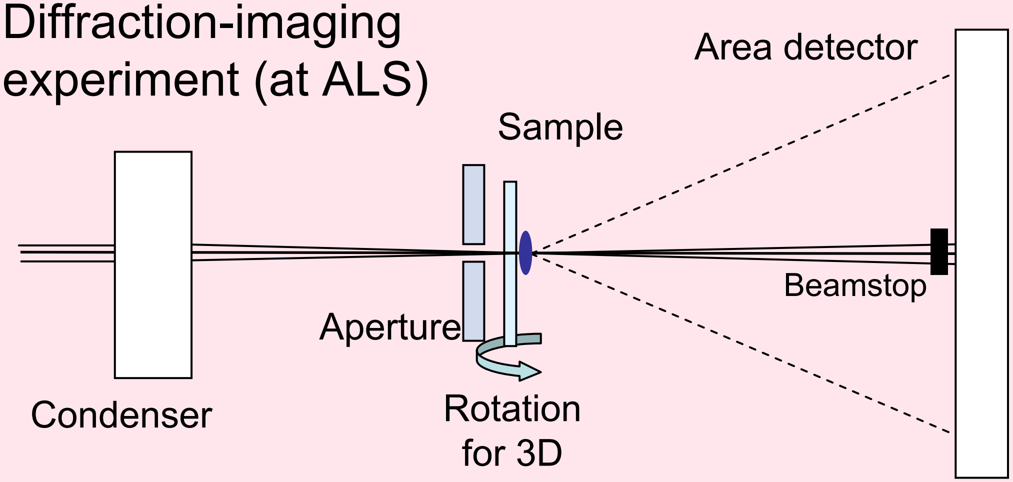
X-ray free-electron lasers may enable atomic-resolution imaging of biological macromolecules



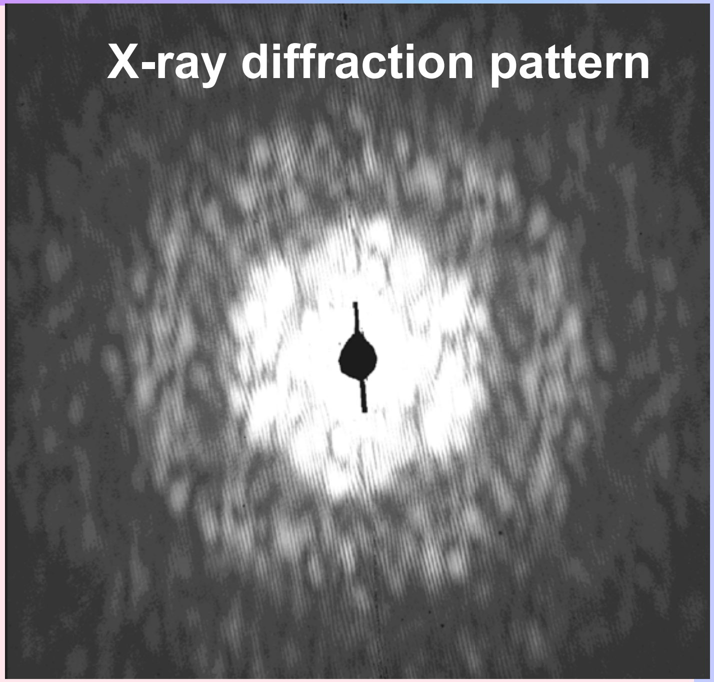


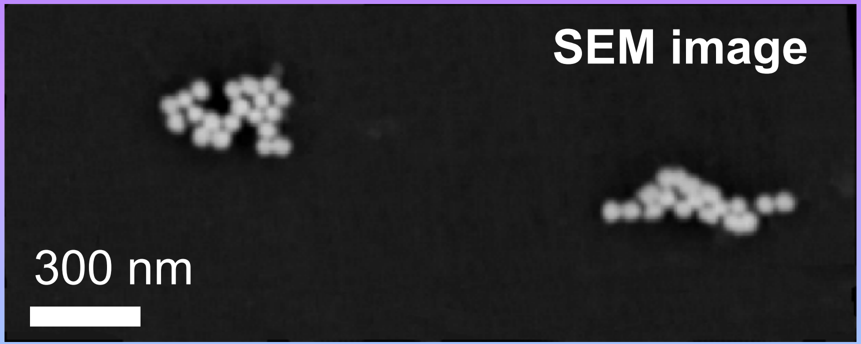
H. Chapman

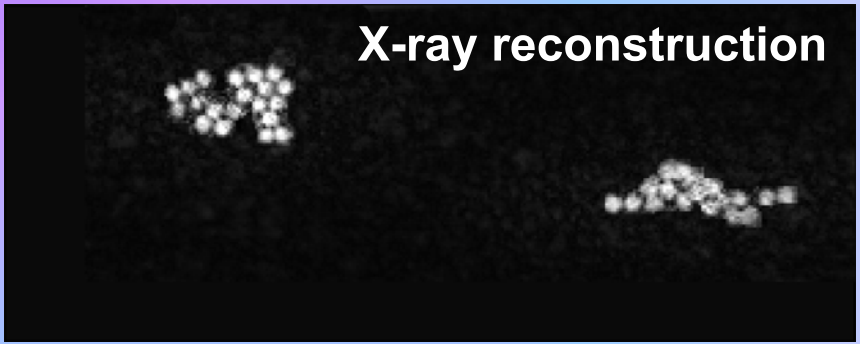
Diffraction-imaging experiment (at ALS)



λ = 1.6 nm, Rayleigh resolution = 10 nm





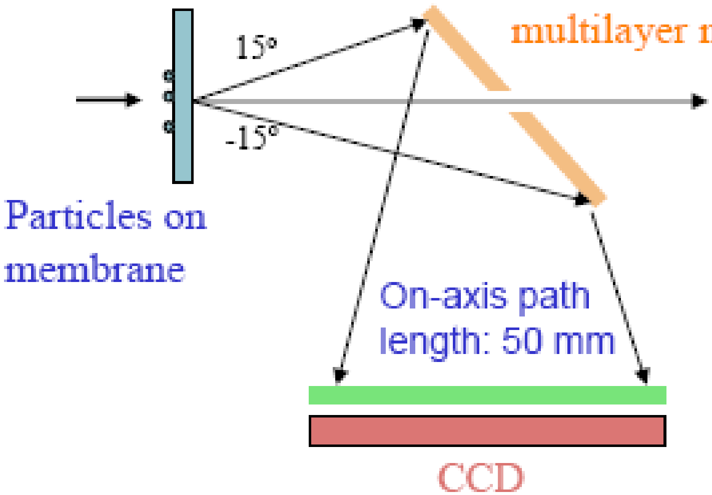


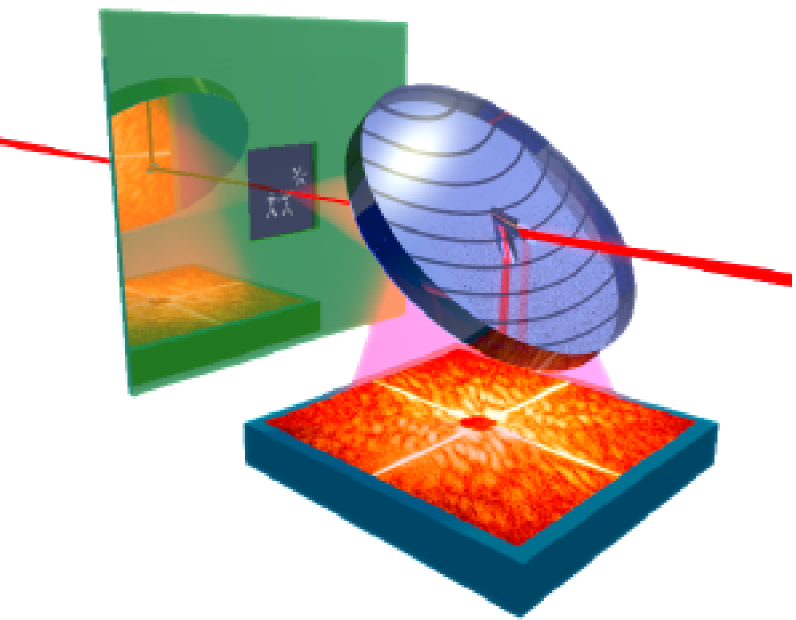
Sample: 50 nm gold spheres

Reconstruction performed with our breakthrough **shrinkwrap** algorithm

Stefano Marchesini, Anton Barty, Malcolm Howells, John Spence , Abraham Szoke, Henry Chapman

CAMERA USED in the VUV-FEL EXPERIMENTS
Multilayers: Sasa Bajt, Engineering: Bruce Woods (LLNL)





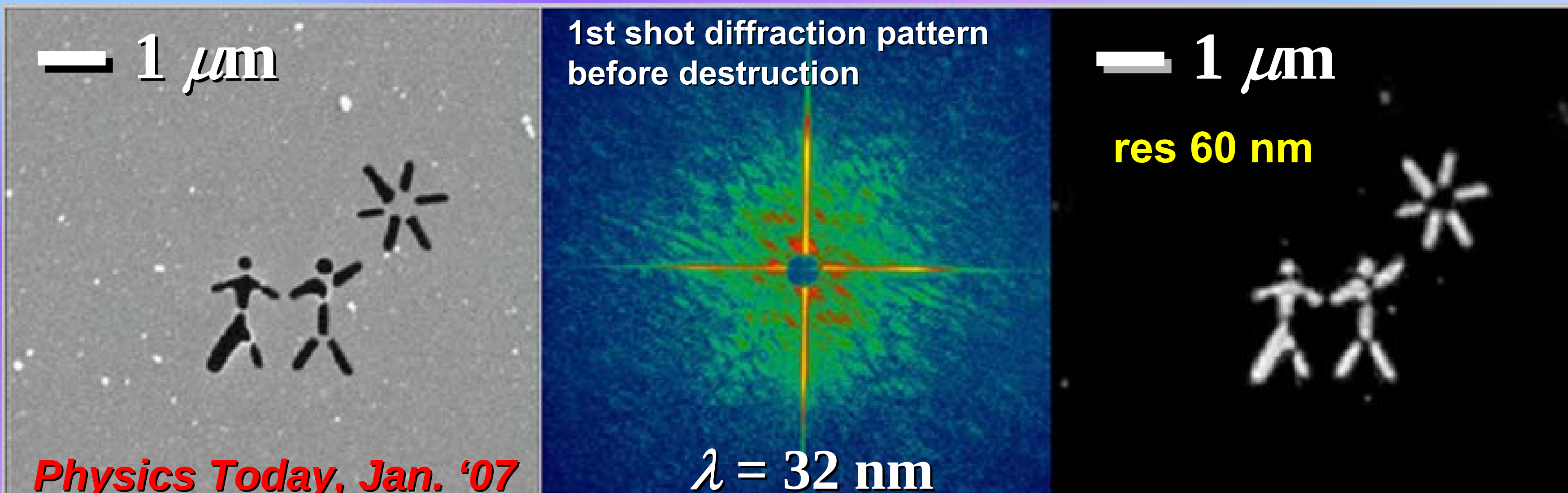
Multilayer mirror:

Si, Mo, and B_4C, gradually increasing from 18 nm to 32 nm period. Variation matches angle of incidence (30° to 60°) to maintain Bragg condition for λ = 32 nm.

Reflectivity: 45% over the surface for 32 nm.

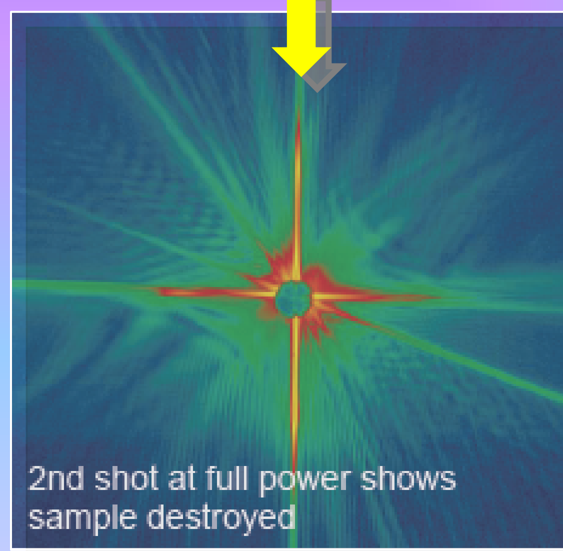
The mirror protects the CCD and works as a
(i) bandpass filter (bandwidth = 9 nm at 45°)
(ii) filter for off-axis stray light (1% reflectivity)

Image Reconstructed from an Ultra-Fast (25 fs) FEL Diffraction Pattern at *FLASH*



Starting Image

(etched into silicon nitride film)



Reconstructed Image

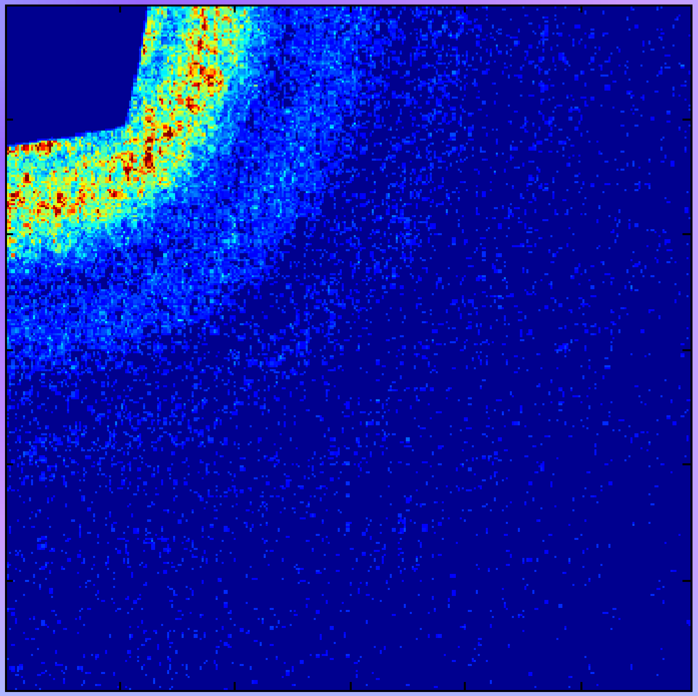
The 20-μm-wide square film was destroyed by the laser pulse, but a computer algorithm reconstructed the original image from the diffraction pattern.

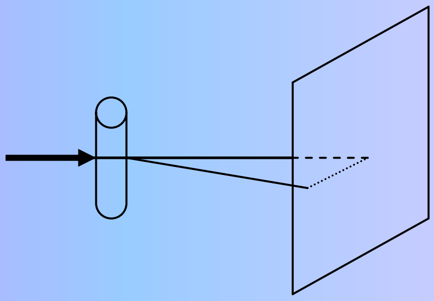
H. Chapman, J. Hajdu

Reconstruction by A. Barty, Feb. '06

Dynamics

Silica: 2610 Å, ΔR/R=0.03, 10 vol% in glycerol, T=-13.6C, η ≈ 56000 cp





22μm direct illumination
1k x 1k CCD

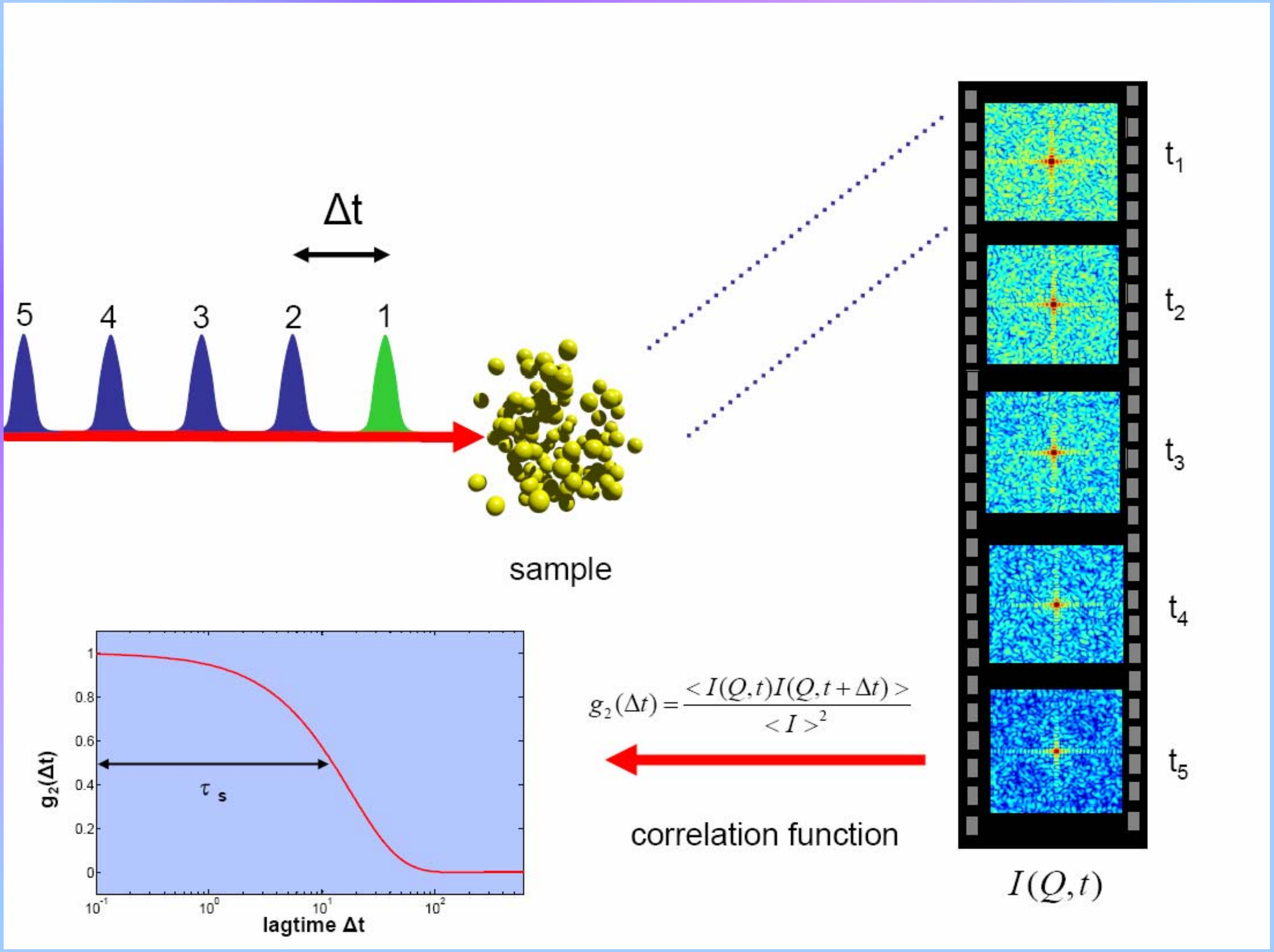
1 MHz ADC

1 s exposure
4 s overhead

today: τ ≈1 s

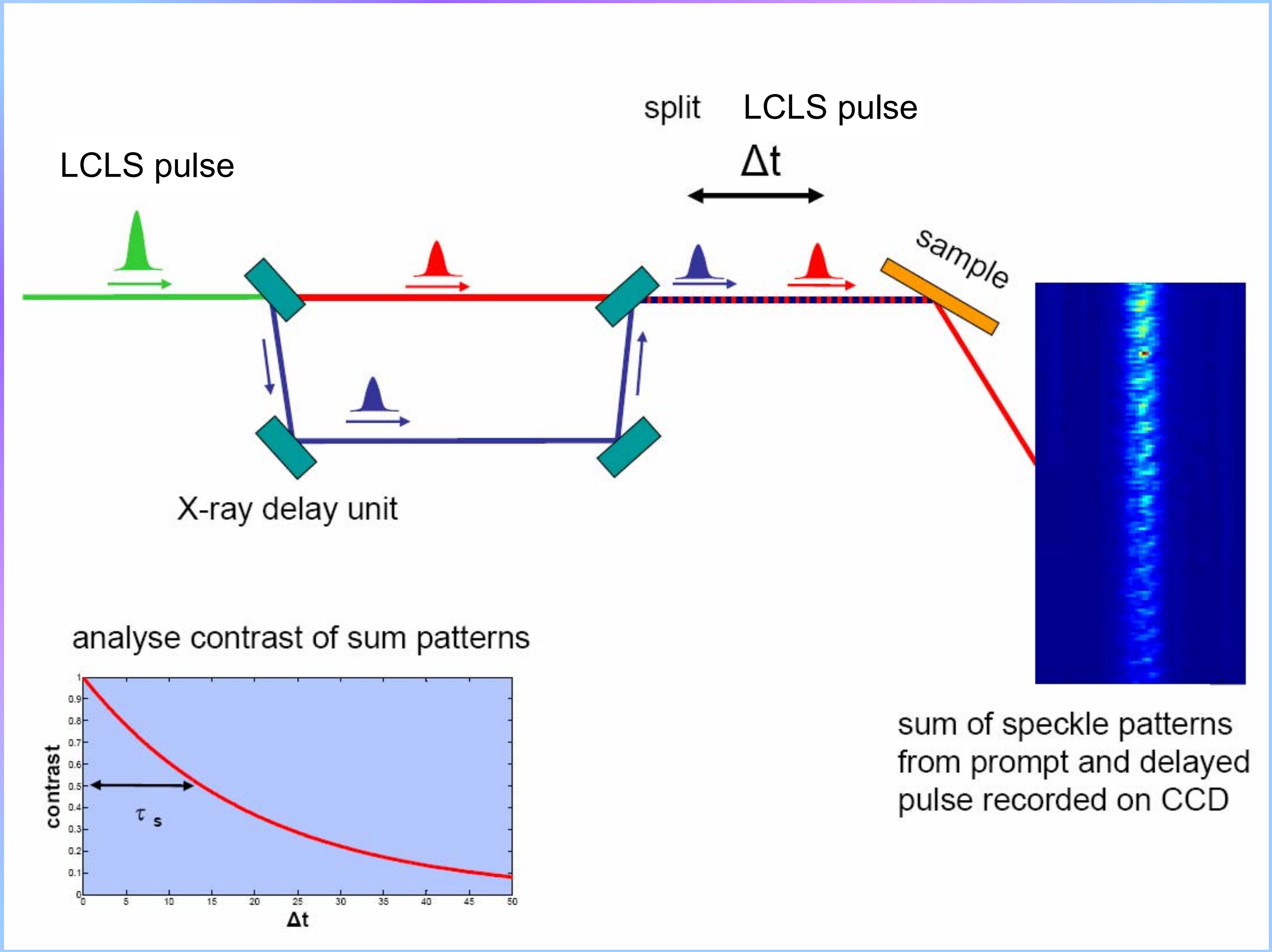
V. Trappe and A. Robert

XPCS set-up: movie mode



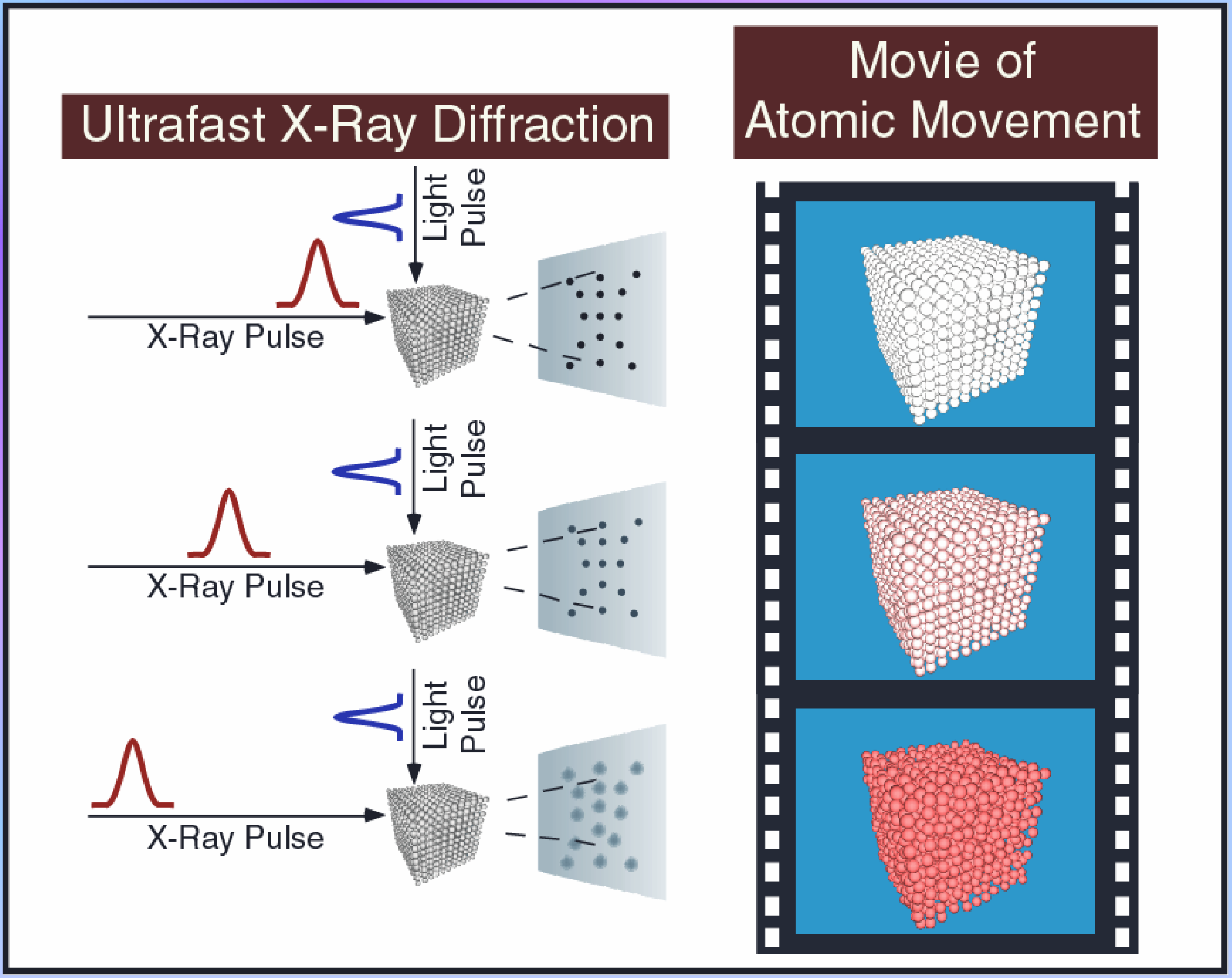
"Movie" Mode: > 0.1 s (luminosity limited)

XPCS set-up: delay line mode



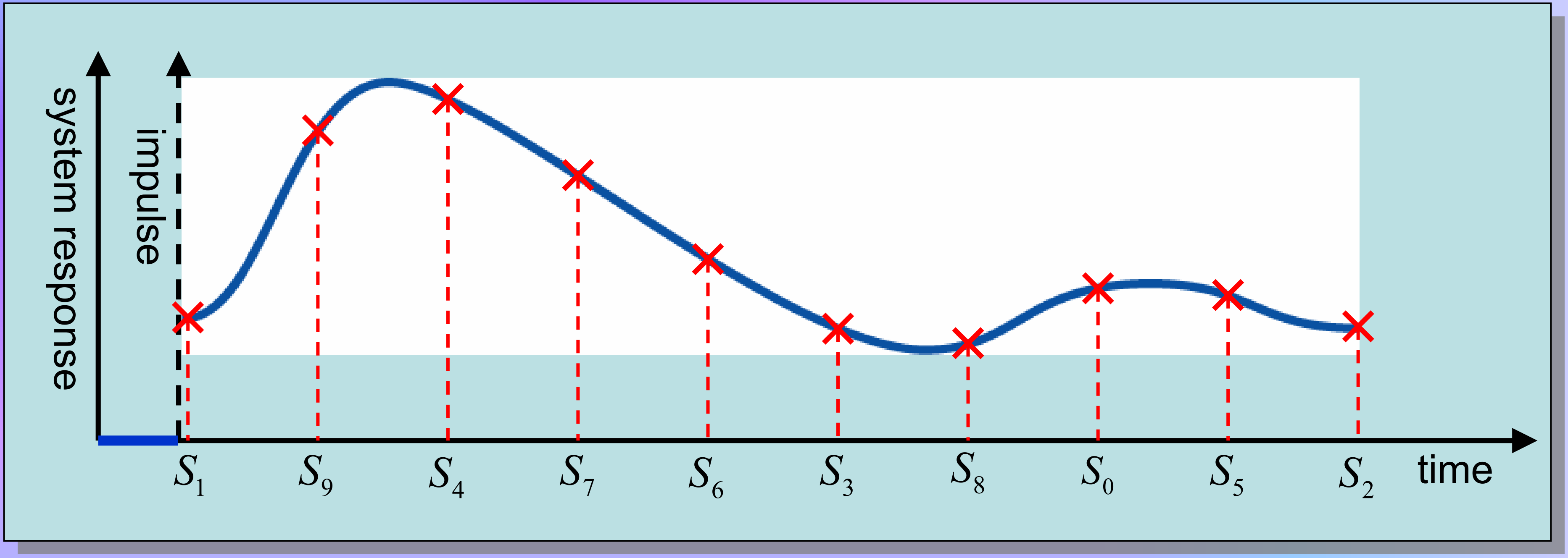
"Delay Line" Mode: 1ps < Δt < 10ns (1 ps ⇔ 0.3 mm; 1ns ⇔ 3000 mm)

Scattering experiments



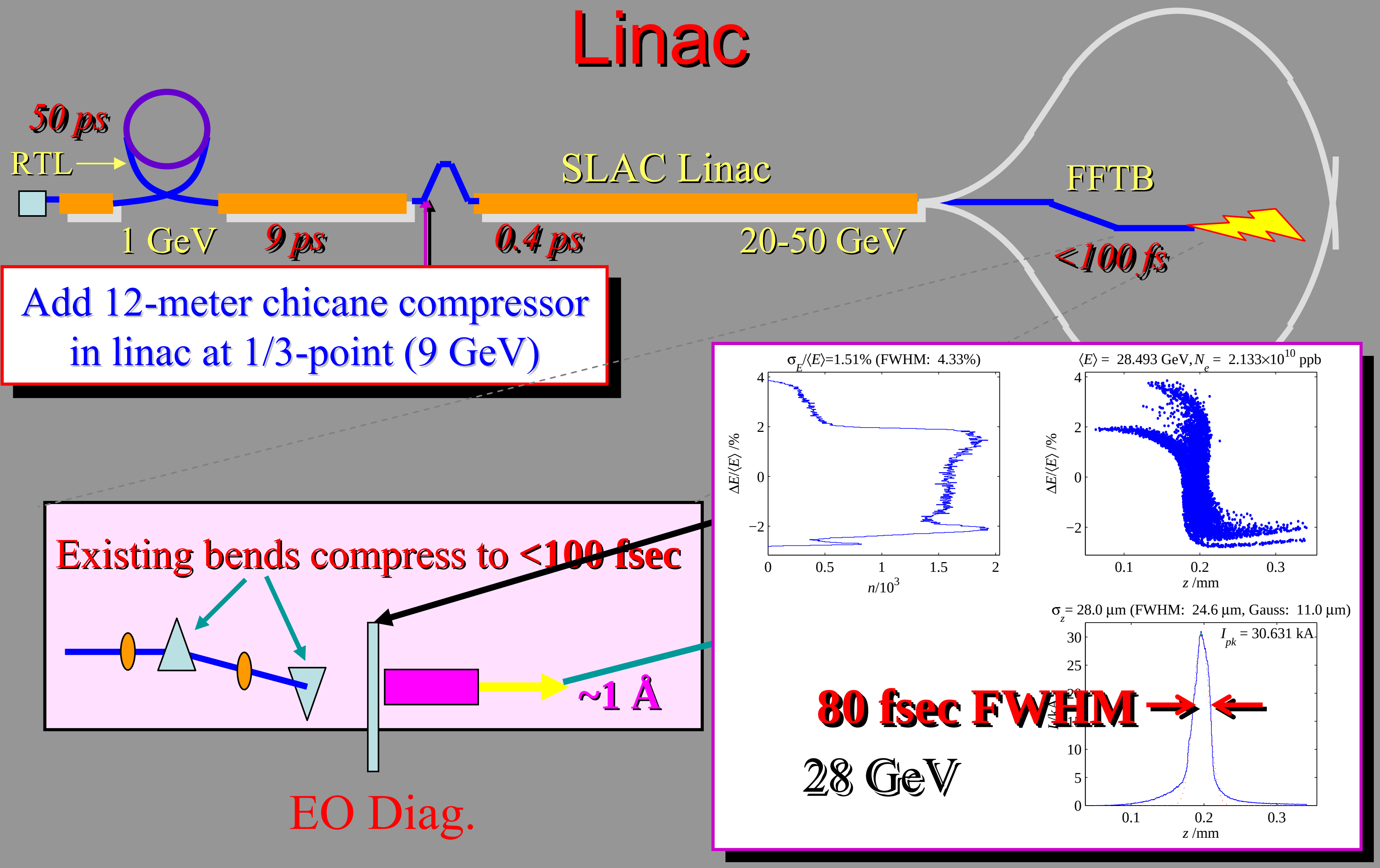
EOS and "Pump-Probe"

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

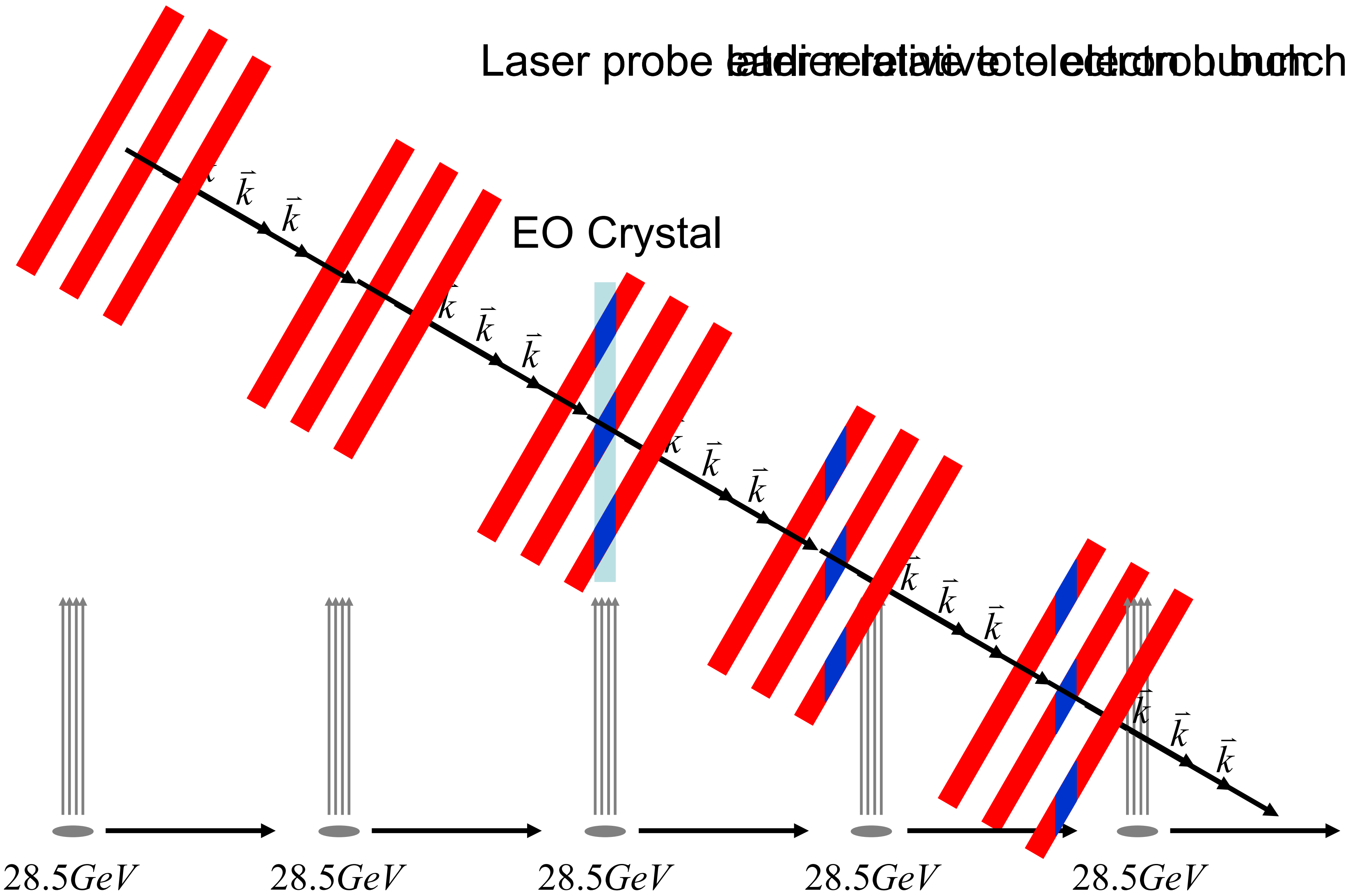


- Electro-Optic Sampling (EOS) delivers arrival time to users
  - Pump-Probe experiments now possible at XFELs
  - Machine jitter exploited to sample time-dependent phenomena

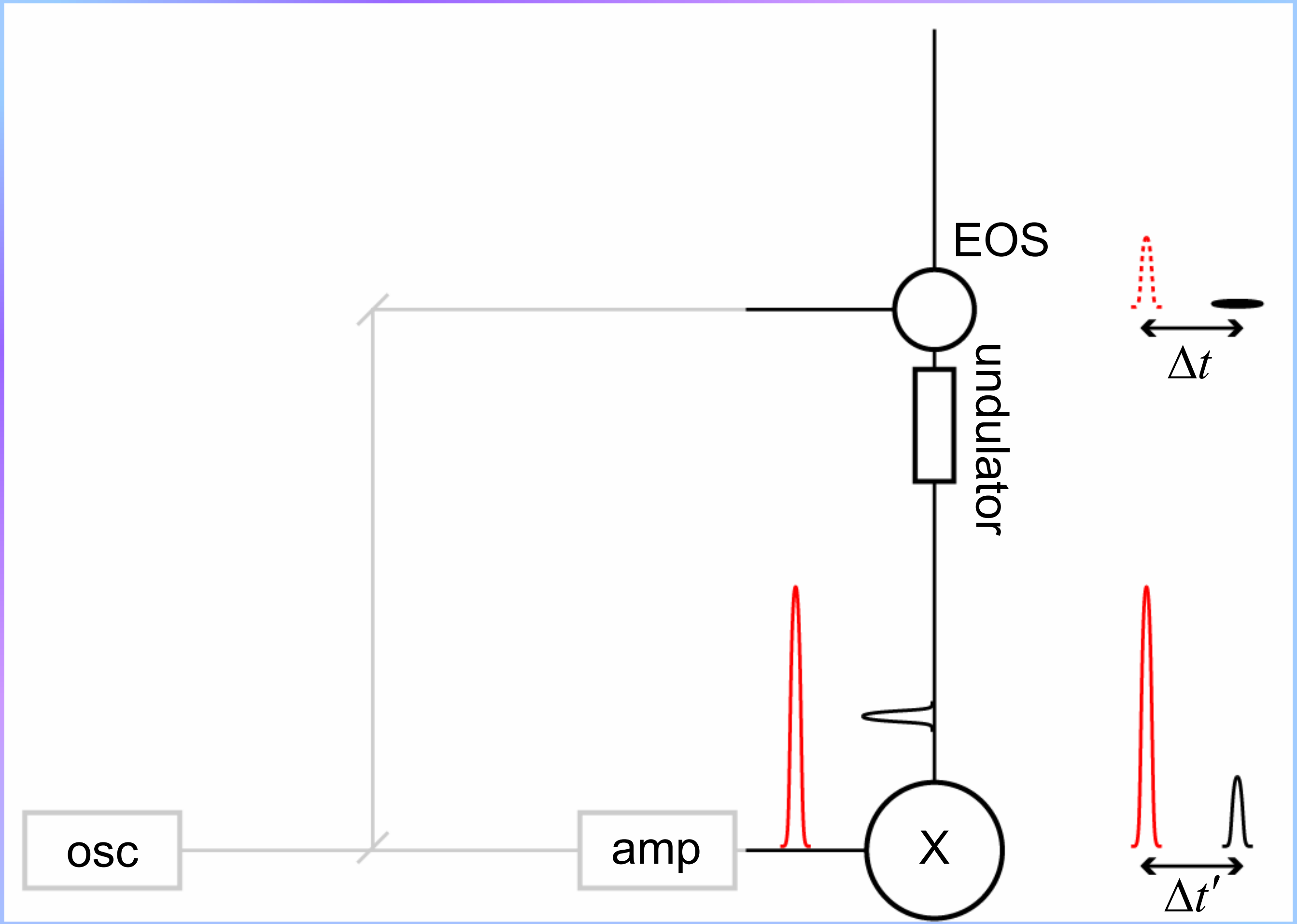
Short Bunch Generation in the SLAC Linac



Spatially Resolved Electro-Optic Sampling



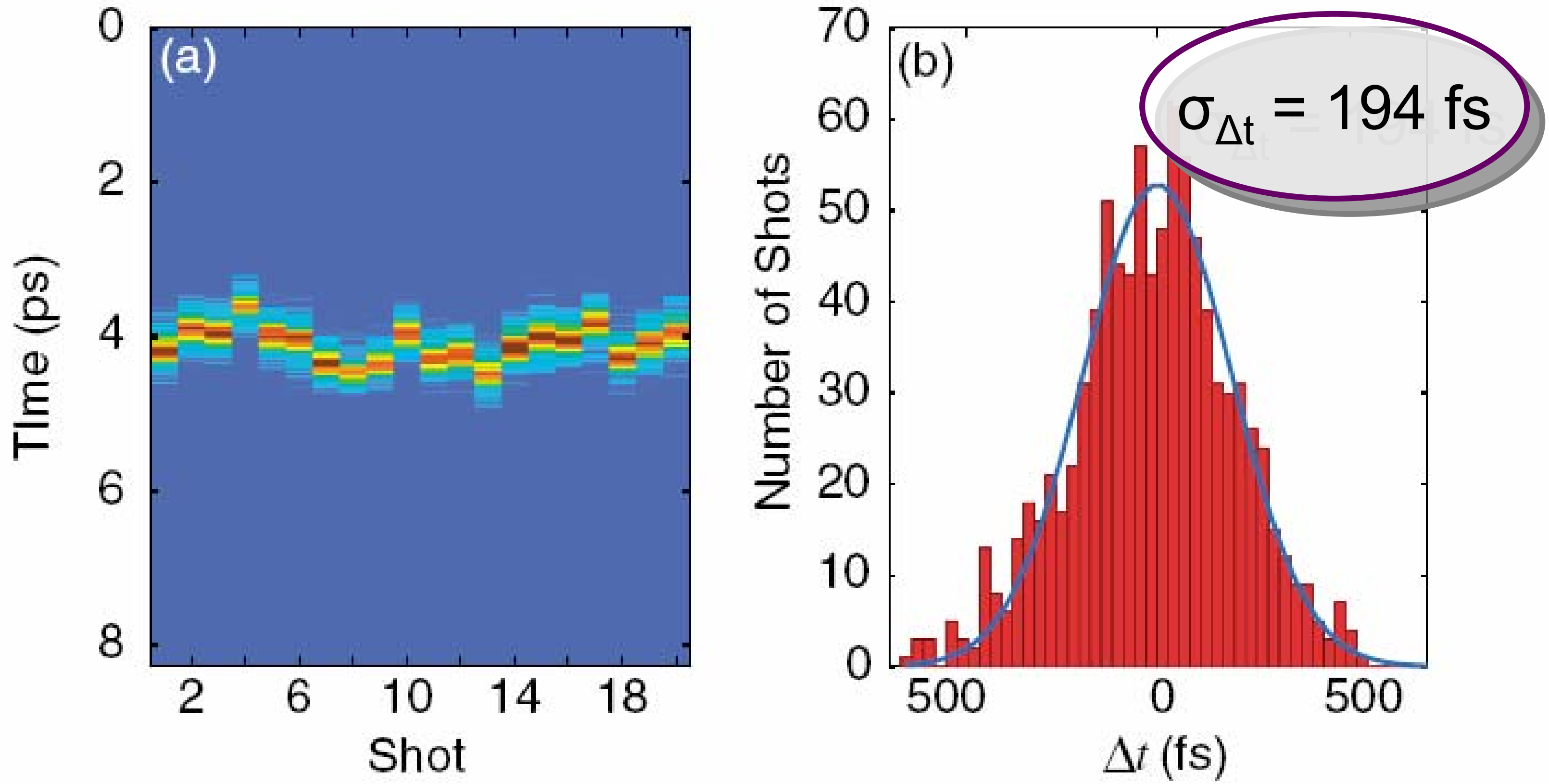
Indirect X-ray Pulse Arrival Time



EOS timing applicable if optical path lengths remain constant

A. Cavalieri *et al*., Phys. Rev. Lett. 94 144801, 2005

Single-Shot EOS Data at SPPS (200μm ZnTe) (best)



20 shots

jitter

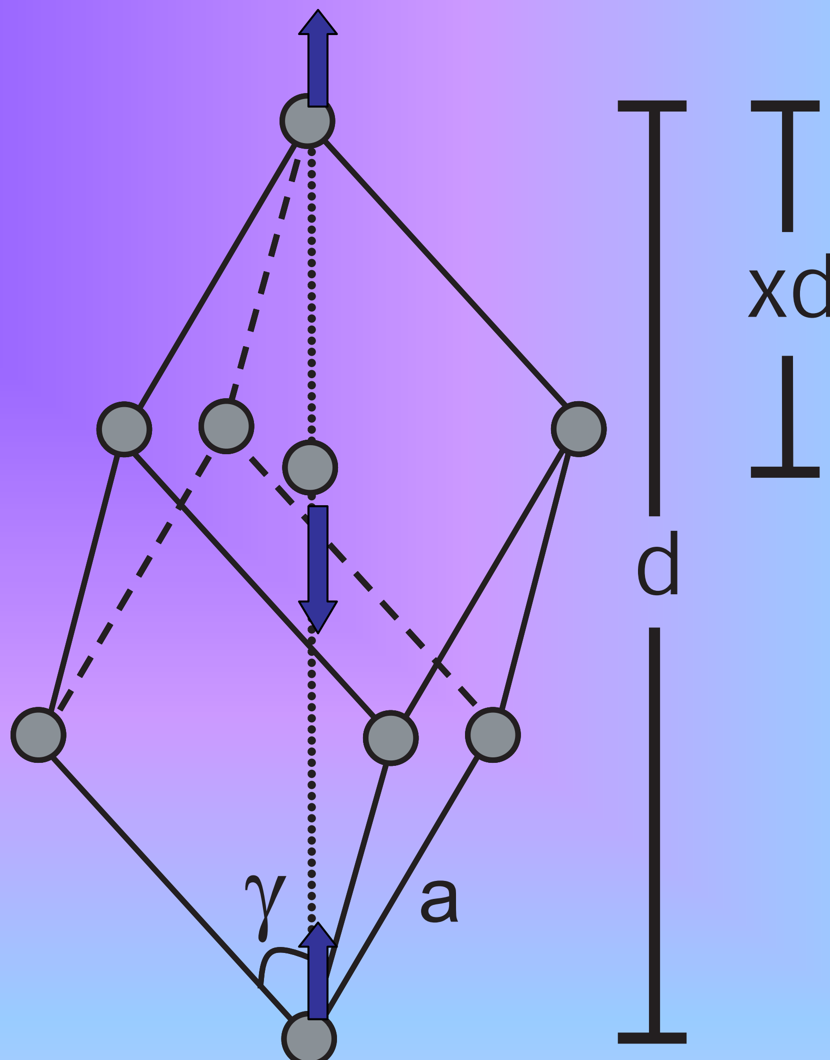
Bi Structure

$$\gamma = 57.35^o$$

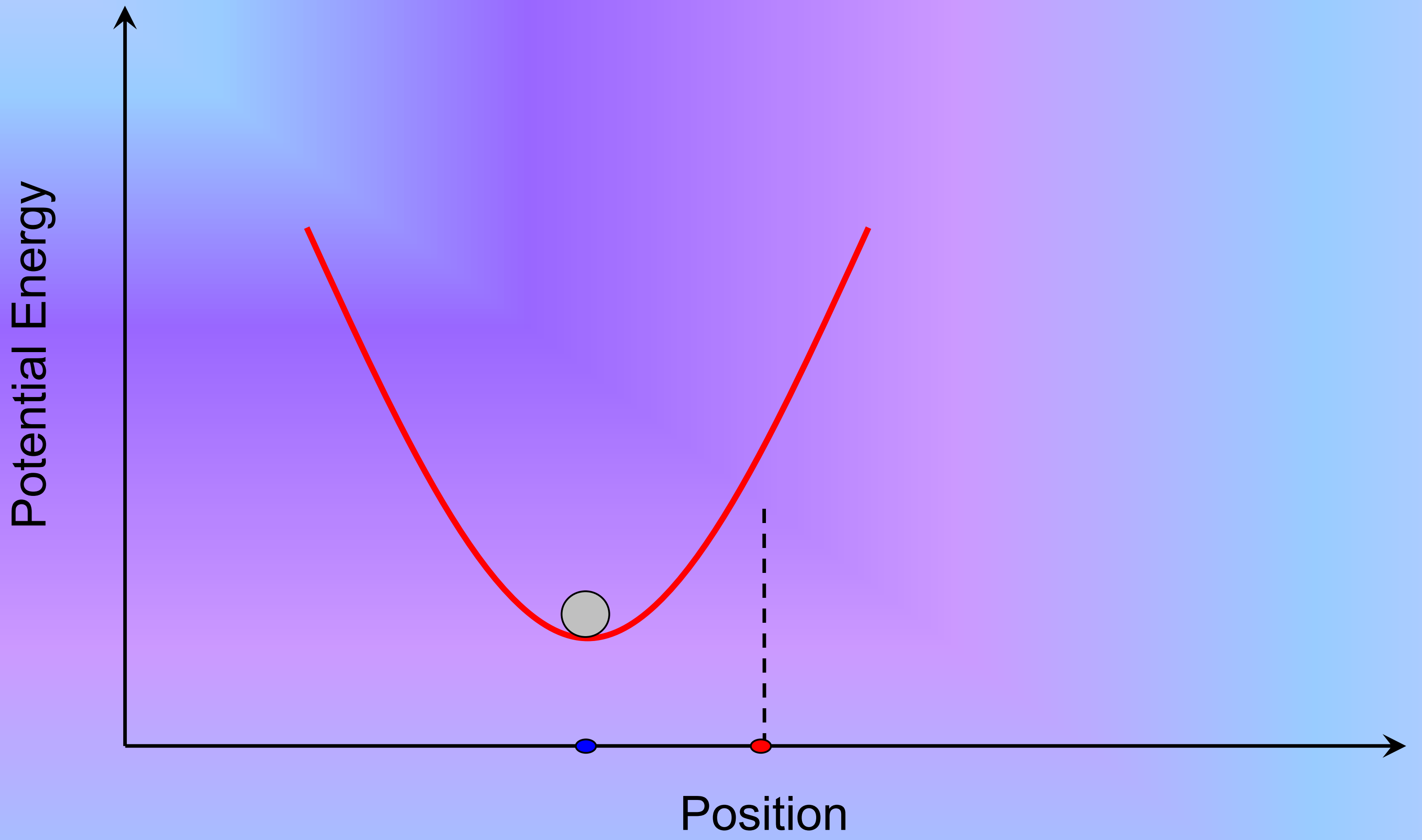
$$a = 0.47\,nm$$

$$d = 1.18\,nm$$

$$x_o = 0.46814$$

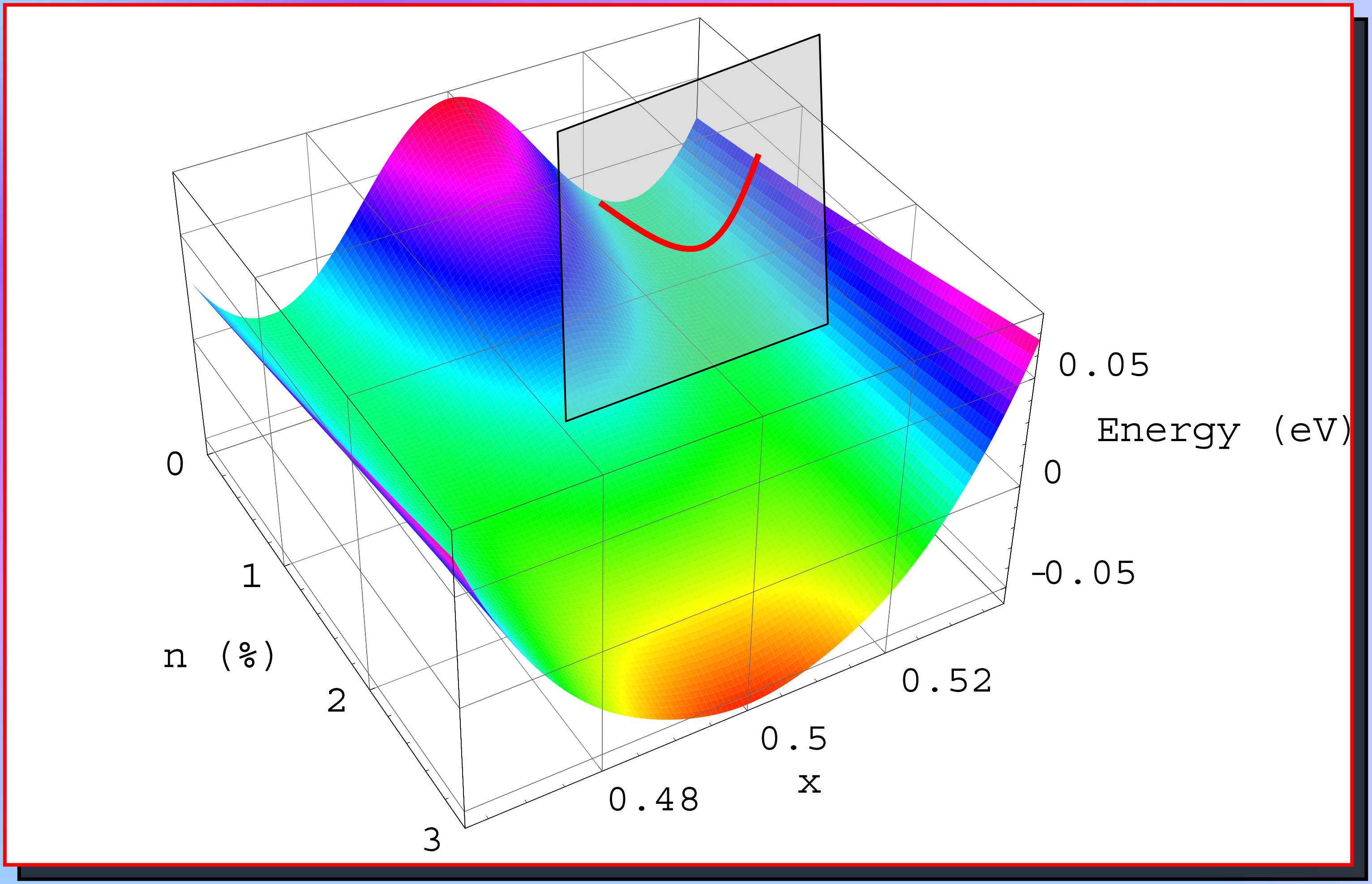


Displacive Excitation



Interatomic potential is altered impulsively, exciting a coherent phonon mode

Density functional calculations of the Bi photoexcited interatomic potential (photon energy = 1.5 eV)

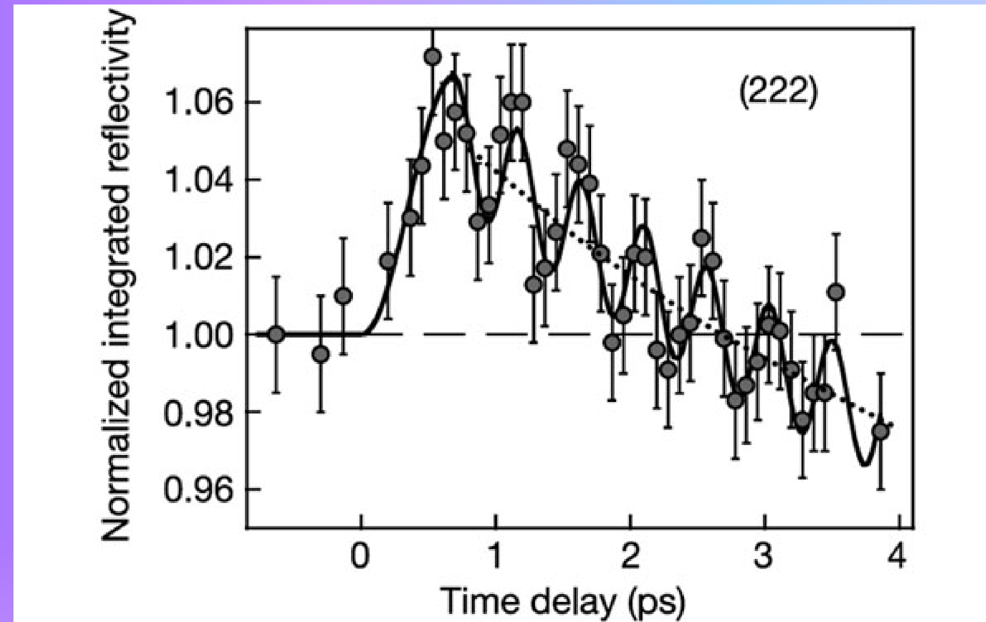


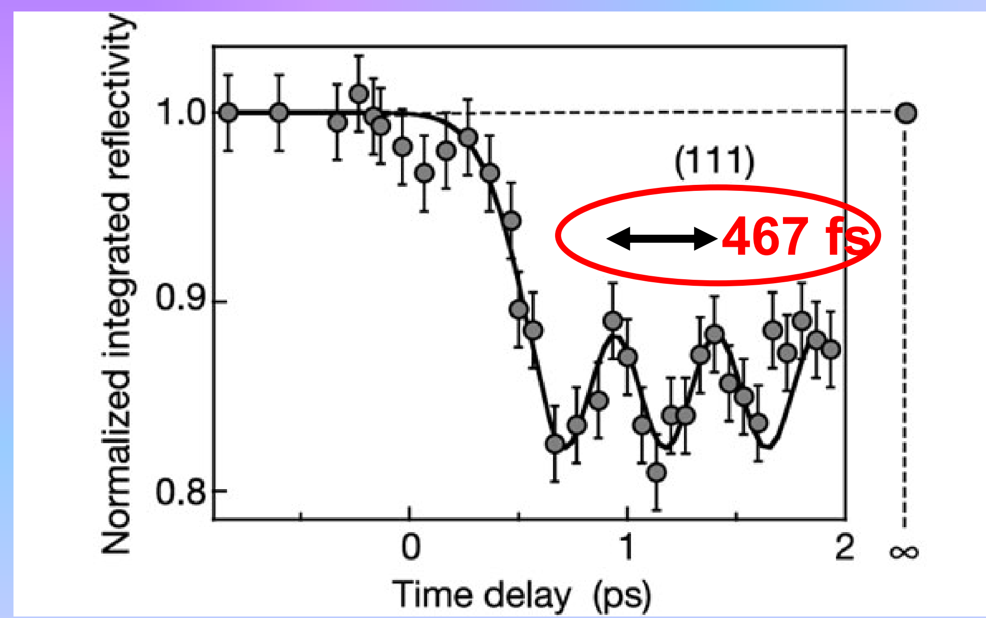
Eamonn Murray & Stephen Fahy, University College, Cork, Ireland
Murray *et al.* PRB 72, 060301 (R) 2005.

Femtosecond X-ray measurement of coherent lattice vibrations near the Lindemann stability limit

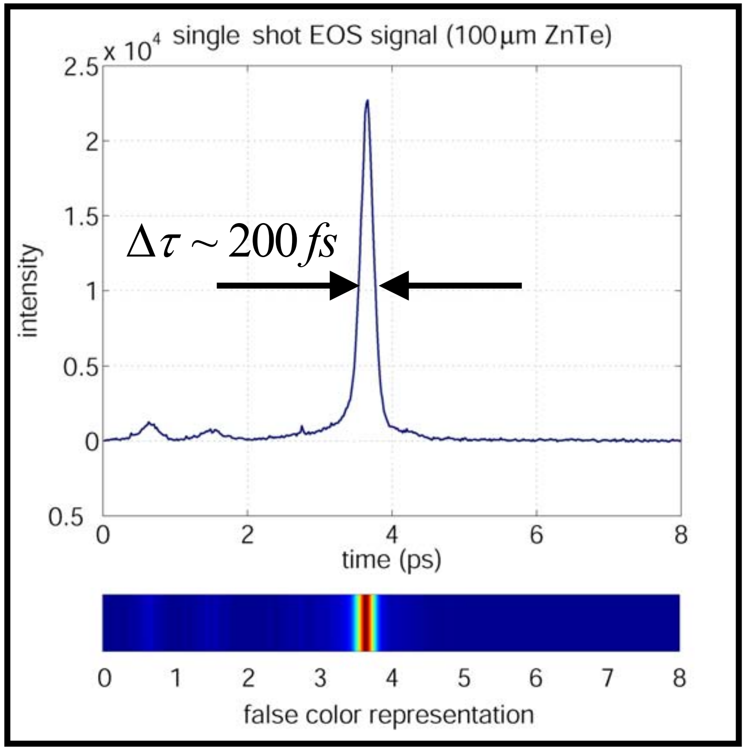
Klaus Sokolowski-Tinten*, Christian Blome*, Juris Blums*, Andrea Cavalleri†, Clemens Dietrich*, Alexander Tarasevitch*, Ingo Uschmann‡, Eckhard Förster‡, Martin Kammler§ Michael Horn-von-Hoegen* & Dietrich von der Linde*

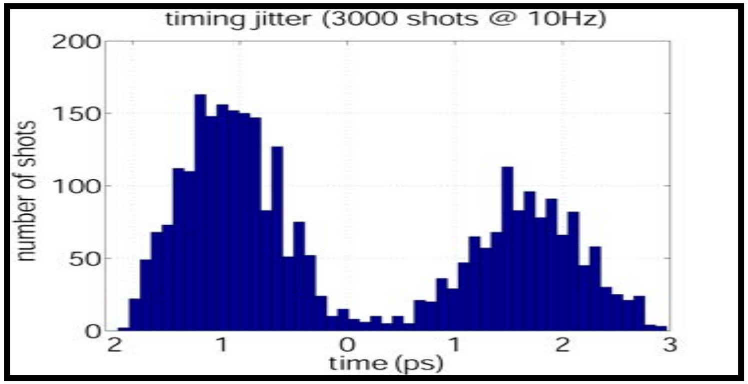
Nature 422, 287 (2003)

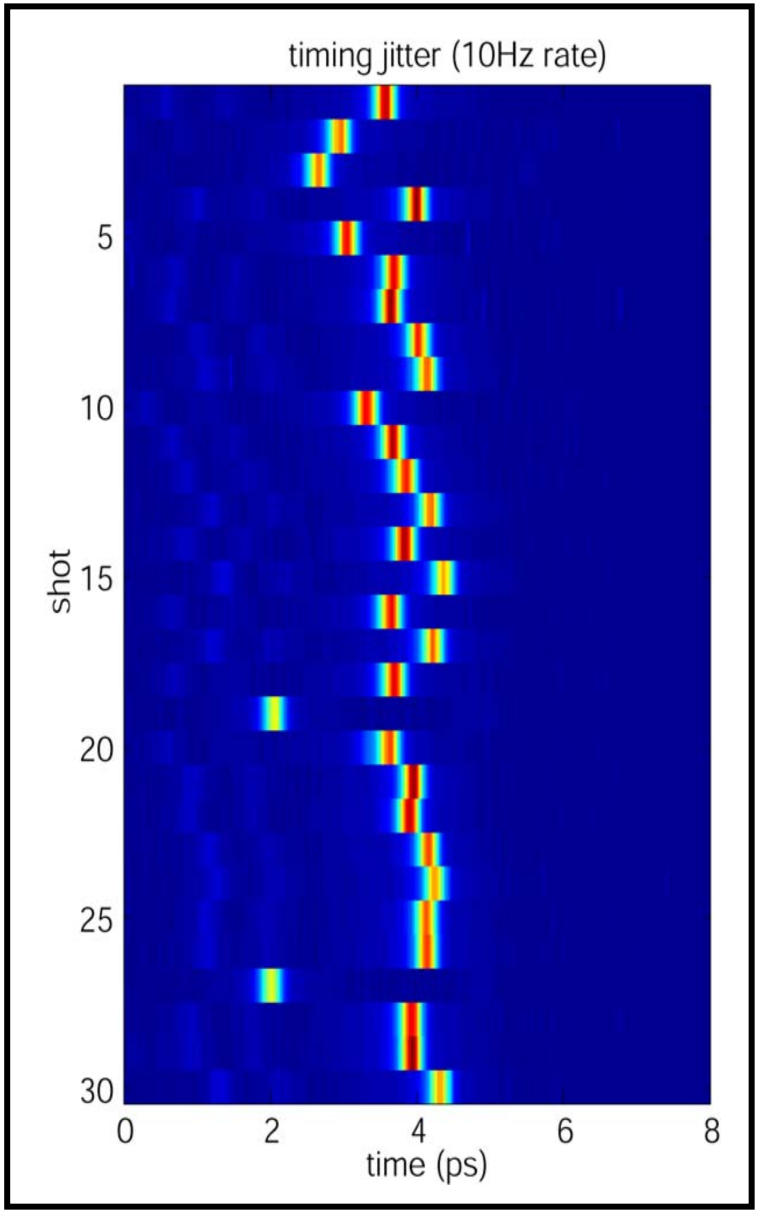




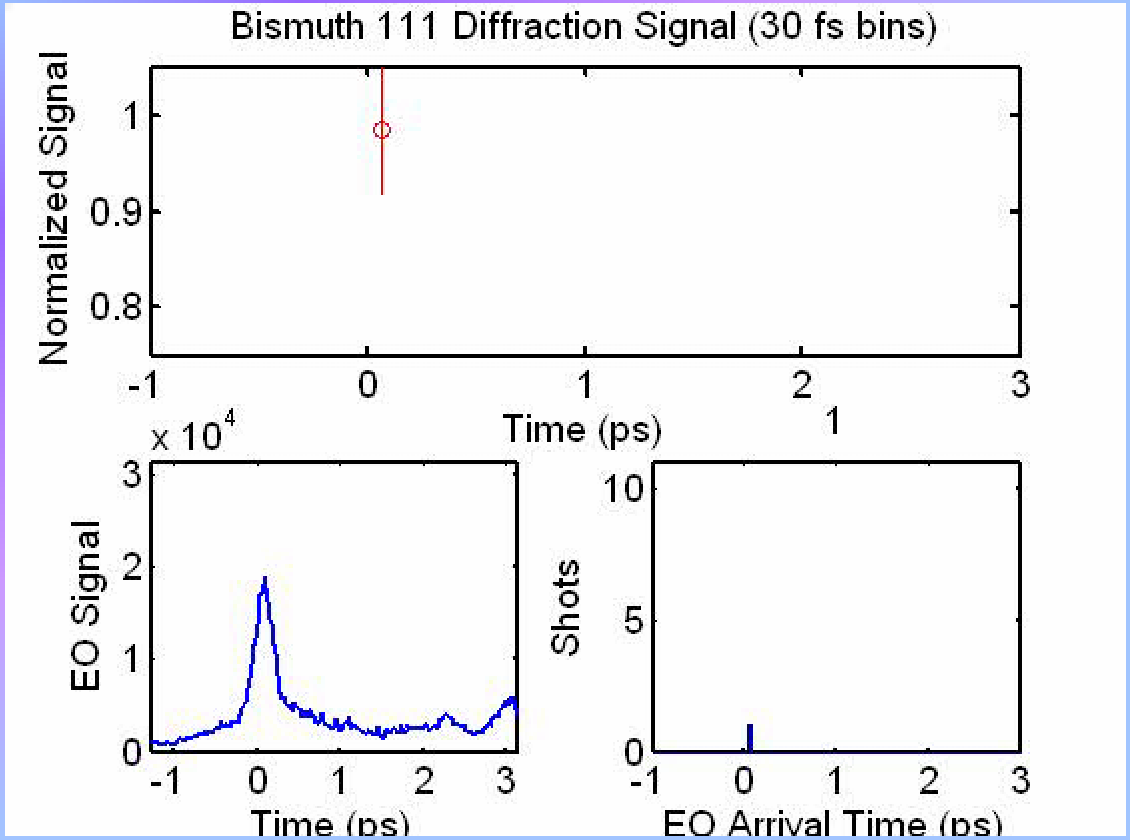
(Typical)Single-Shot EOS Data at SPPS (100µm ZnTe)





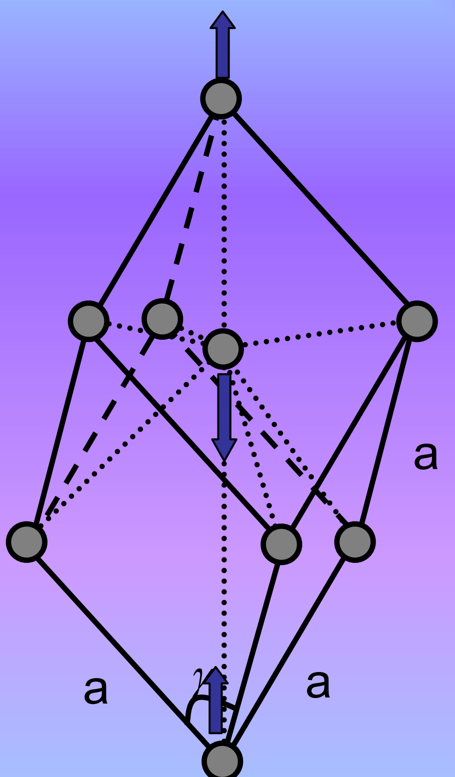


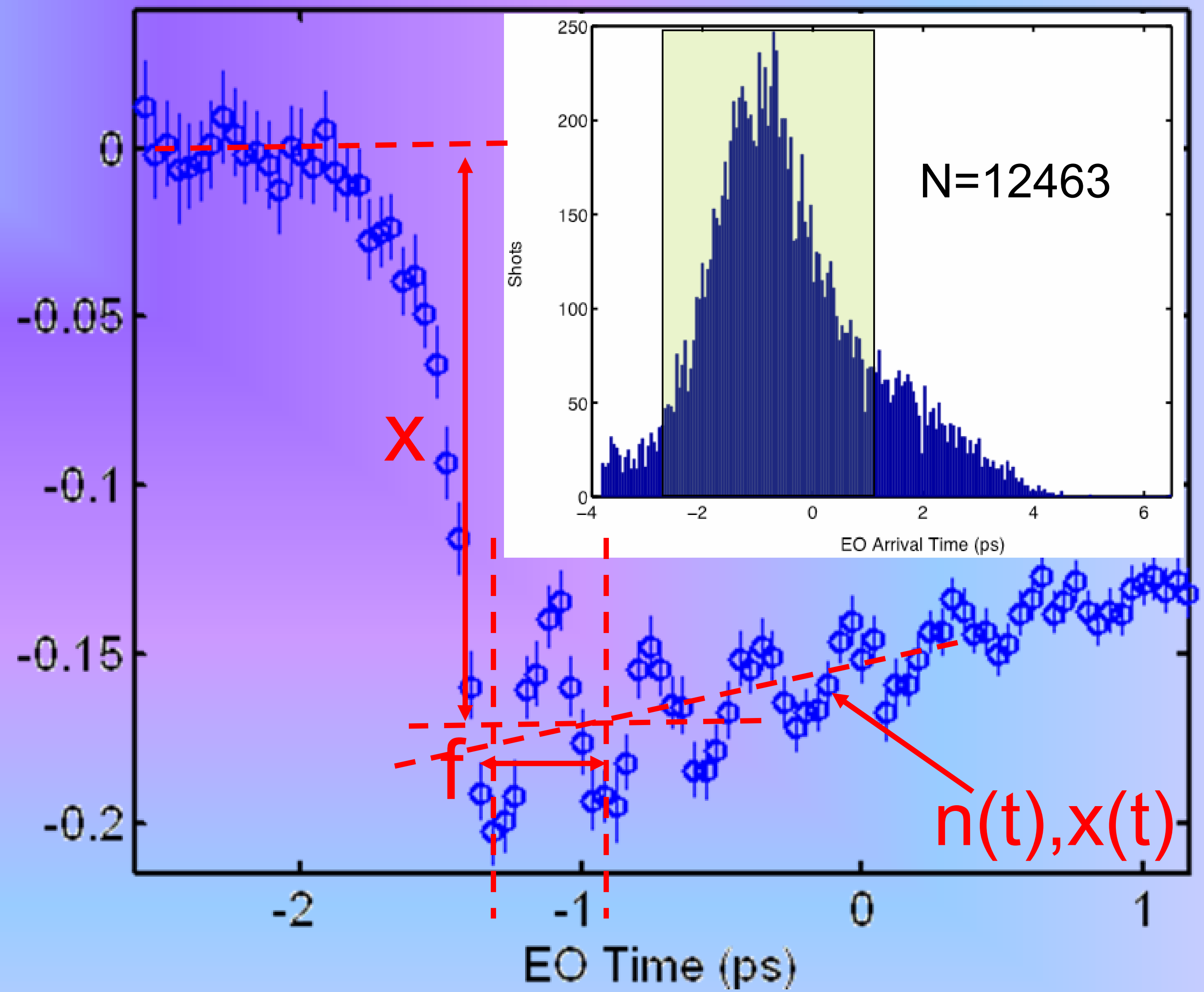
Using the jitter at SPPS for Random Sampling



D. M. Fritz *et al.* unpublished

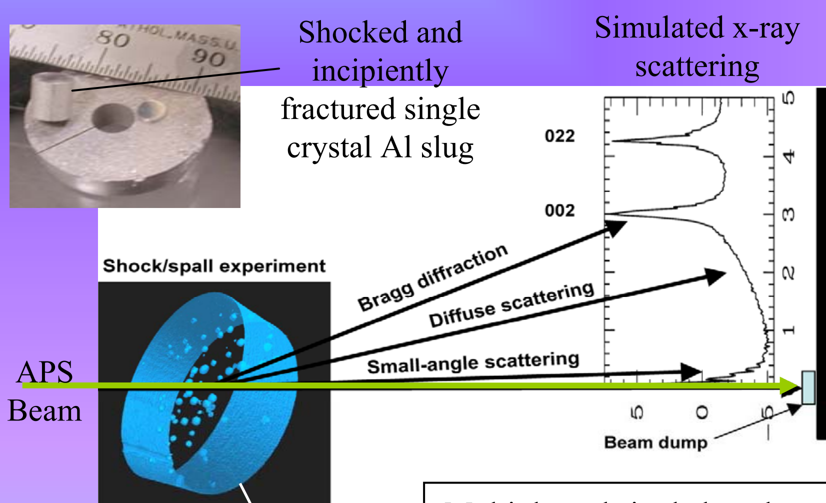
Ultrafast measurement of atomic displacements





High brightness of LCLS will enable unique studies of *in situ* material failure

Current:
Post Processing x-ray scattering

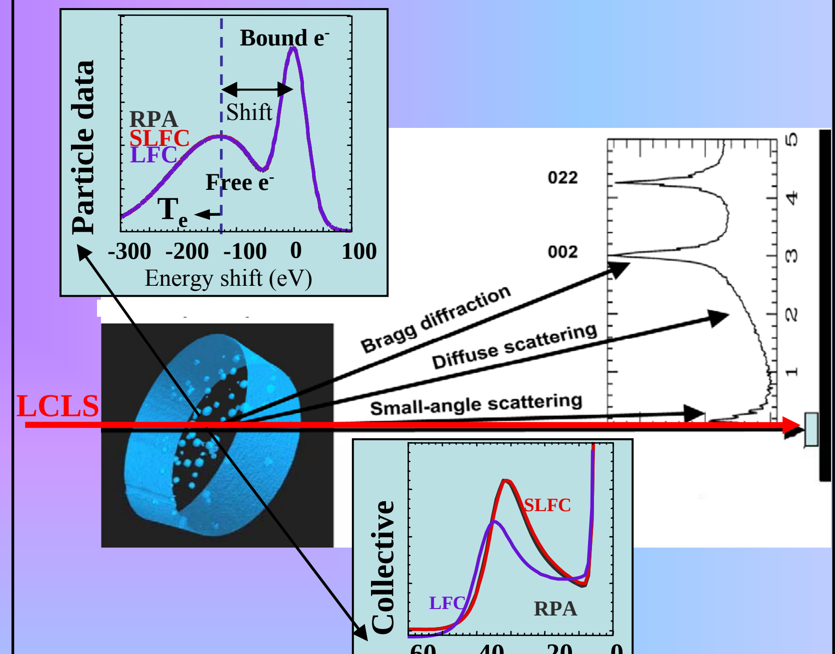


3-D x-ray tomographic reconstruction of dynamic fracture

Multiple and single bunch x-ray scattering from shock recovered samples in progress

- ***Diffraction* → *lattice compression and phase change***
- ***SAXS* → *sub-micron defect scattering***
- ***Diffuse* → *dislocation content and lattice disorder***

Future:
Measure during pressure pulse

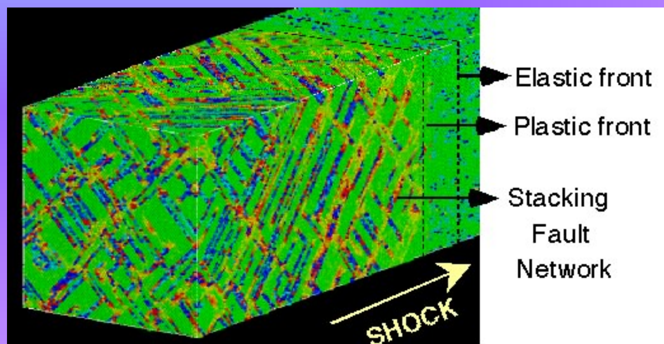


- **LCLS will provide unprecedented fidelity to measure dynamics of the microstate with sub-picosecond resolution**

R. Lee

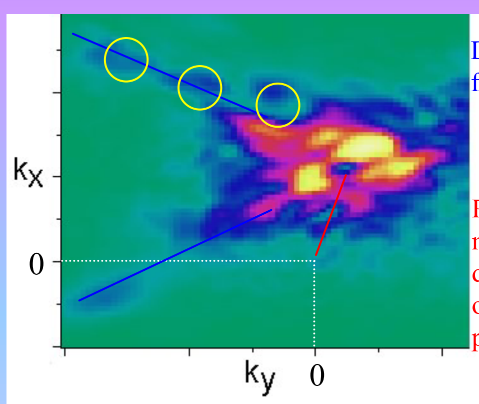
LCLS enables real-time, *in situ* study of deformation at high pressure and strain rate

Current Status
Simulation Classical scattering



• MD simulation of FCC copper

Periodic features ⇒ average distance between faults



Diffuse scattering from stacking fault

Peak diffraction moves from 0,0 due to relaxation of lattice under pressure

• X-ray diffraction image using LCLS probe of the (002) shows *in situ* stacking fault information

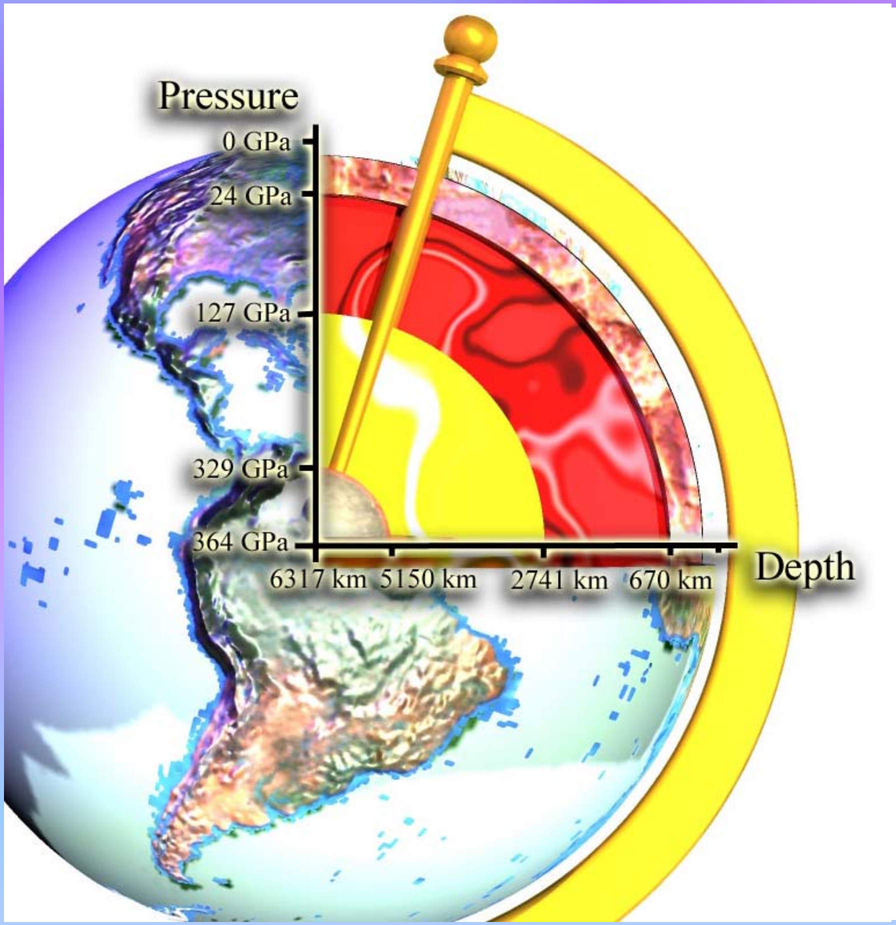
Future with LCLS
Unique capabilities

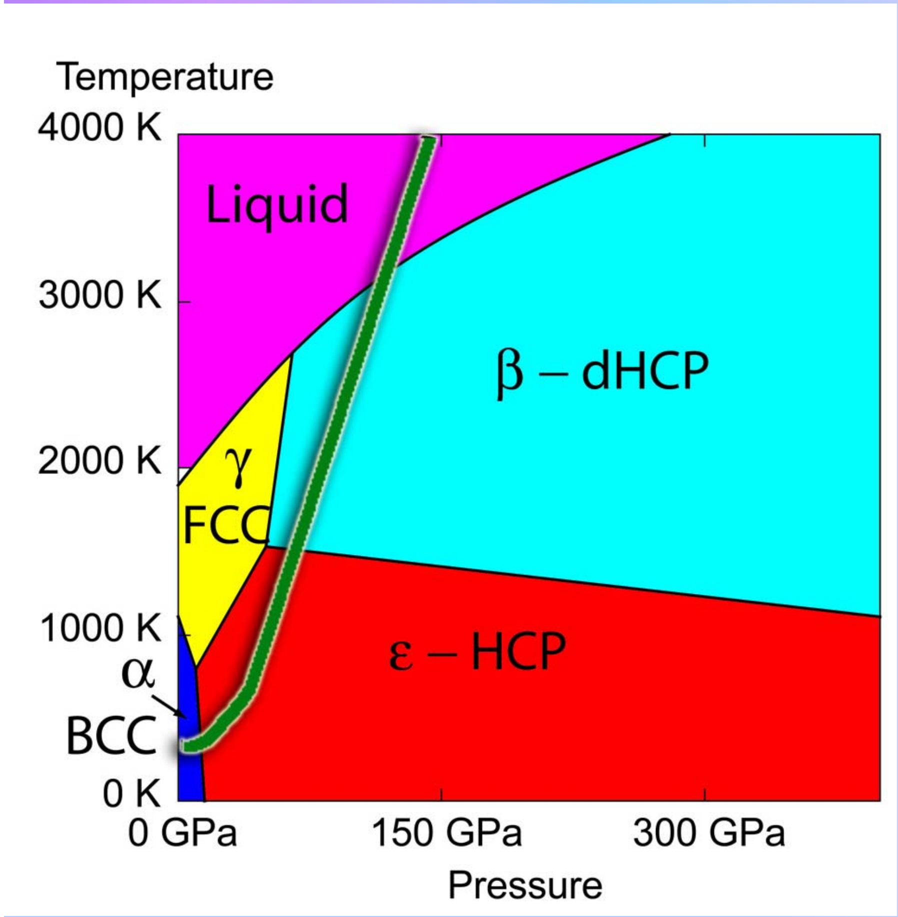
- **Imaging capability**
  - **Point projection imaging**
    - **Phase contrast**
    - **High resolution (sub-µm)**
  - **Direct determination of density contrast**
- **Diffraction & scattering**
  - **Detection of high pressure phase transitions**
  - **Lattice structure, including dislocation & defects**
  - **Liquid structure**
  - **Electronic structure**
    - **Ionization**
    - **T_e, *f*(v)**

These complement the standard instruments, e.g., VISAR and other optical diagnostics

Iron is important due to our geophysics and developments of modern technology

- Phase diagram shows Fe is BCC at ambient conditions and under a shock goes to HCP



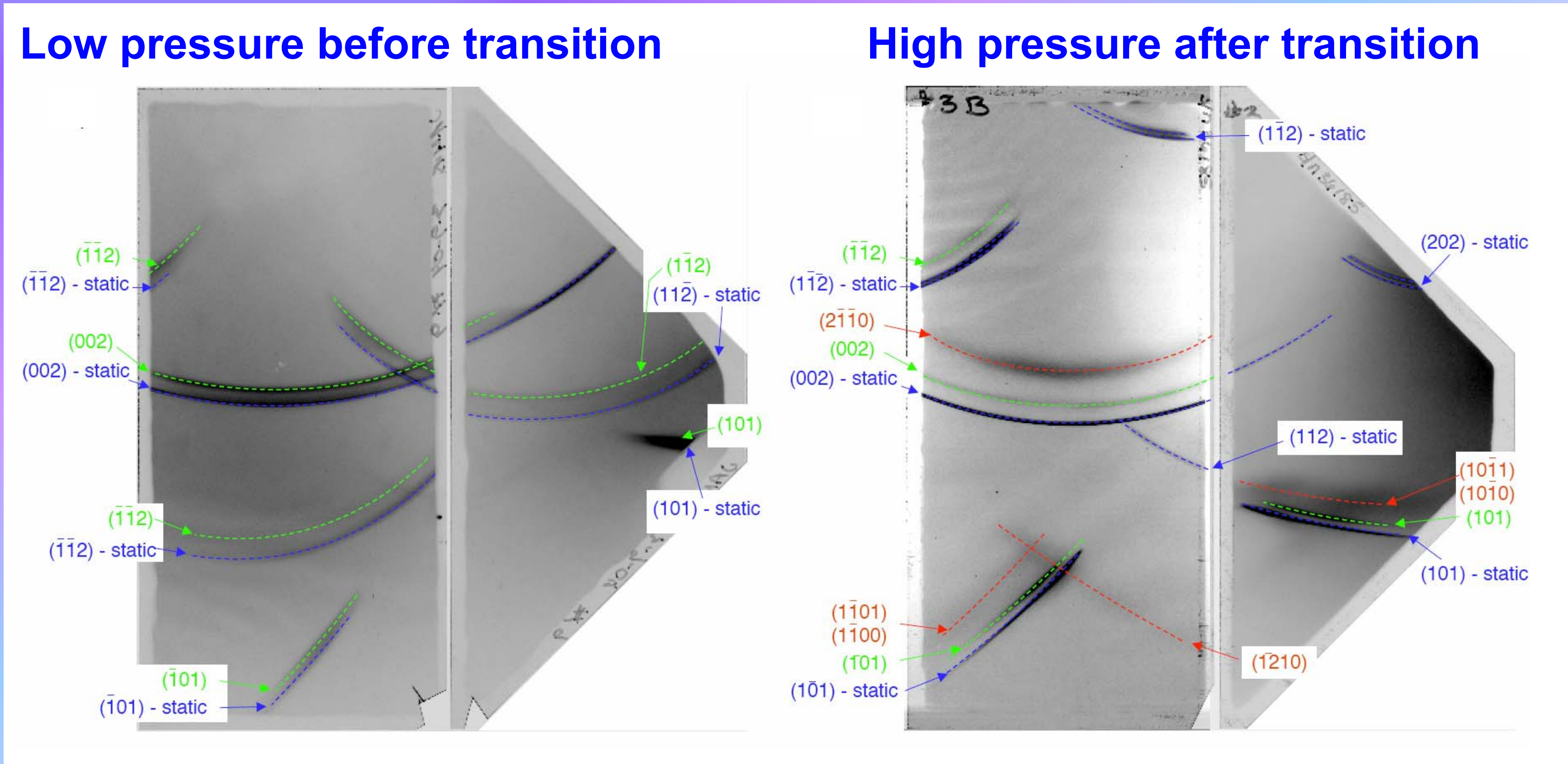


A.M. Dziewonski and D. L. Anderson
Physics of the Earth and Planetary Interiors **25**, 297 (1981).

S. K. Saxena & L. S. Dubrovinsky, American Mineralogist **85**, 372 (2000).
J. C. Boettger & D. C. Wallace, Physical Review B 55, 2840 (1997).
C. S. Yoo et al., Physical Review Letters **70**, 3931 (1993).

Phase transitions in Fe have been studied using high energy lasers with ns resolution

- Recent direct measurement of lattice showing phase transformation α–ε occurs in sub-ns time scales



BCC static

BCC compressed

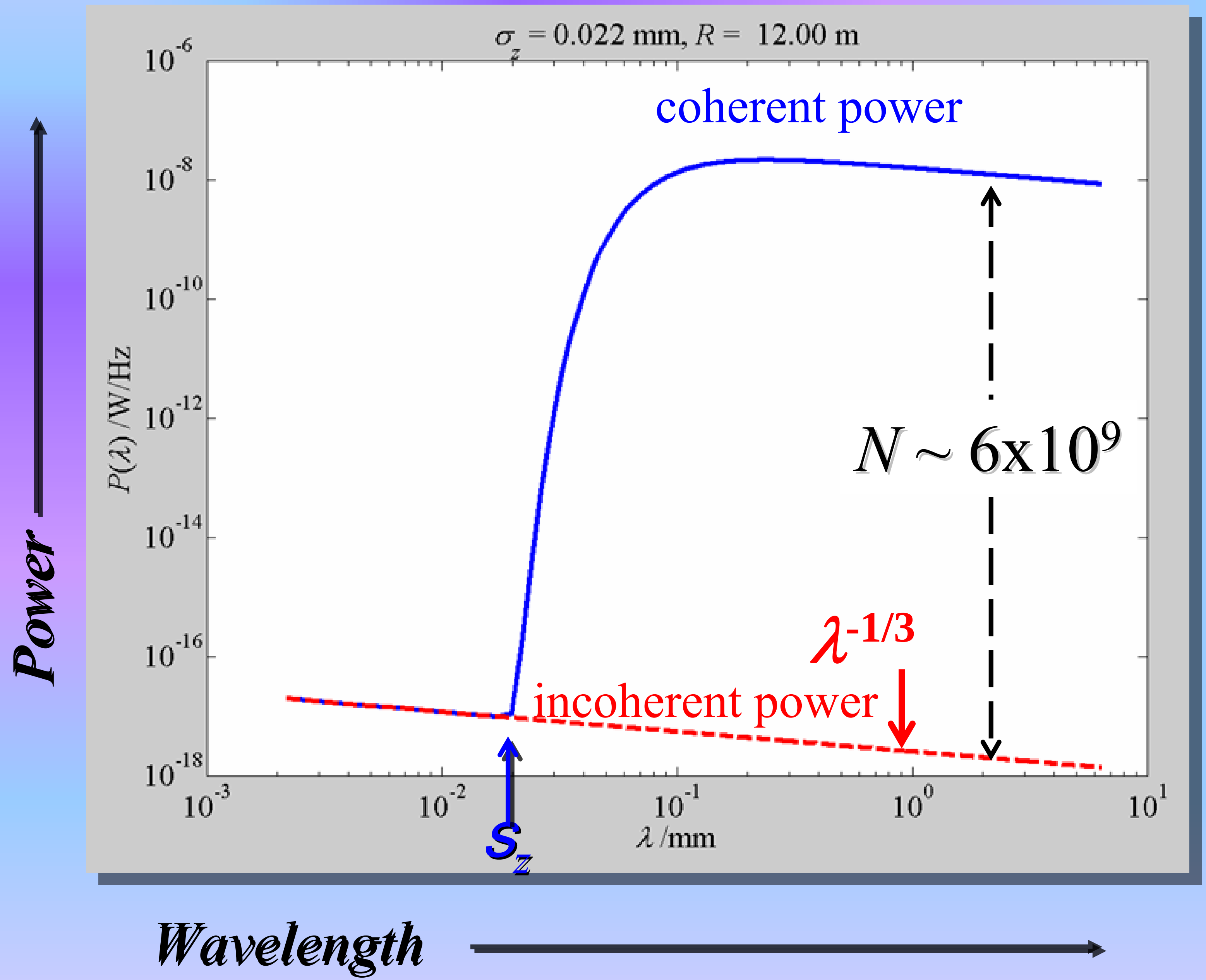
New HCP

However, the MD simulations indicates that the transition takes ~ 1 ps

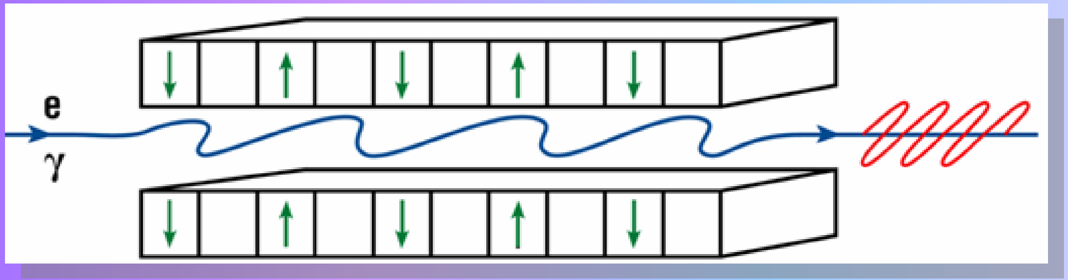
Grey = static BCC   Blue = compressed BCC   Red = HCP

- 8 million atoms, total run time 10 ps (K. Kadau LANL)
- Require LCLS to time-resolve kinetics of the transition

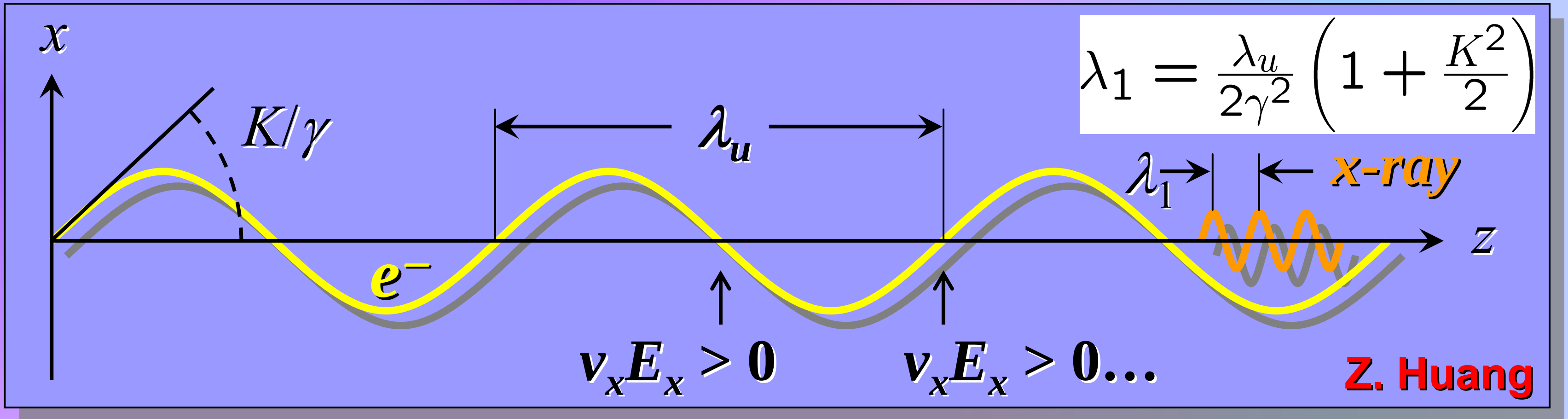
Coherent Synchrotron Radiation



FEL Principles

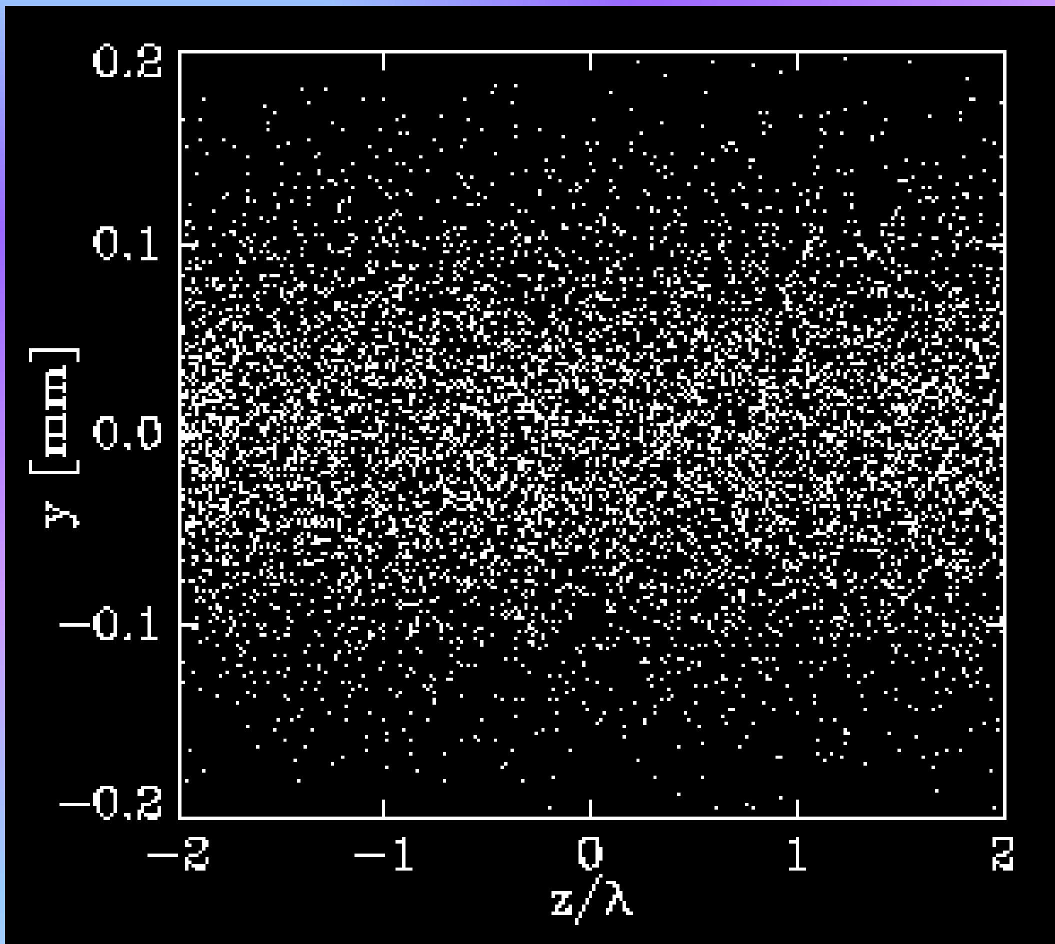


- Electrons slip behind EM wave by λ_1 per undulator period (λ_u)

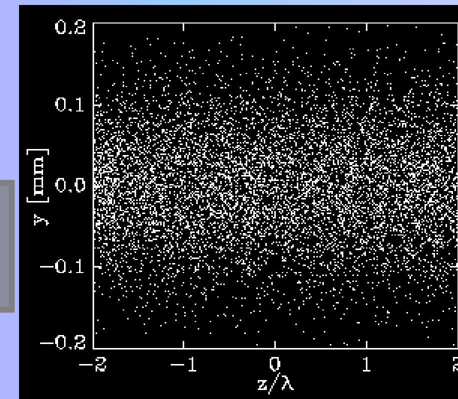


- Due to sustained interaction, some electrons lose energy, while others gain ➔ energy modulation at λ_1
- e^- losing energy slow down, and e^- gaining energy catch up ➔ density modulation at λ_1 (microbunching)
- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ exponential growth of radiation power

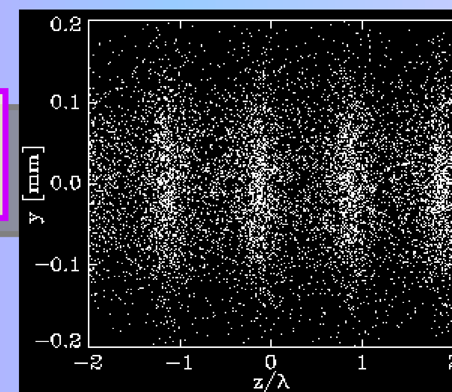
Microbunching through SASE Process



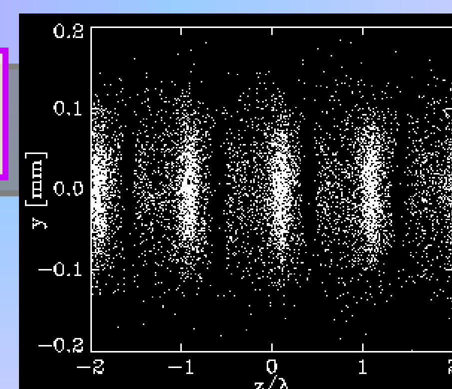
undulator entrance



half-way saturation



full saturation



GENESIS **- simulation for TTF parameters**

Courtesy - Sven Reiche (UCLA)

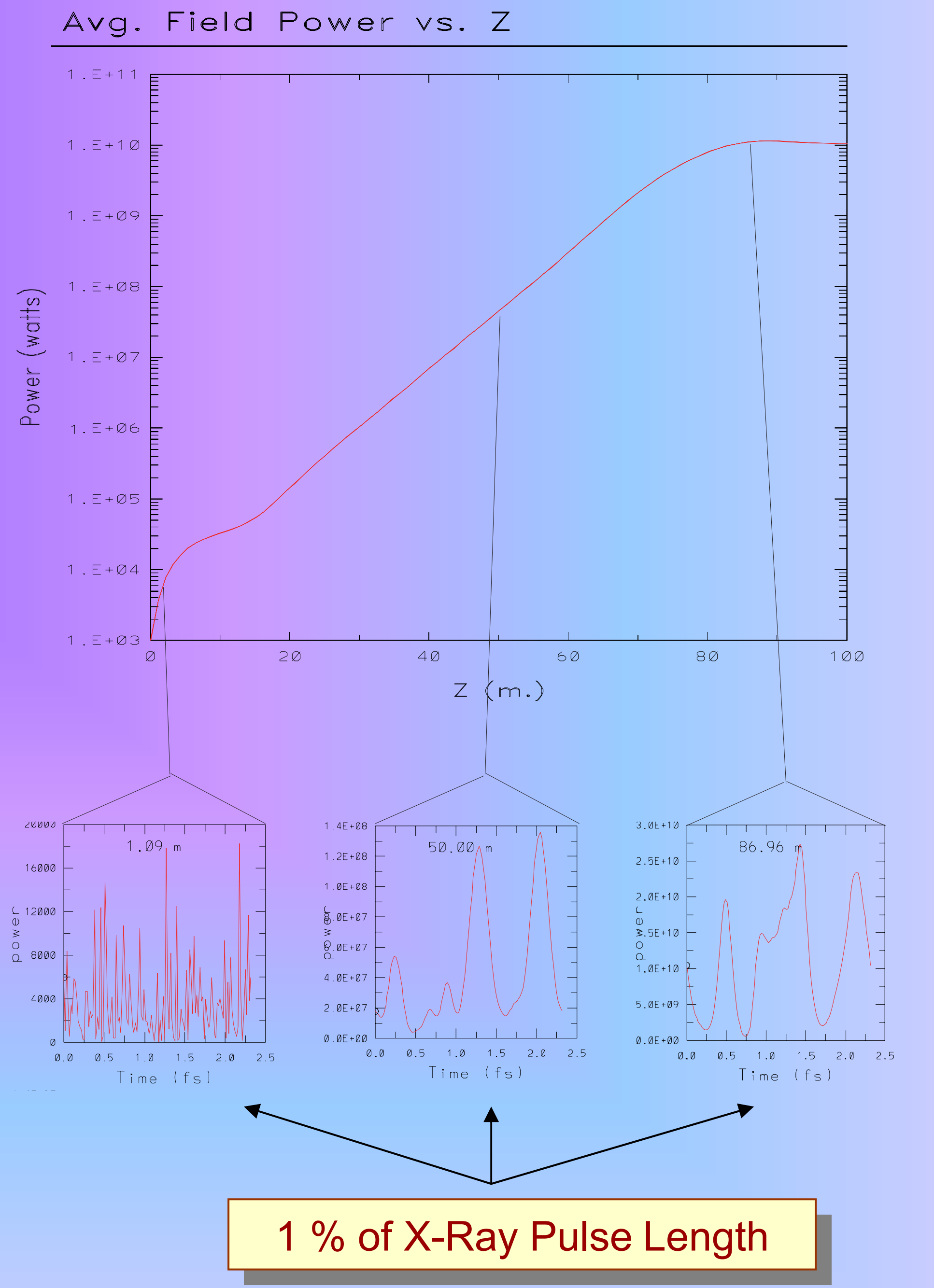
SASE temporal spikes

Due to noisy start-up, SASE has many intensity spikes, no phase correlation from one spike to another

LCLS spike ~ 1000 λ_1 ~ 0.15 nm ~ 0.5 fs

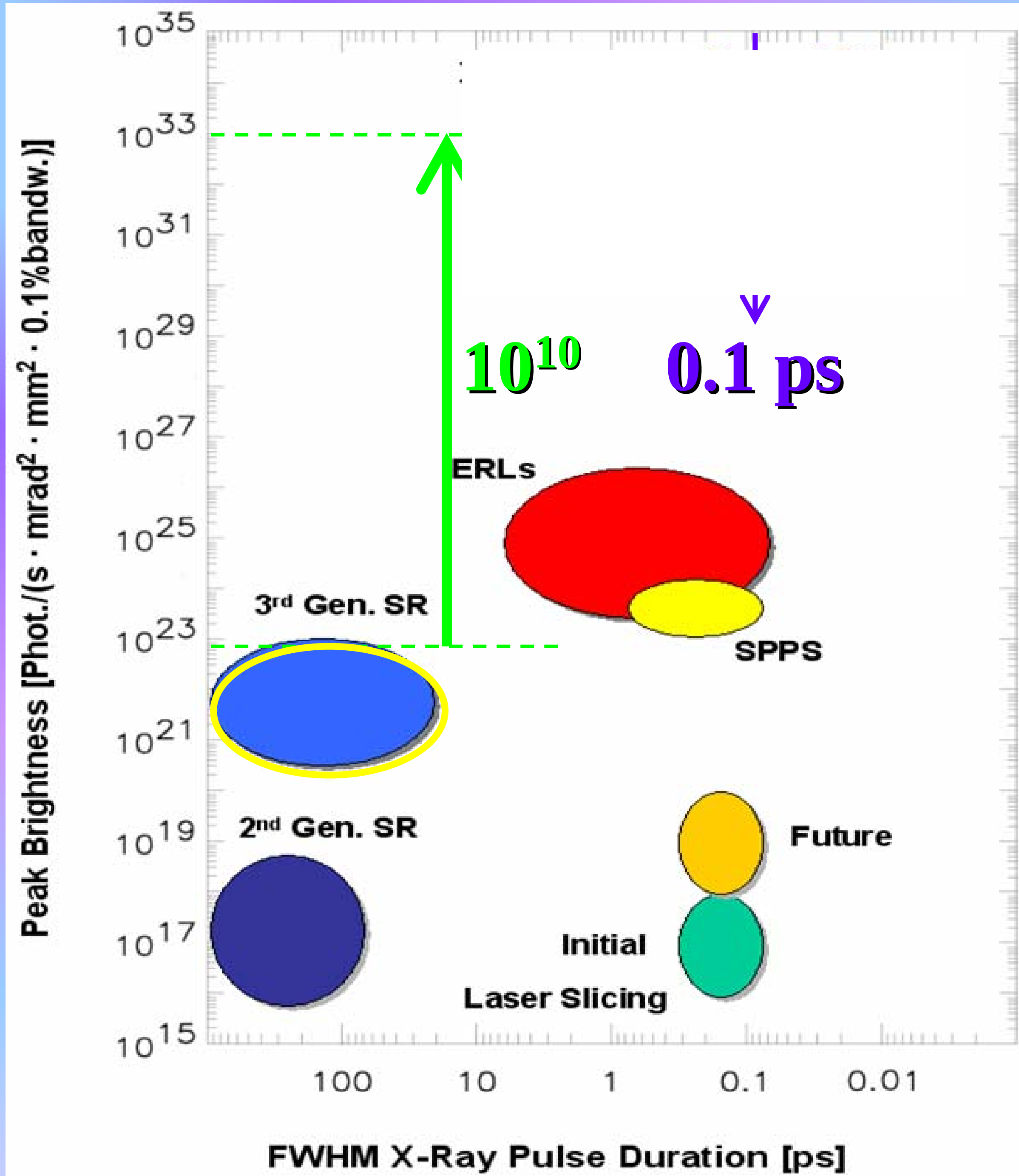
Each spike lases indepedently, depends only on the local (slice) beam parameters

LCLS pulse length ~ 200 fs with ~ 400 SASE spikes ~ x-ray energy fluctuates 5%



from H.-D. Nuhn

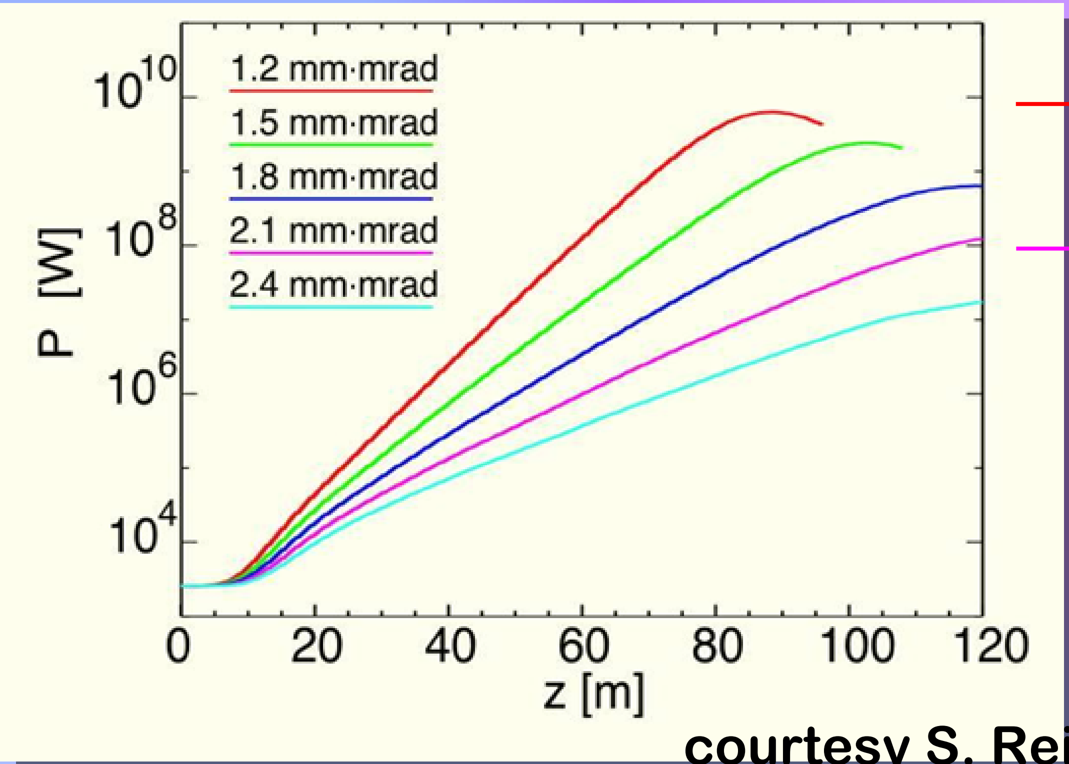
Light Source Survey at ~1 Å



H.-D. Nuhn,
H. Winnick

Toward attosecond pulses

LCLS requires very bright electron beam (emittance)…



courtesy S. Reiche

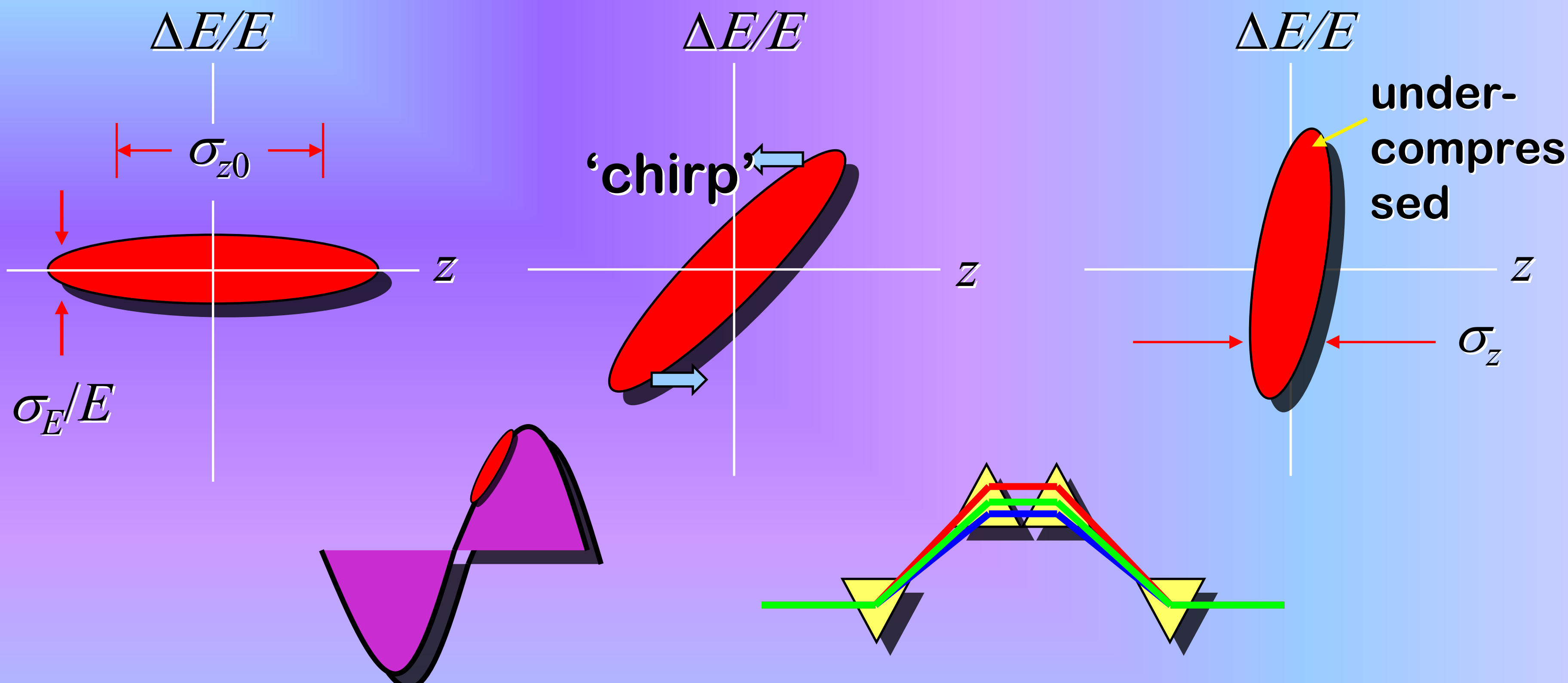
$\varepsilon_N = 1.2\ \mu m$ → $P \approx 10$ GW

$\varepsilon_N = 2.0\ \mu m$ → $P \approx 0.1$ GW

SASE FEL is not forgiving — instead of mild luminosity loss, power nearly switches **OFF**

electron beam *must* meet brightness requi

Magnetic Bunch Compression

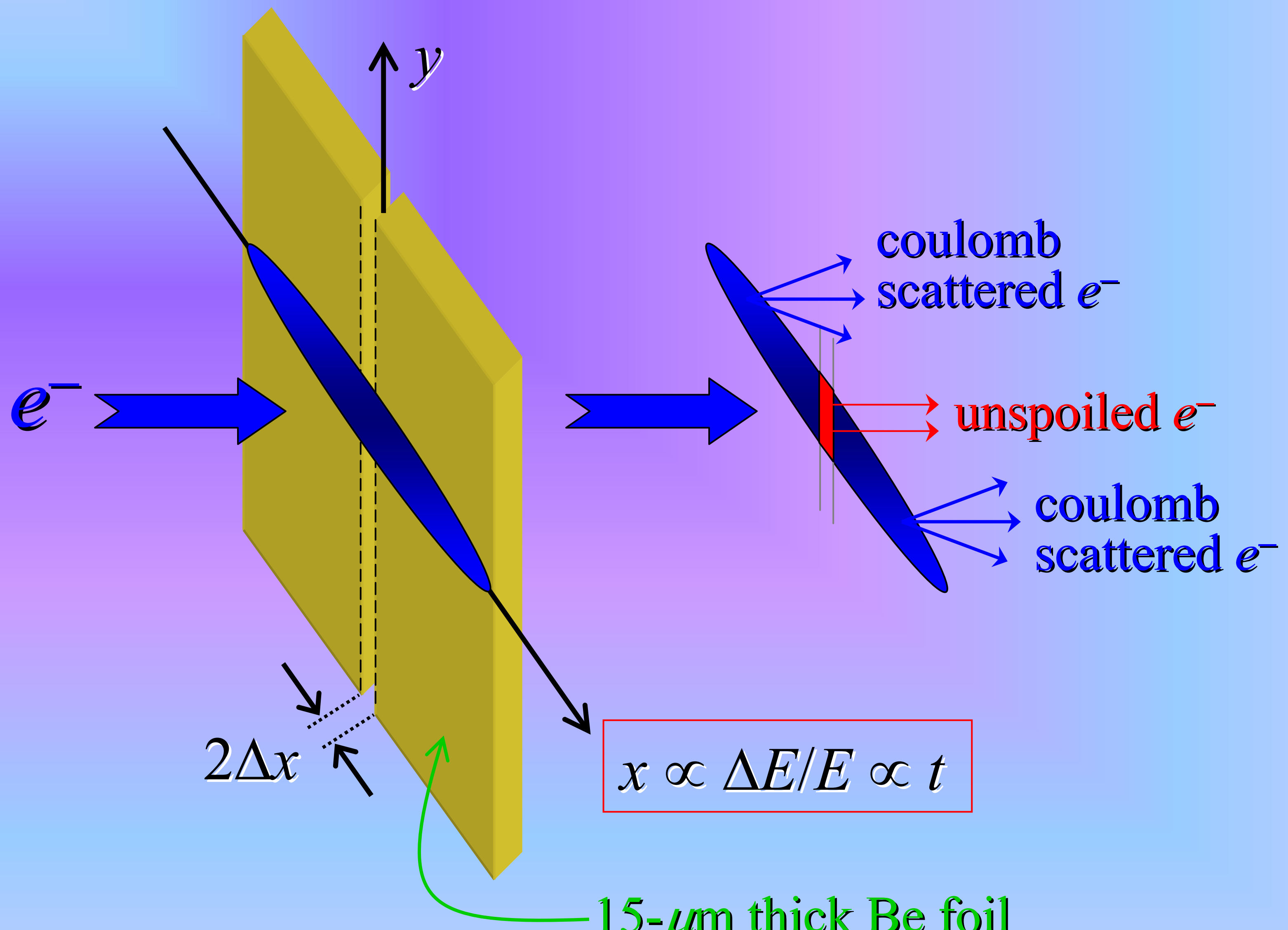


$$V = V_0 \sin(\omega\tau) \qquad \Delta z = R_{56}\Delta E/E \quad (\gamma >> 1)$$

RF Accelerating Voltage

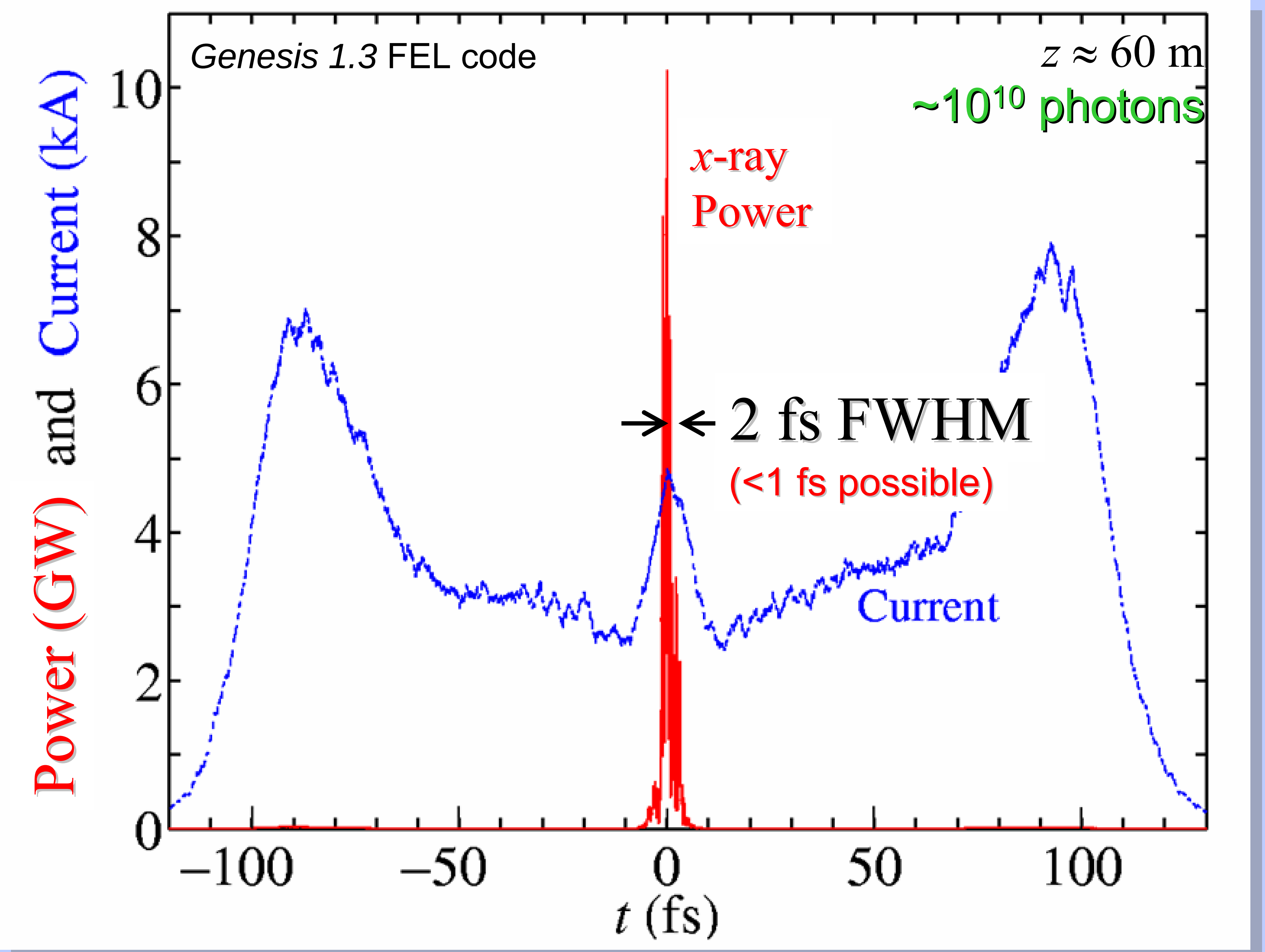
Path Length-Energy Dependent Beamline

Generating 1-fsec x-ray pulse with a thin slotted foil at center of the 2nd chicane



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

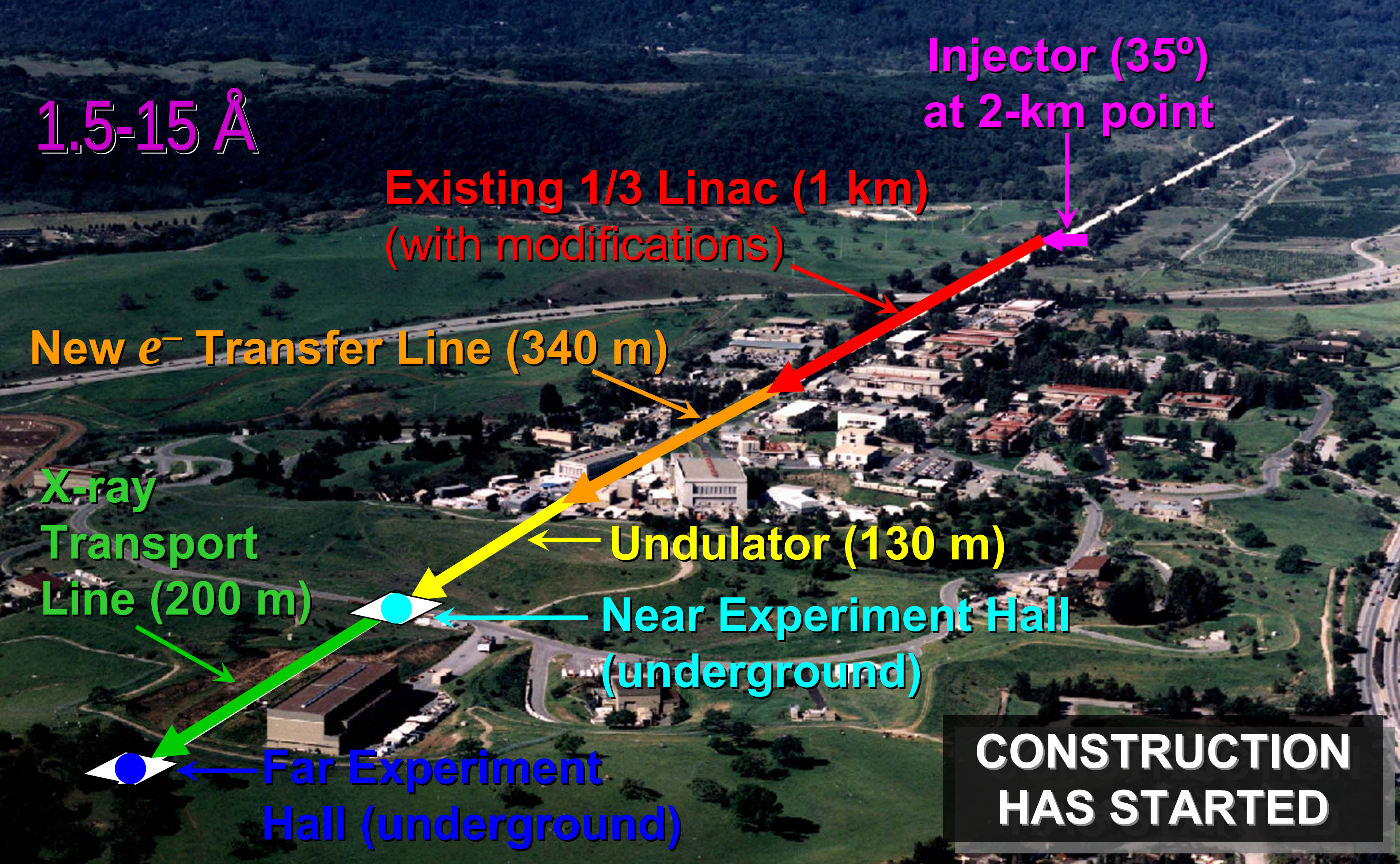
P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)



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)
t (fs)
0
2
4
6
8
10
−100
−50
0
50
100

Linac Coherent Light Source at *SLAC*

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



Beam Transport from Linac Through X-Ray Halls

Linac End

Beam Transport Hall (BTH):
After linac: 227-m, above-grade facility to transport electron beam

Undulator Hall (UH):
170-m, underground tunnel housing undulators

Electron Beam Dump:
40-m long underground facility to separate electron and x-ray beams

Near Experimental Hall (NEH):
underground facility to house 3 experimental hutches, prep, and shops

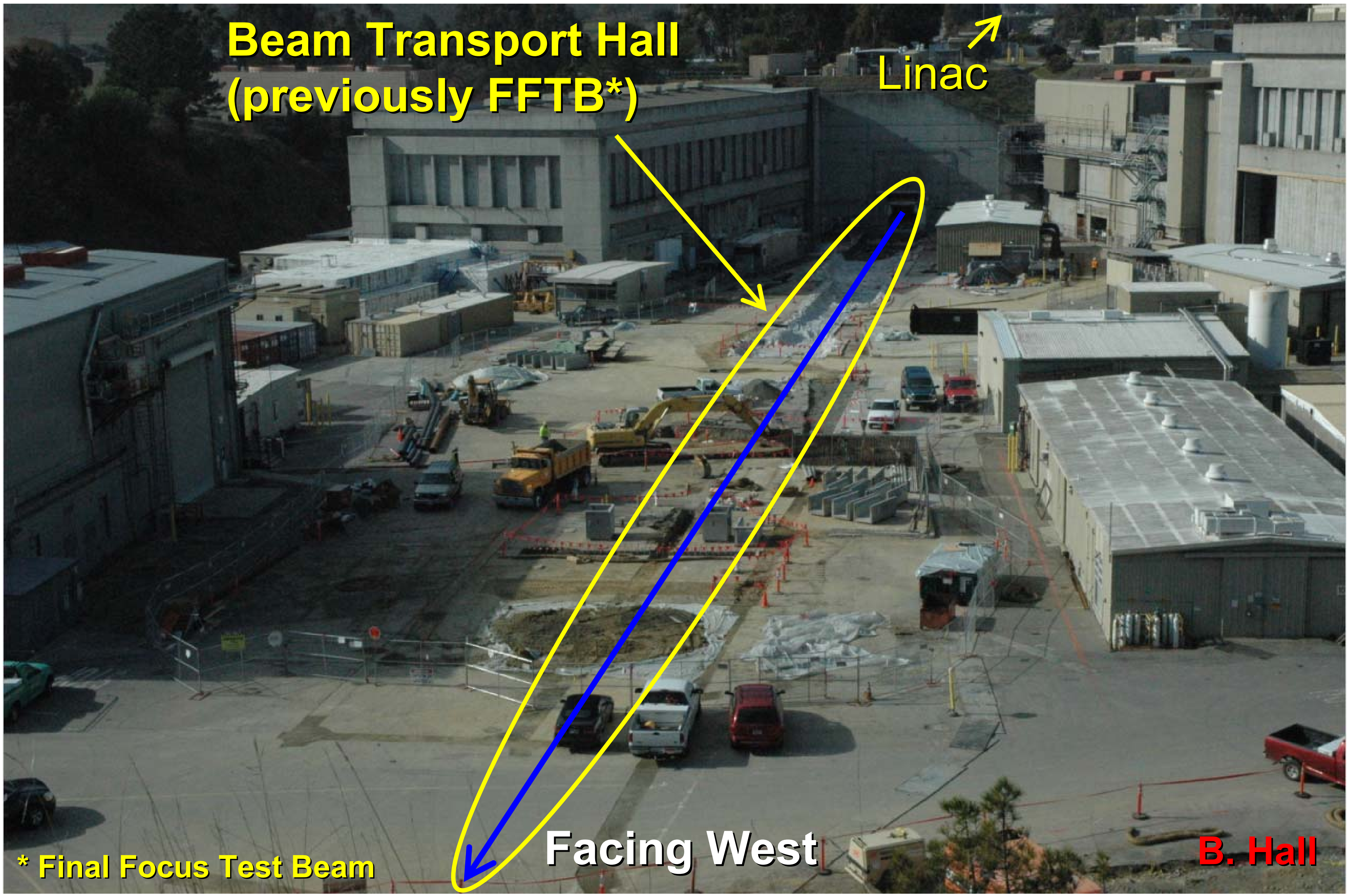
Front End Enclosure (FEE):
40-m long underground facility housing photon beam diagnostic equipment

X-Ray Transport Tunnel:
200-m long underground tunnel to transport photon beams from NEH to FEH

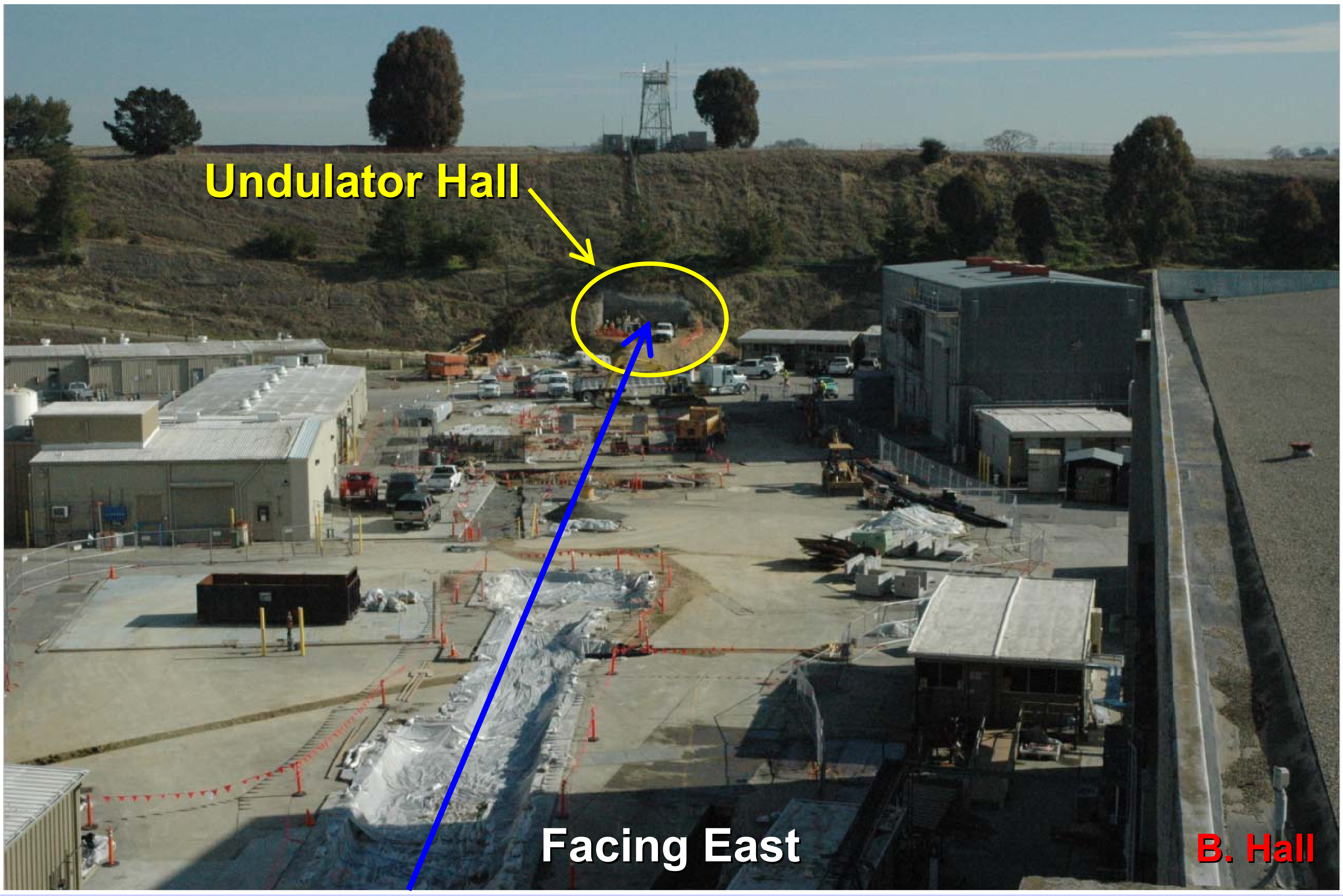
access tunnel

Far Experimental Hall (NEH): 210' long underground 44' dia. cavern housing 3 experimental hutches and prep space

Beam Transport Hall (BTH) Construction (Jan. 2007)



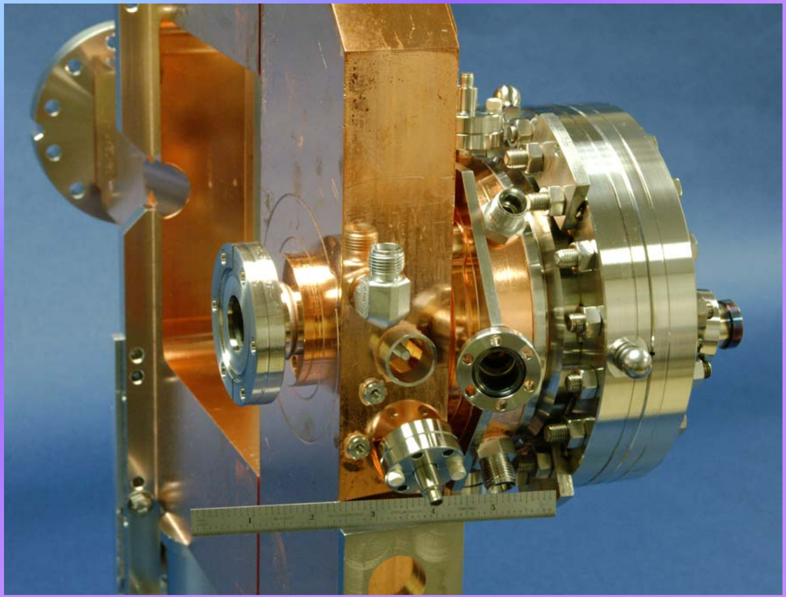
Undulator Hall (UH) Construction (Jan. 2007)

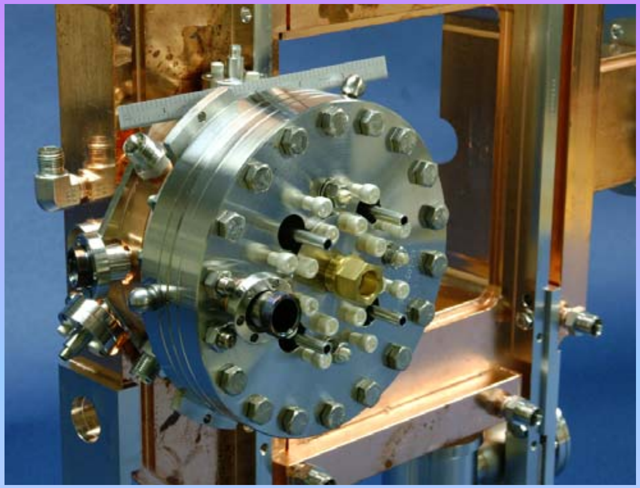


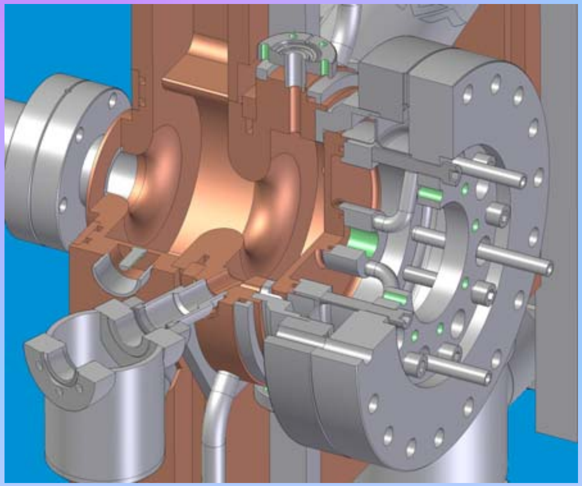
Near Experimental Hall (NEH) Construction (Jan. 2007)

RF Gun Fabrication and Cold RF Testing Finished & Preparing for High-Power Tests

Gun only pictures







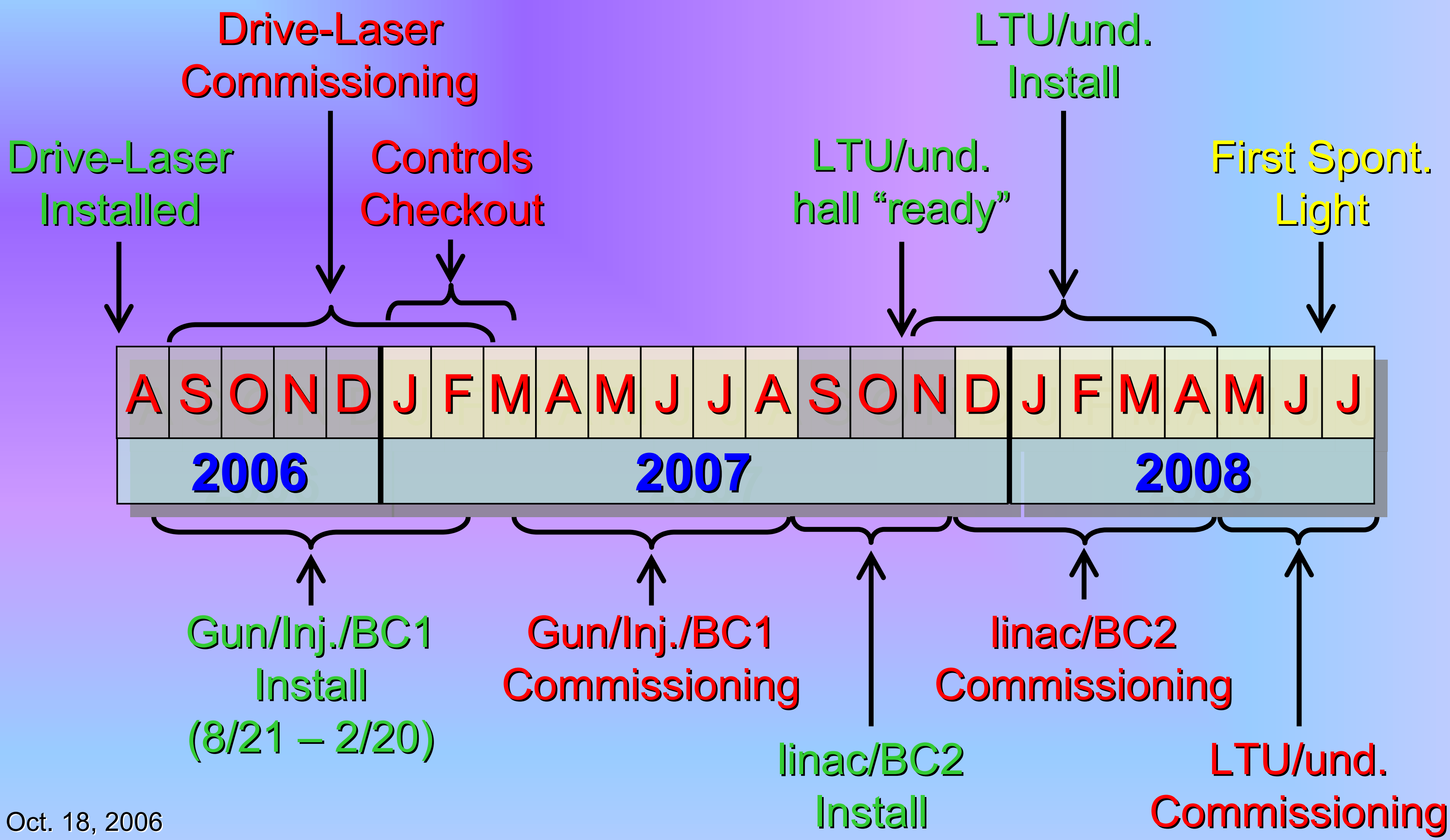
CAD cut away view of gun interior

First Measurements and the SLAC MMF

There are 7 productions undulators now at SLAC, 1 at ANL

The vendor has roughly 4 more and is completing > 2 per week

LCLS Installation and Commissioning Time-Line



Oct. 18, 2006

Concluding Remarks

- Very short x-ray pulses are key to exploring ultra-fast science at future light sources
- Linac-based FEL's offer high power, very high brightness, and possibly sub-femtosecond pulses at ~1-Å wavelengths
- The unknown awaits us in 2009 when the LCLS starts operations
- **Thanks to the many at SLAC and elsewhere who contributed to this presentation…**