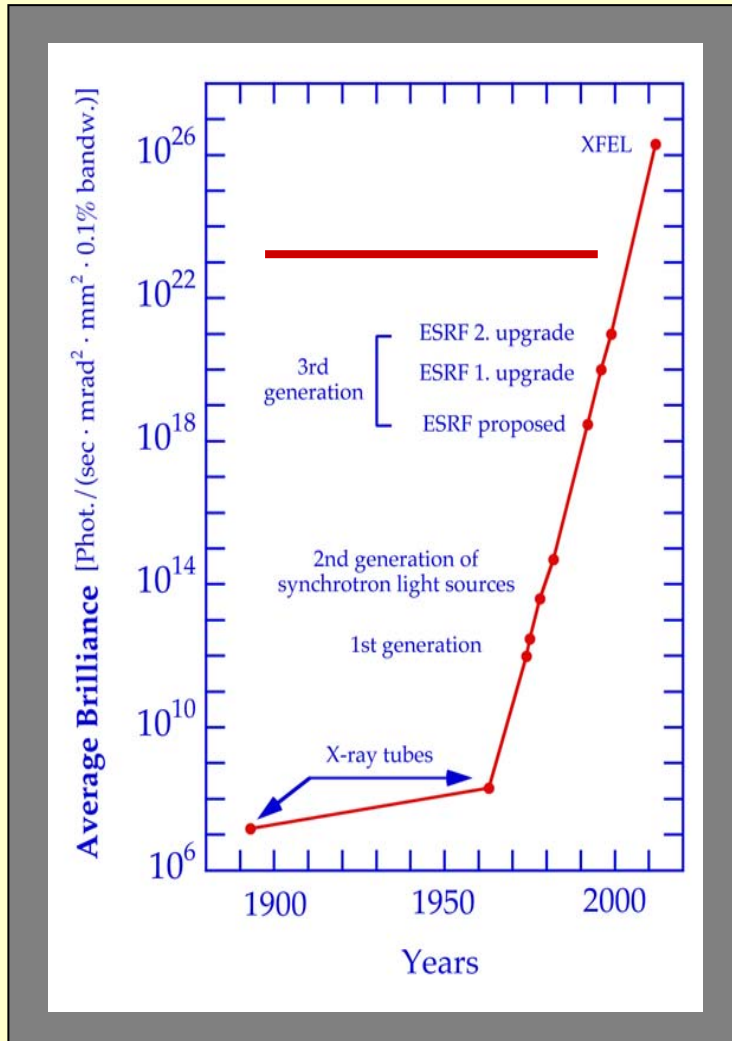


Trends in X-ray Synchrotron Radiation Research

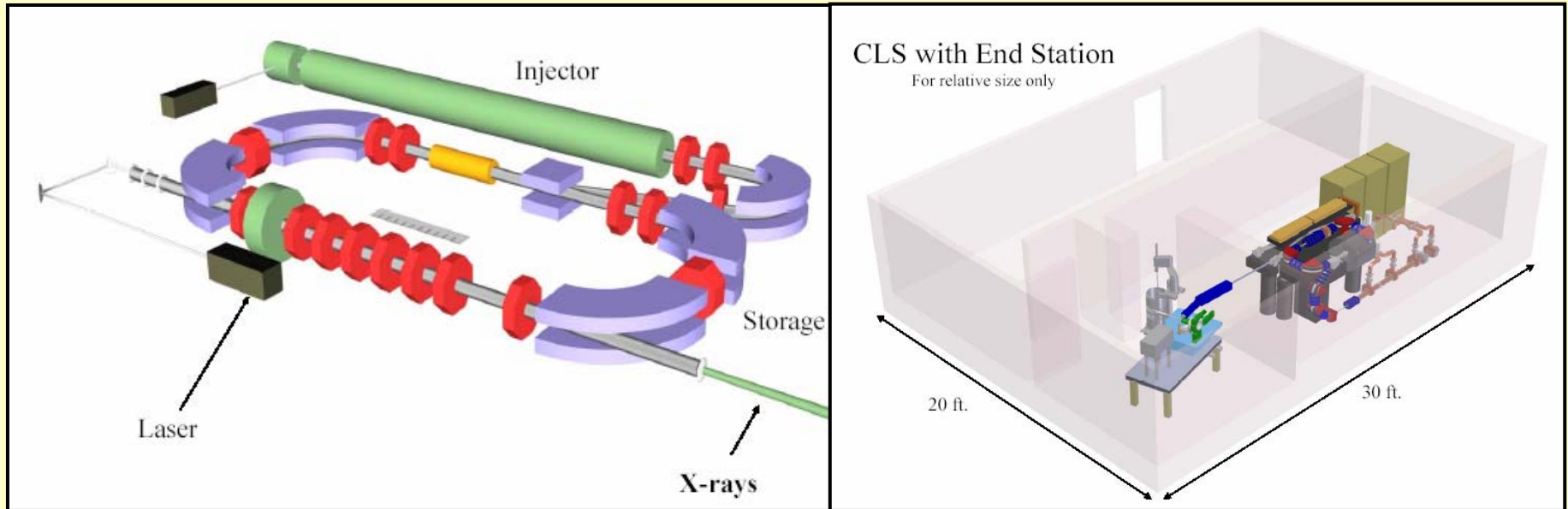
- **Storage rings**
- *Energy Recovery Linacs (ERL)*
- **Free Electron Lasers**

*Jochen R. Schneider
DESY*



Since the discovery of X-rays in 1895 the average brilliance increased by more than **3 orders of magnitude every 10 years.**

However, today's storage ring technology approaches its theoretical limits



2 March 2006: Today, Ronald Ruth, Ph.D., president of Lyncean Technologies, announced that the CLS prototype is up and running and has **just produced its first X-ray beams**

"With the production of its first X-ray beam, the CLS has now demonstrated its feasibility," said Jeremy M. Berg, Ph.D., director of NIGMS. "The option for having such intense, tunable X-ray sources on site at many institutions has the potential to transform numerous fields of biomedical research."

Opening of new opportunities at existing 3rd generation sources

- ***Undulators***
 - ***Optics, especially focusing: KB mirrors, zone plates, refractive lenses***
 - ***Sample environment: Extreme conditions***
 - ***Detectors***
 - ***General user software***
-
- ***Establishing strong in-house research programmes***
 - ***Connections to Universities***
 - ***Science centers on site:*** ***Nano Science Centers in the US,
Carl Branden Center at ESRF***

Trend to long beamlines (pioneered at SPring-8)



Shanghai Synchrotron Radiation Facility



Third Generation Storage Ring and IR Ring

Highly Optimized X-ray Storage Ring



Dedicated Enhanced Infrared Ring

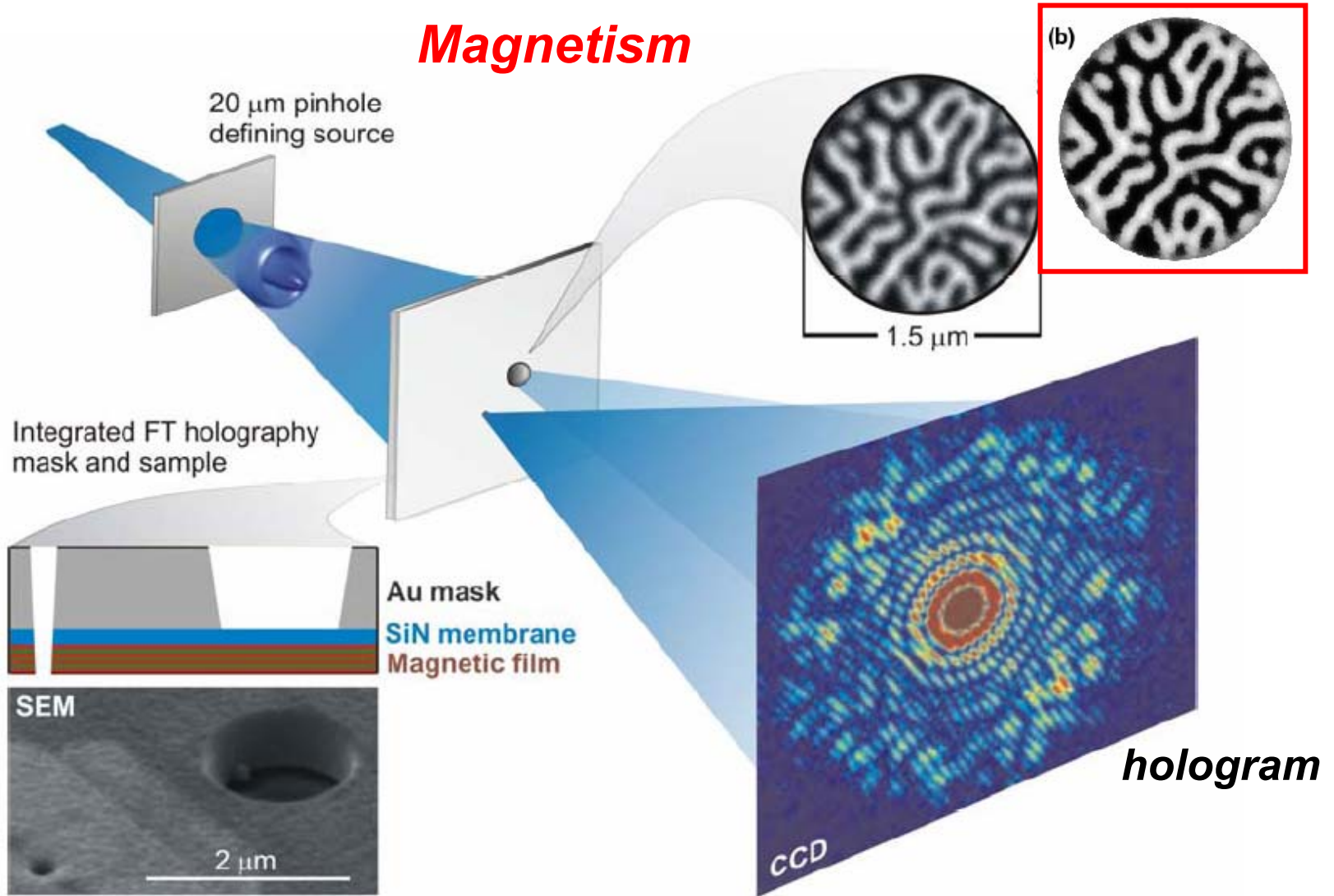
800 MeV, 1000 mA, Top-off Injection



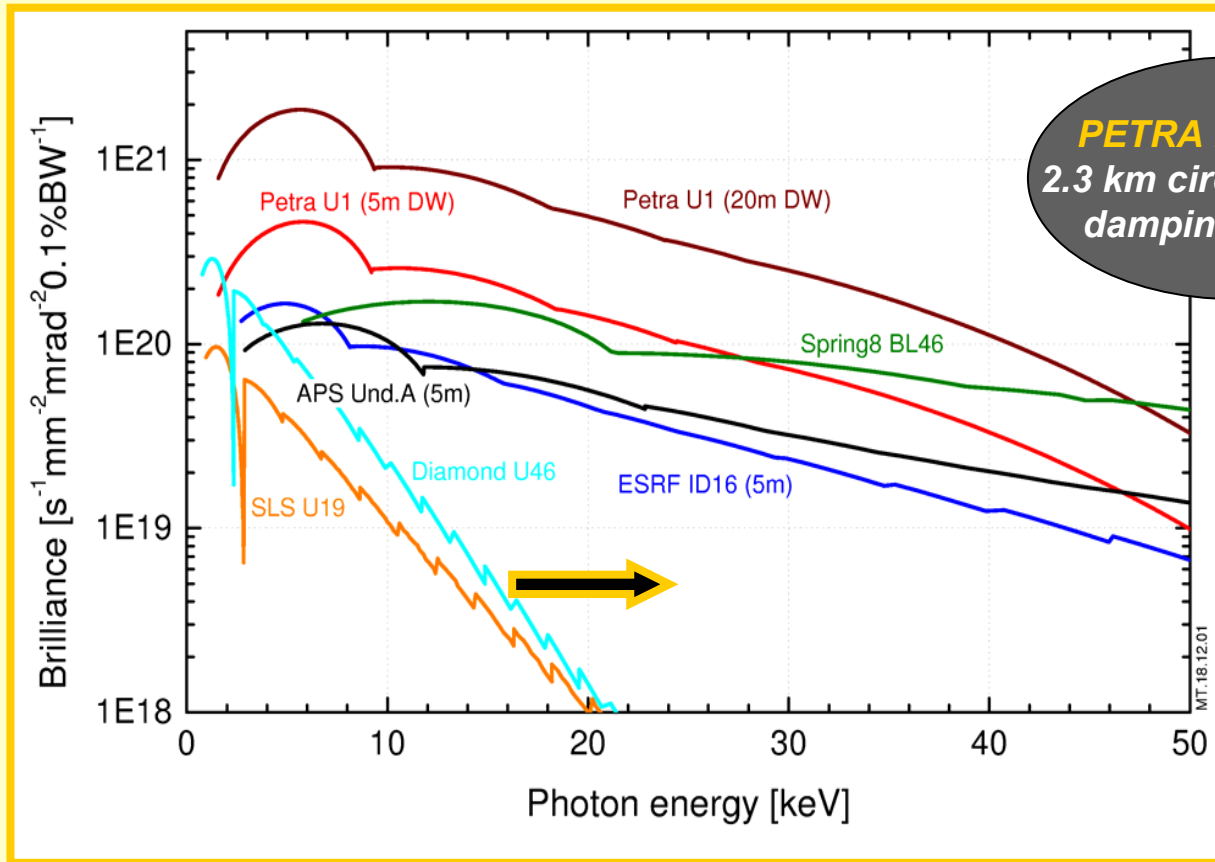
- 3 GeV, 500 mA, Top-off Injection
- 24 Cell, Triple Bend Achromat
- Circumference 620 m
- 21 Insertion Device Straight Sections (7 m)
- 24 Bending Magnet Ports
- Ultra-Low Emittance (ϵ_x, ϵ_y) 1.5, 0.008 nm
(Diffraction limited in vertical at 10 keV)
- Brightness $\sim 10^{21}$ p/s/0.1%bw/mm²/mrad²
- Flux $\sim 10^{16}$ p/s/0.1%bw
- Beam Size (σ_x, σ_y) 84.6, 4.3 μ m
- Beam Divergence (σ_x', σ_y') 18.2, 1.8 μ rad
- Pulse Length (rms) 11 psec
- Exceptional intensity and position stability
- Upgradeable to ERL operation in future

**improvement of emittance by
installing damping wigglers**

Magnetism



S. Eisebitt et al. (2004) **BESSY & SSRL**

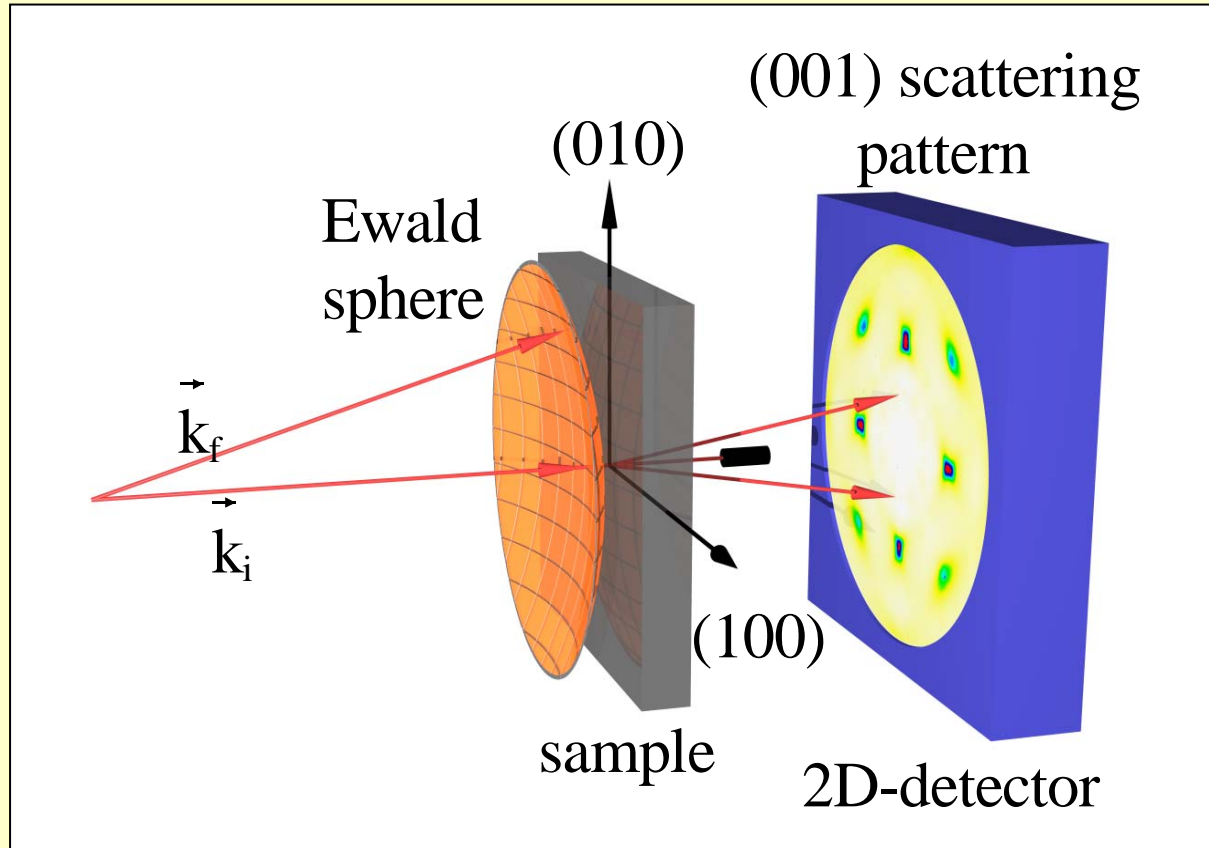


extension to higher photon energies

cold in-vacuum undulators, undulators in super-conducting technology

**High penetration power,
Momentum space geometry like 100 keV Electrons**

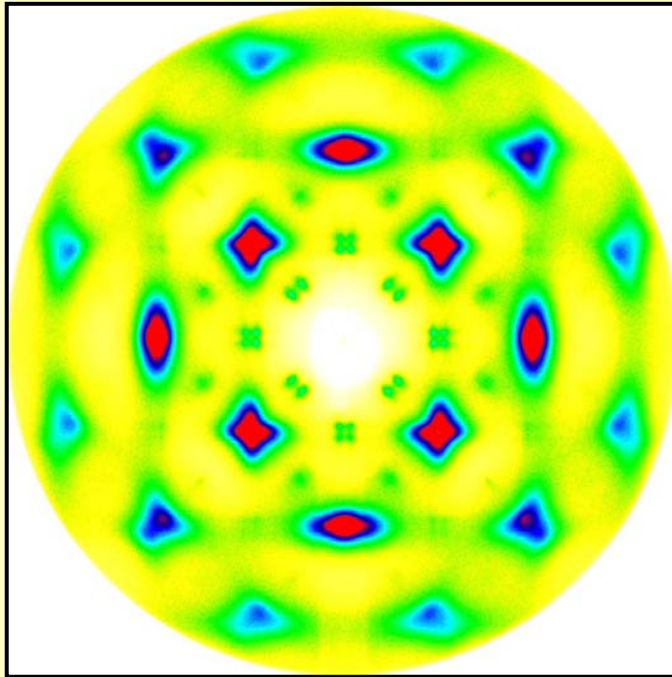
$E \sim 100 \text{ keV}$



**1 Million
data points
parallel**

Cu_3Pd

A. Schöps, Ph.D. Thesis, 2003

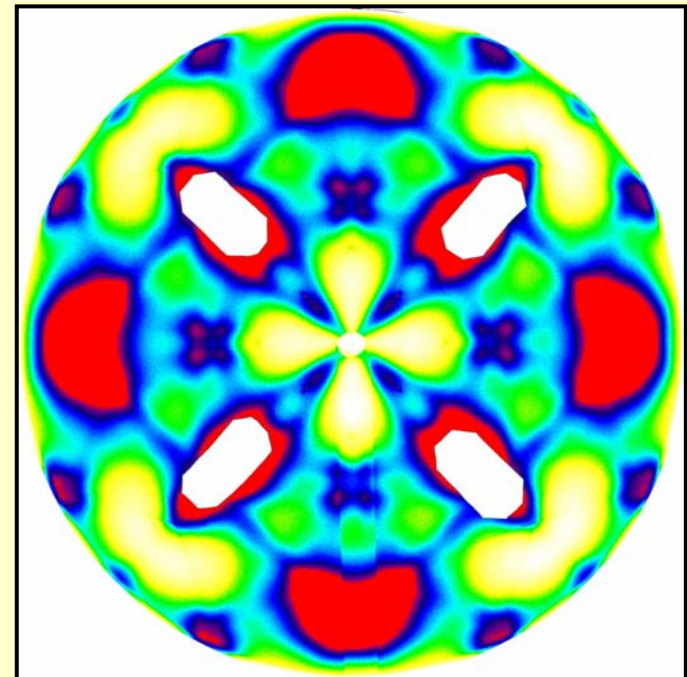


Detailed information on the **interatomic potentials**



Au_3Ni

H. Reichert et al., 2003

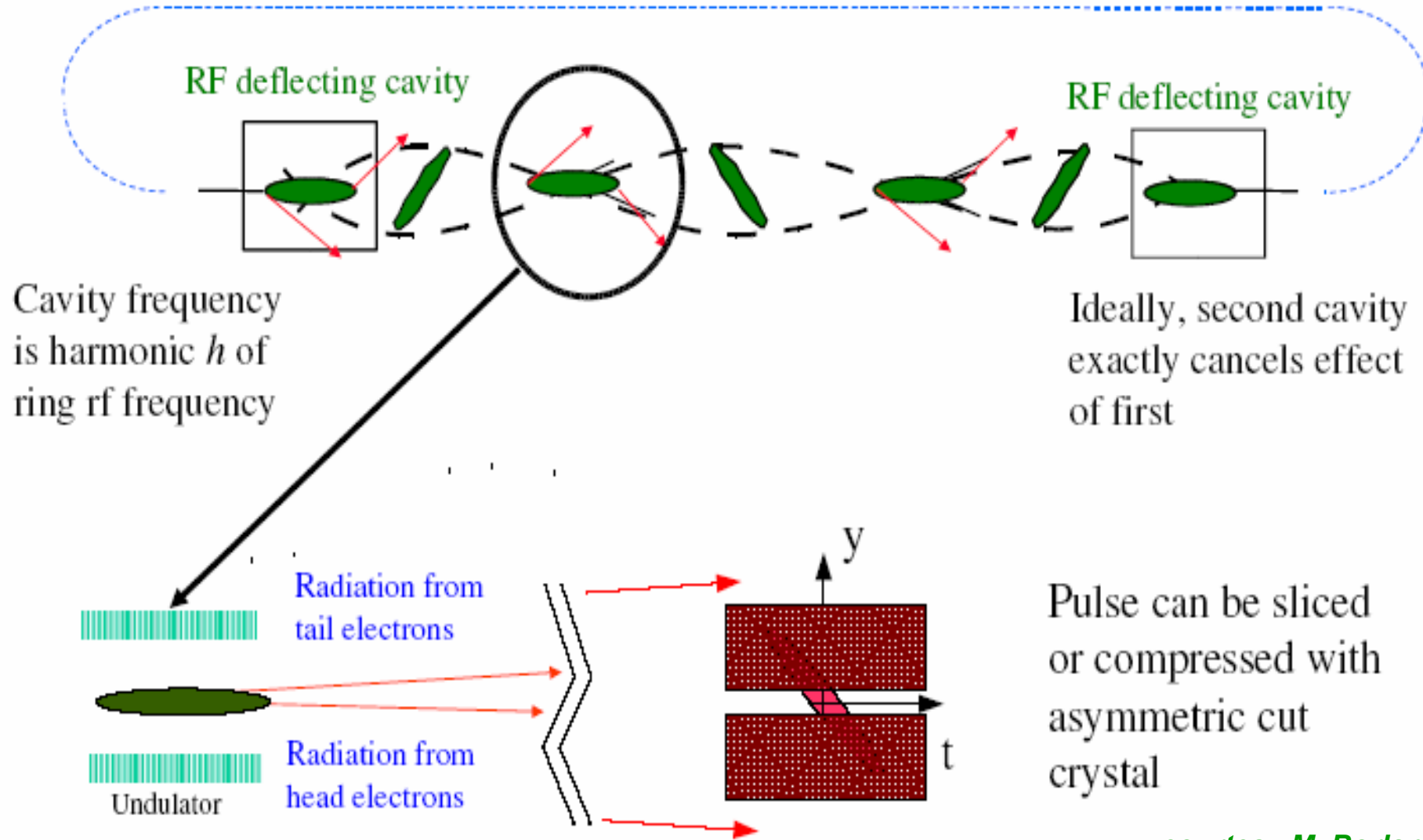


Complex phase behavior due to interplay of **ordering and phase separation** in the same system

60-80 keV Synchrotron Radiation

Short pulse option with deflecting cavities

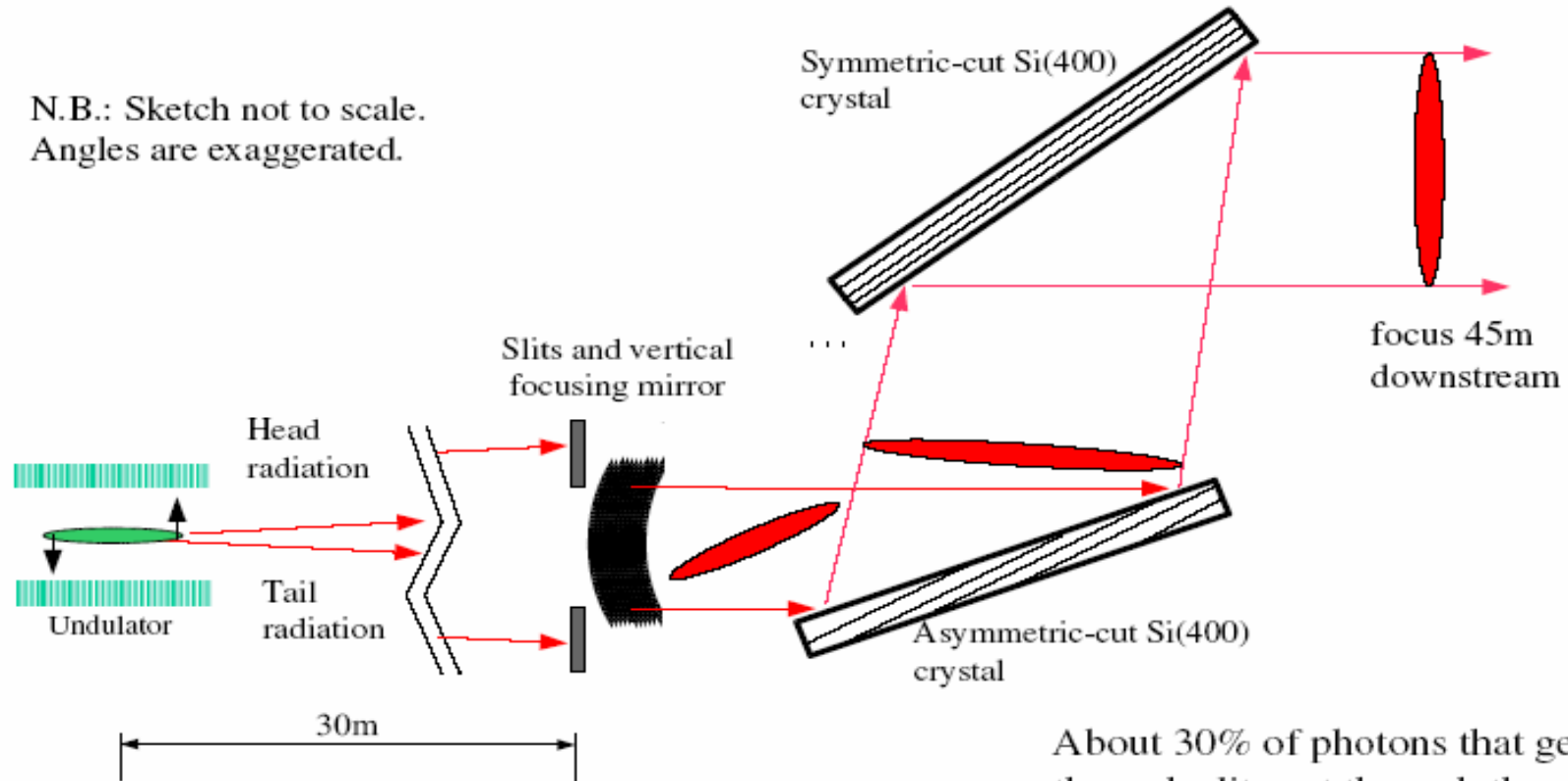
(Adapted from A. Zholents' August 30, 2004 presentation at APS Strategic Planning Meeting.)



courtesy M. Borland

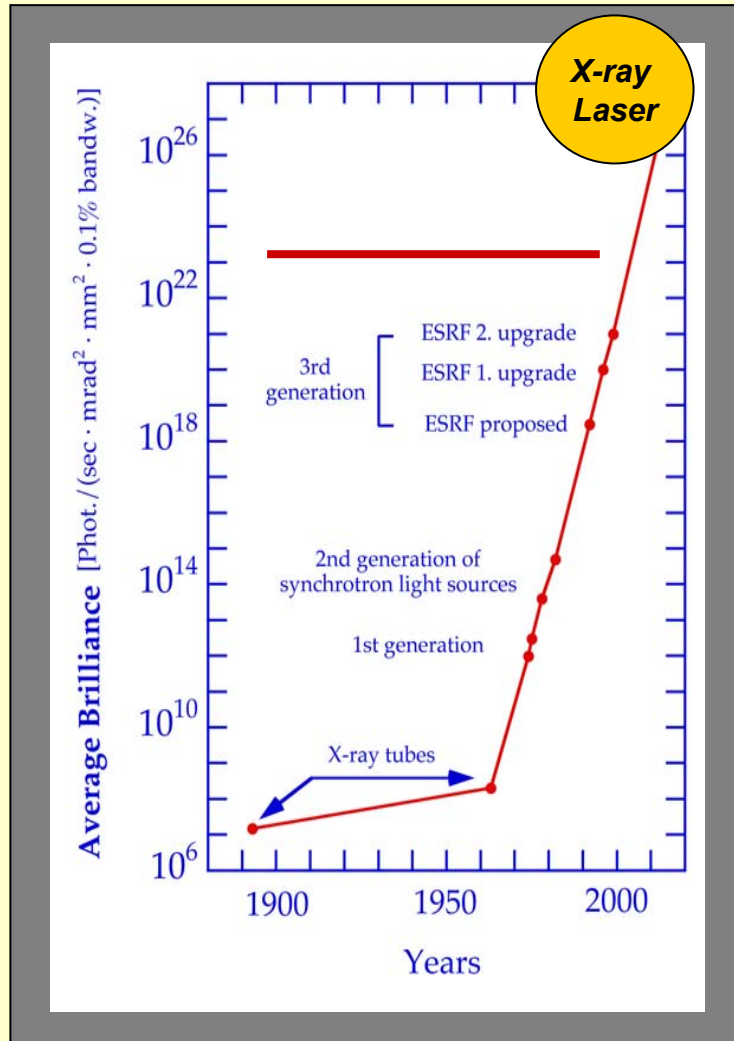
6: APS Optics Concept for 10 kV

N.B.: Sketch not to scale.
Angles are exaggerated.



About 30% of photons that get through slits get through the compression optics.

After S. Shastri, APS



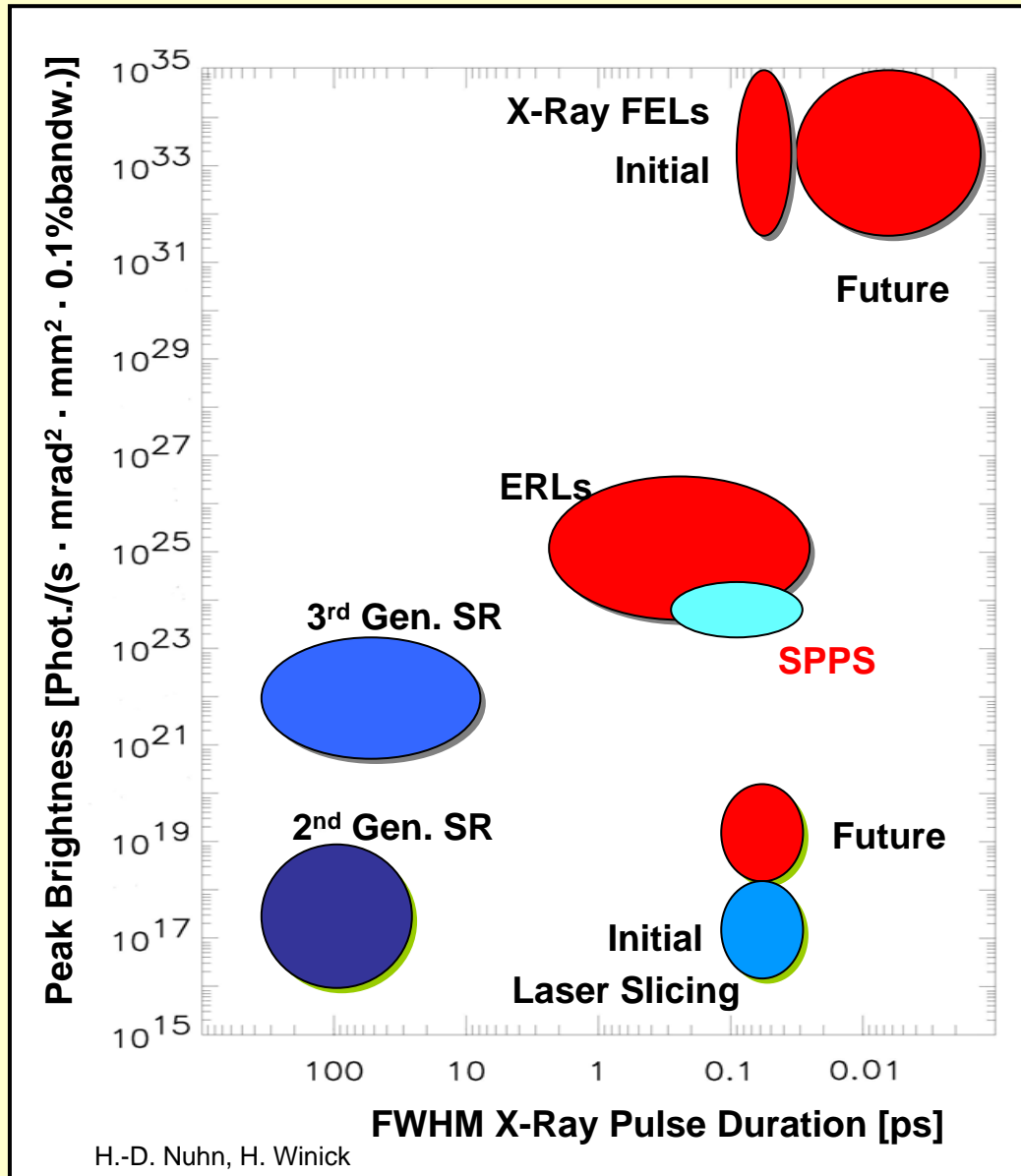
Since the discovery of X-rays in 1895 the average brilliance increased by more than **3 orders of magnitude every 10 years.**

However, today's storage ring technology approaches its theoretical limits:

A new X-ray source is needed for studies of the **dynamic state of matter** on nature's time scales

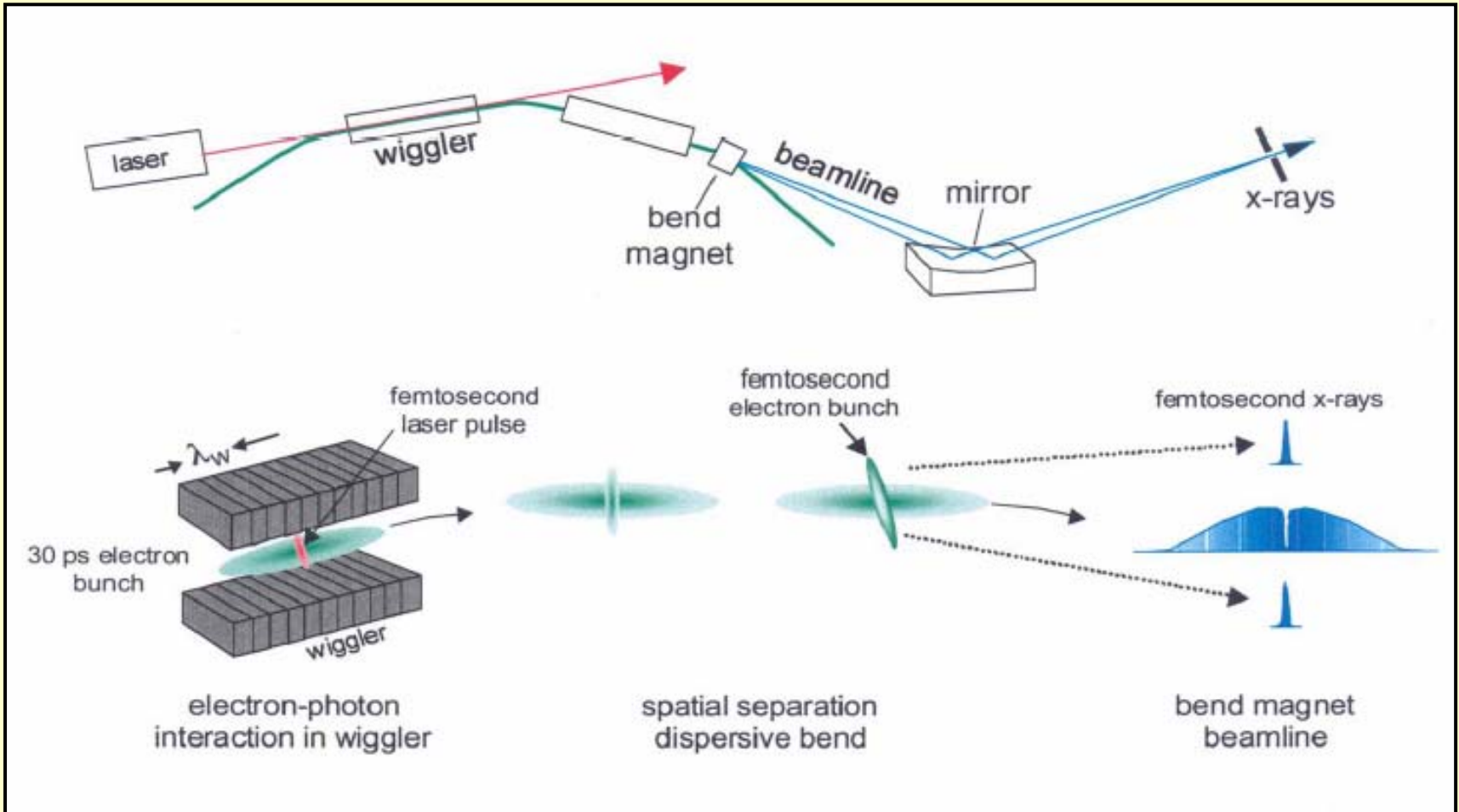
Linac driven Free-Electron Lasers open the new horizon.

Peak brilliance of pulsed X-ray sources

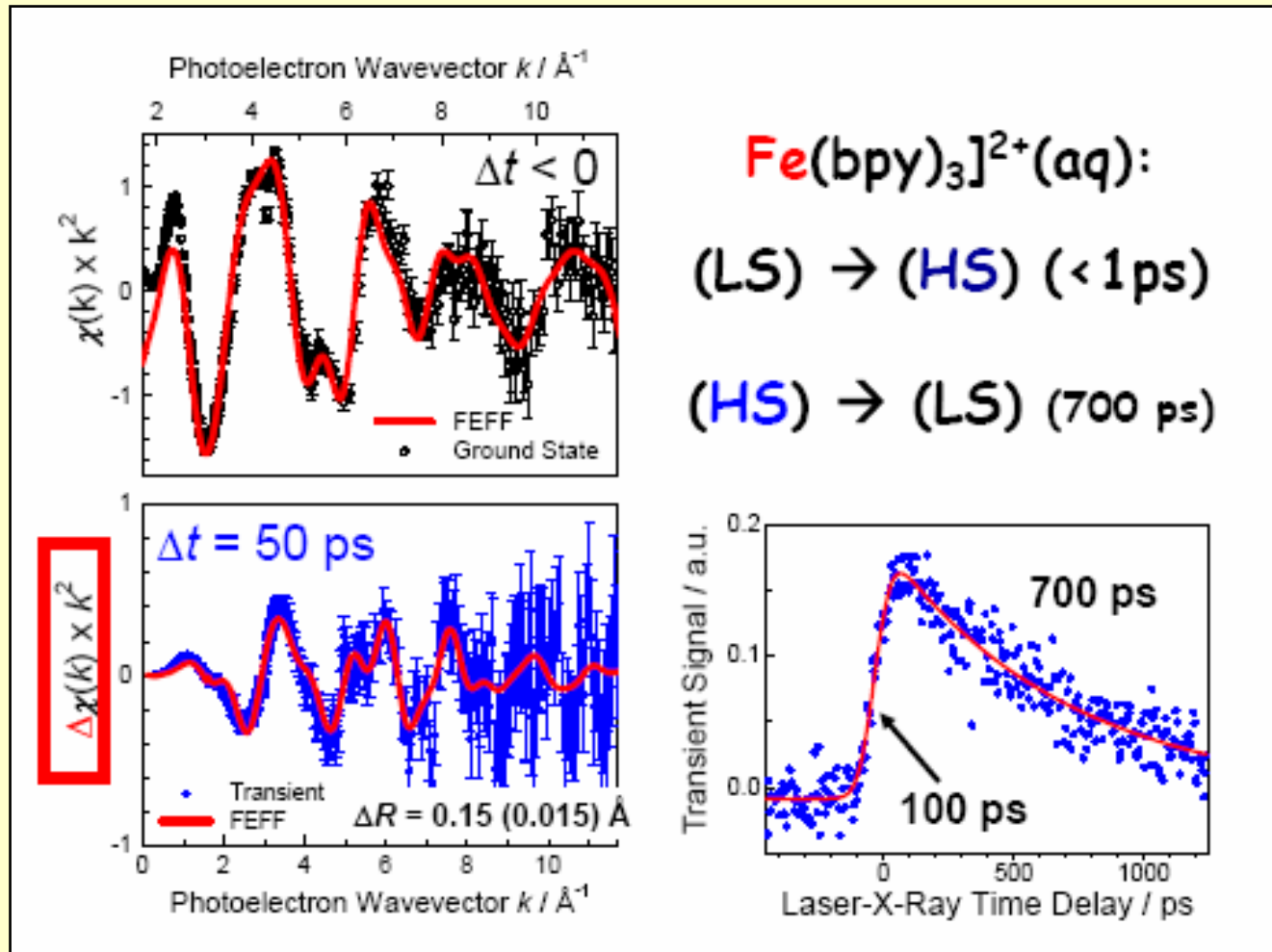


Ultrafast x-ray sources will probe space and time with atomic resolution.

Schoenlein, Chattopadhyay, Chong, Glover, Heimann, Shank, Zholents, Zolotorev
Science **287** (2000) 2237

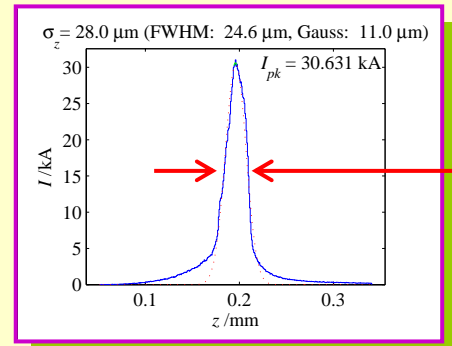
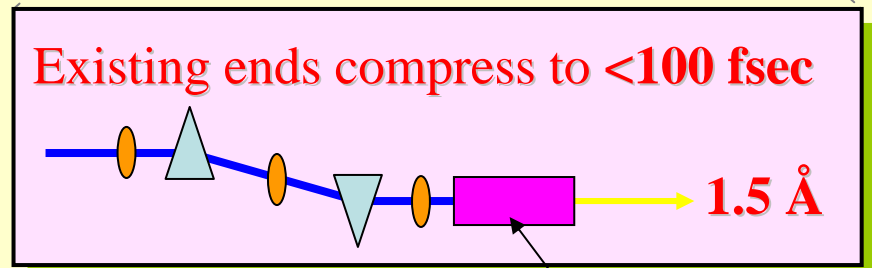
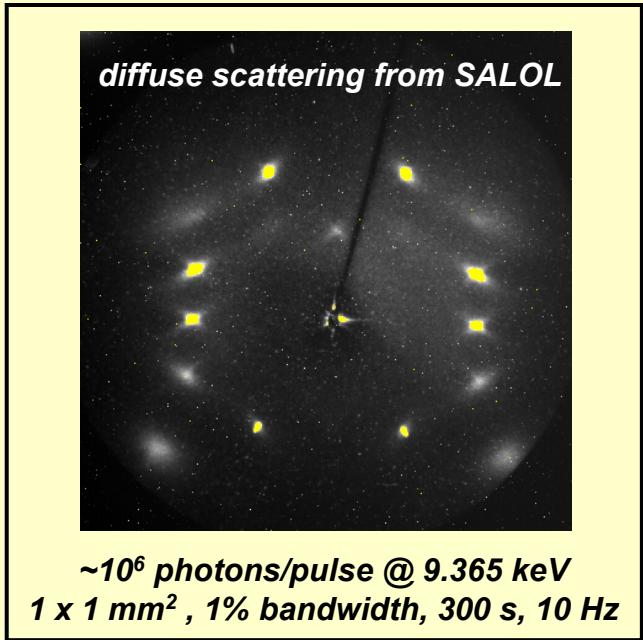
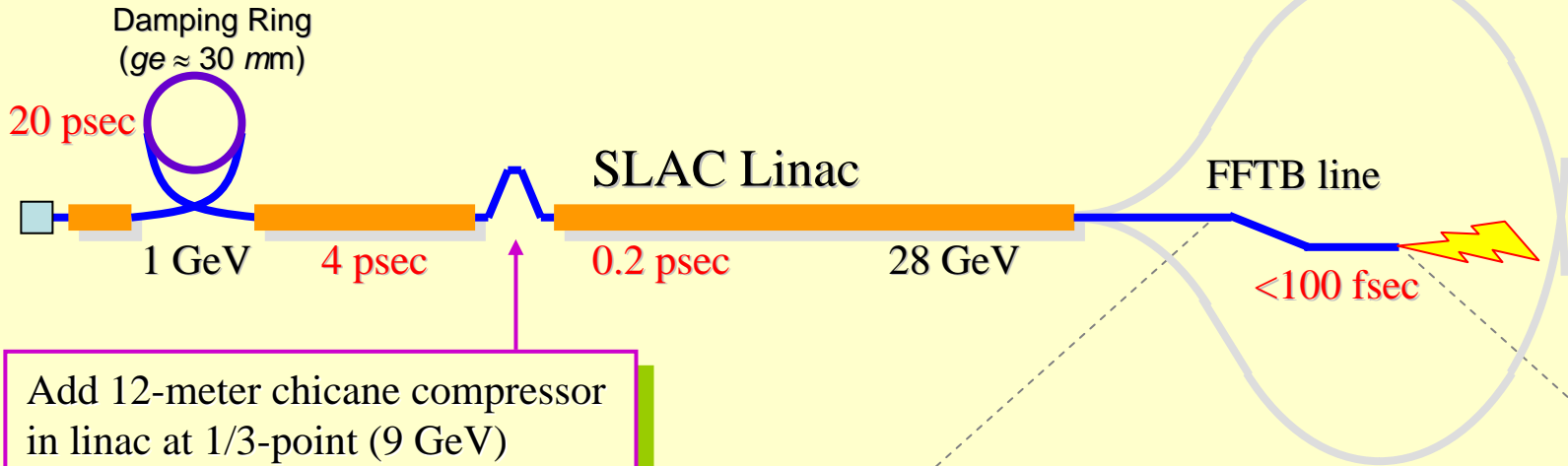


static



Christian Bressler et al. (EPFL Lausanne)

Sub-Picosecond Pulse Source (SPPS)



PRL 94, 114801 (2005)

PHYSICAL REVIEW LETTERS

week ending
25 MARCH 2005

Clocking Femtosecond X Rays

A. L. Cavalieri,¹ D. M. Fritz,¹ S. H. Lee,¹ P. H. Bucksbaum,¹ D. A. Reis,¹ J. Rudati,² D. M. Mills,² P. H. Fuoss,³ G. B. Stephenson,³ C. C. Kao,⁴ D. P. Siddons,⁴ D. P. Lowney,⁵ A. G. MacPhee,⁵ D. Weinstein,⁵ R. W. Falcone,⁵ R. Pahl,⁶ J. Als-Nielsen,⁷ C. Blome,⁸ S. Düsterer,⁸ R. Ischebeck,⁸ H. Schlarb,⁸ H. Schulte-Schrepping,⁸ Th. Tschentscher,⁸ J. Schneider,⁸ O. Hignette,⁹ F. Sette,⁹ K. Sokolowski-Tinten,¹⁰ H. N. Chapman,¹¹ R. W. Lee,¹¹ T. N. Hansen,¹² O. Synnergren,¹² J. Larsson,¹² S. Techert,¹³ J. Sheppard,¹⁴ J. S. Wark,¹⁴ M. Bergh,¹⁵ C. Caleman,¹⁵ G. Huldt,¹⁵ D. van der Spoel,¹⁵ N. Timneanu,¹⁵ J. Hajdu,¹⁵ R. A. Akre,¹⁶ E. Bong,¹⁶ P. Emma,¹⁶ P. Krejcik,¹⁶ J. Arthur,¹⁷ S. Brennan,¹⁷ K. J. Gaffney,¹⁷ A. M. Lindenberg,¹⁷ K. Luening,¹⁷ and J. B. Hastings¹⁷

This measurement indirectly determined the arrival time of each x-ray pulse relative to an external pump laser pulse with a time resolution of better than 60 fs rms.

PRL 95, 125701 (2005)

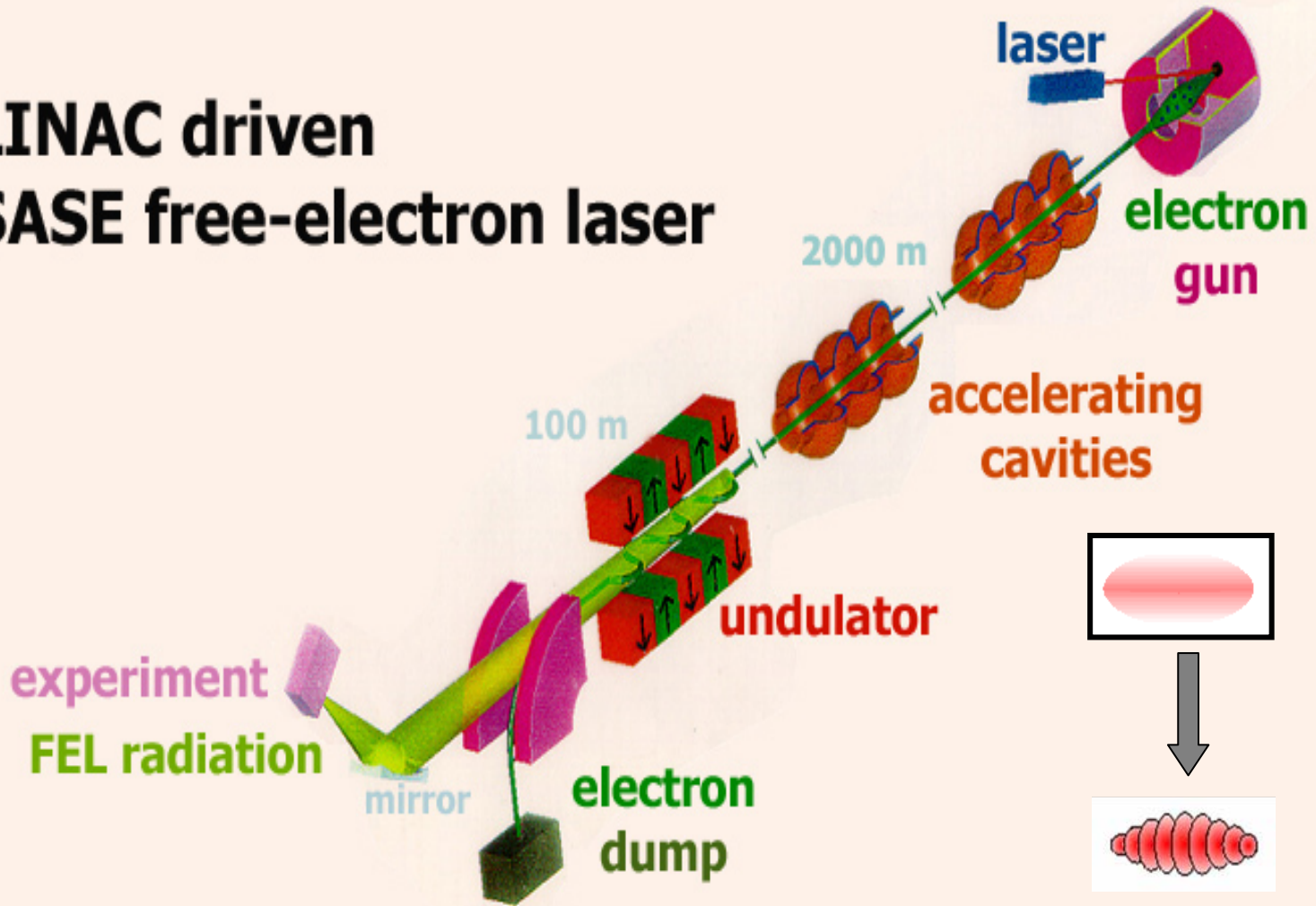
PHYSICAL REVIEW LETTERS

week ending
16 SEPTEMBER 2005

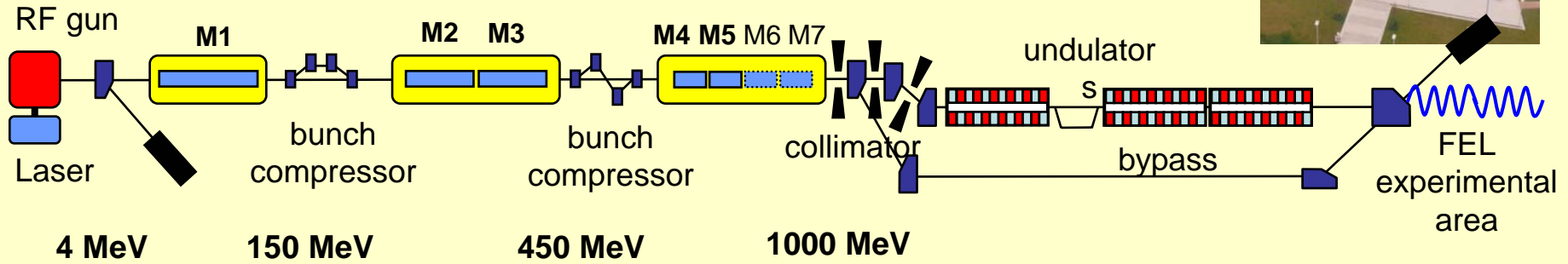
Observation of Structural Anisotropy and the Onset of Liquidlike Motion During the Nonthermal Melting of InSb

K. J. Gaffney,¹ A. M. Lindenberg,¹ J. Larsson,² K. Sokolowski-Tinten,^{3,4} C. Blome,⁵ O. Synnergren,² J. Sheppard,⁶ C. Caleman,⁷ A. G. MacPhee,⁸ D. Weinstein,⁸ D. P. Lowney,⁸ T. Allison,⁸ T. Matthews,⁸ R. W. Falcone,⁸ A. L. Cavalieri,^{9,10} D. M. Fritz,⁹ S. H. Lee,⁹ P. H. Bucksbaum,⁹ D. A. Reis,⁹ J. Rudati,¹¹ A. T. Macrander,¹¹ P. H. Fuoss,¹² C. C. Kao,¹³ D. P. Siddons,¹³ R. Pahl,¹⁴ K. Moffat,¹⁴ J. Als-Nielsen,¹⁵ S. Düsterer,⁵ R. Ischebeck,⁵ H. Schlarb,⁵ H. Schulte-Schrepping,⁵ J. Schneider,⁵ D. von der Linde,⁴ O. Hignette,¹⁶ F. Sette,¹⁶ H. N. Chapman,¹⁷ R. W. Lee,¹⁷ T. N. Hansen,² J. S. Wark,⁶ M. Bergh,⁷ G. Huldt,⁷ D. van der Spoel,⁷ N. Timneanu,⁷ J. Hajdu,⁷ R. A. Akre,¹⁸ E. Bong,¹⁸ P. Krejcik,¹⁸ J. Arthur,¹ S. Brennan,¹ K. Luening,¹ and J. B. Hastings¹

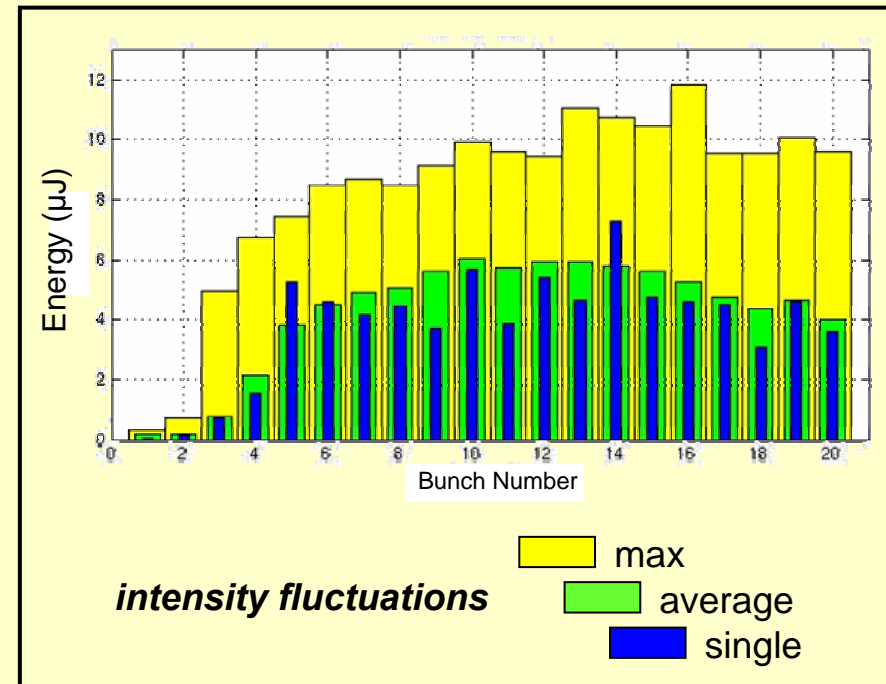
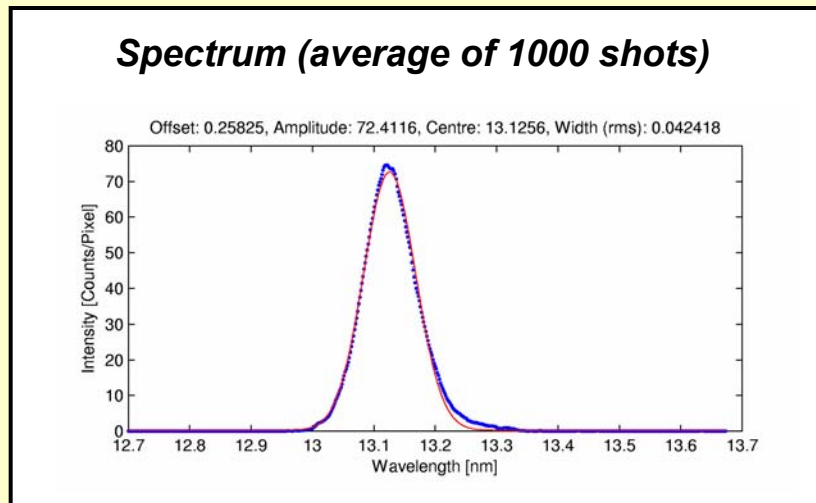
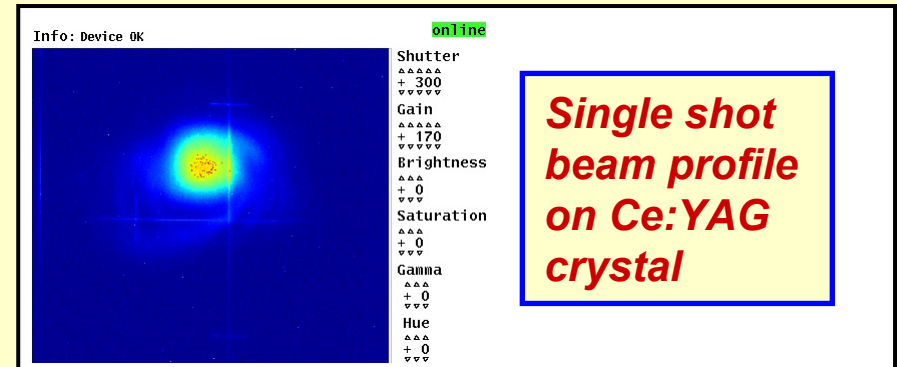
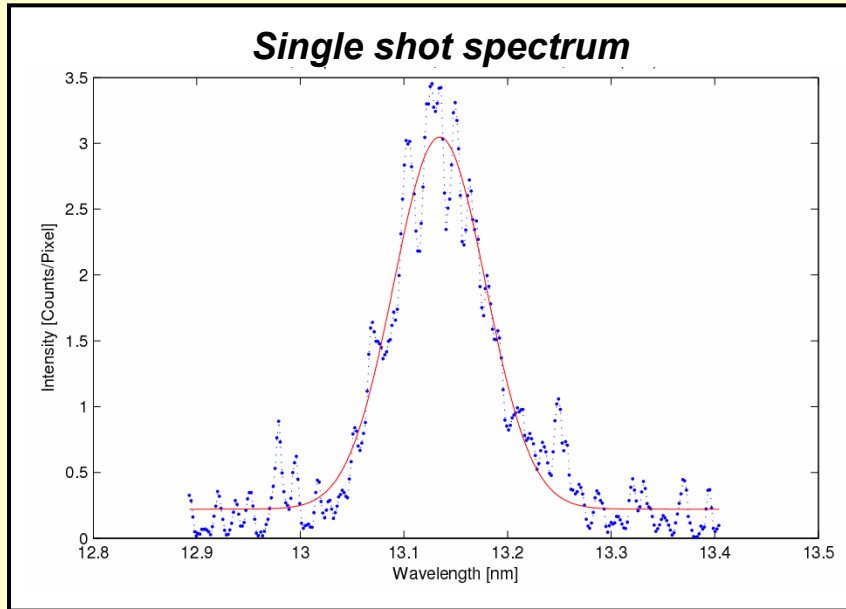
LINAC driven SASE free-electron laser



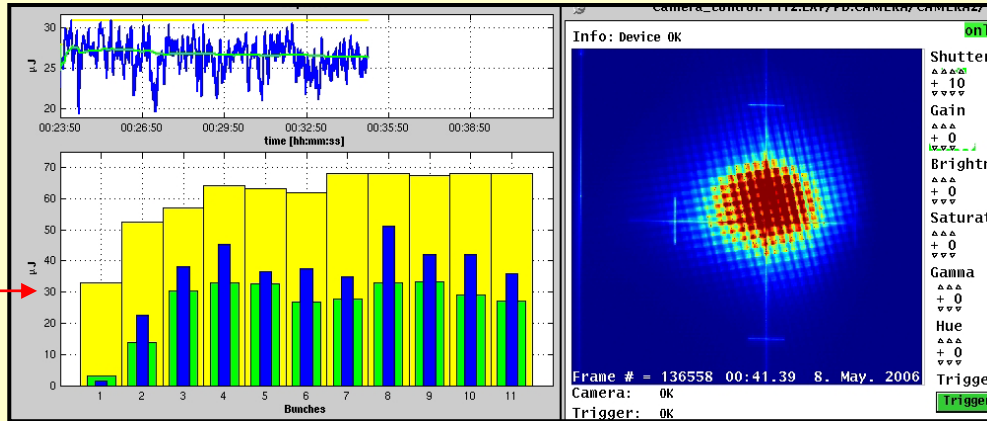
FLASH: the VUV-FEL User Facility at DESY



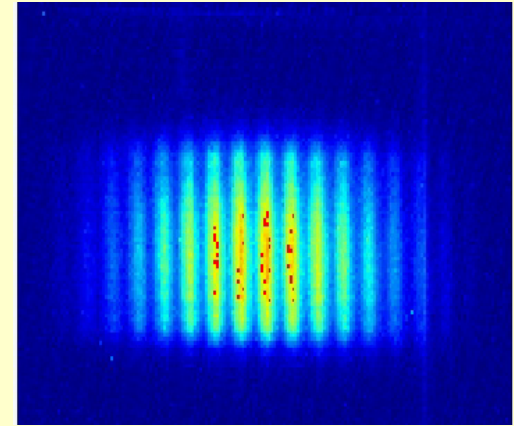
250 m



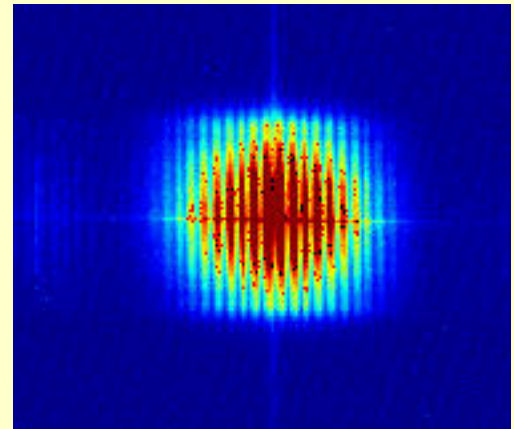




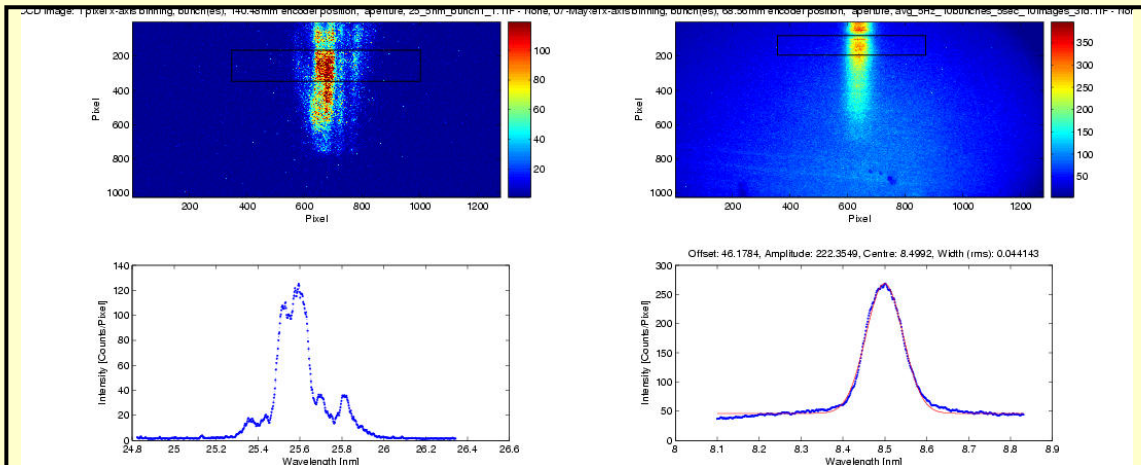
Double slit diffraction



0.15 mm slit distance



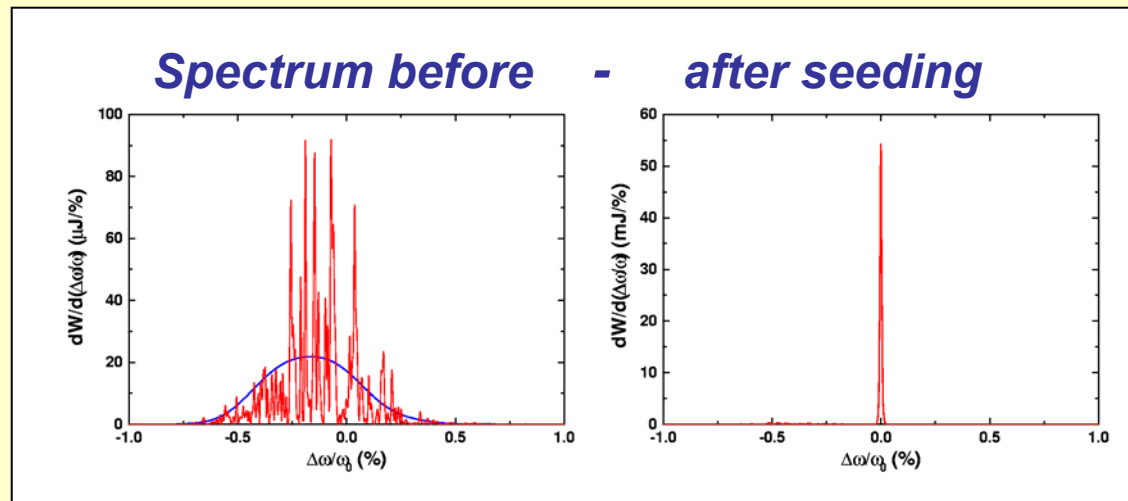
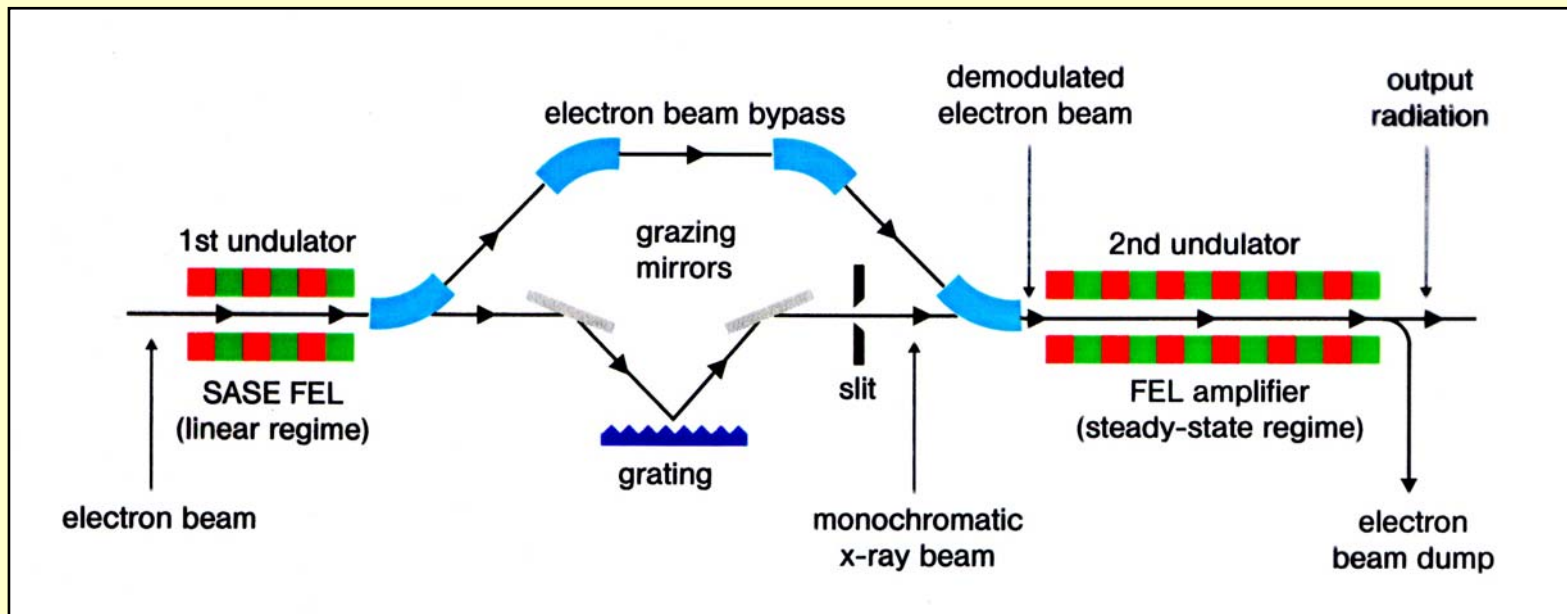
0.6 mm slit distance



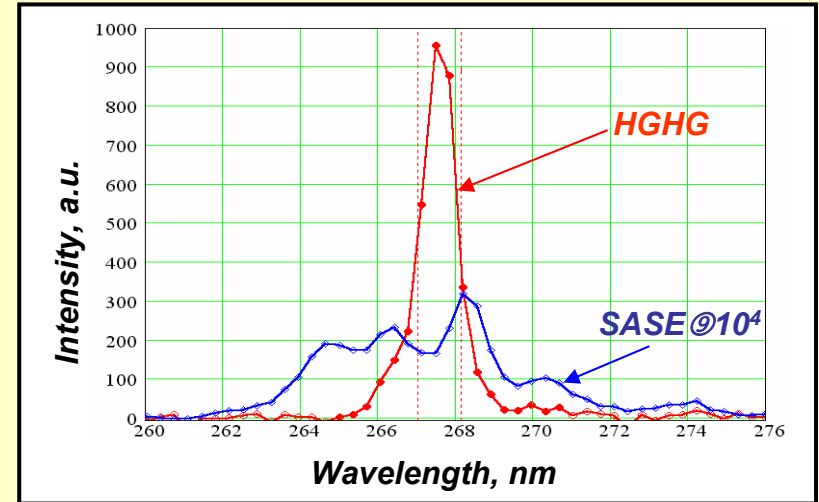
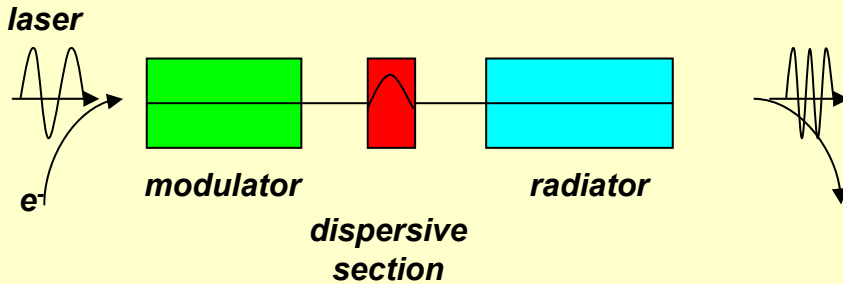
Single shot spectrum

3rd harmonic at 8.5 nm
(2500 shots)

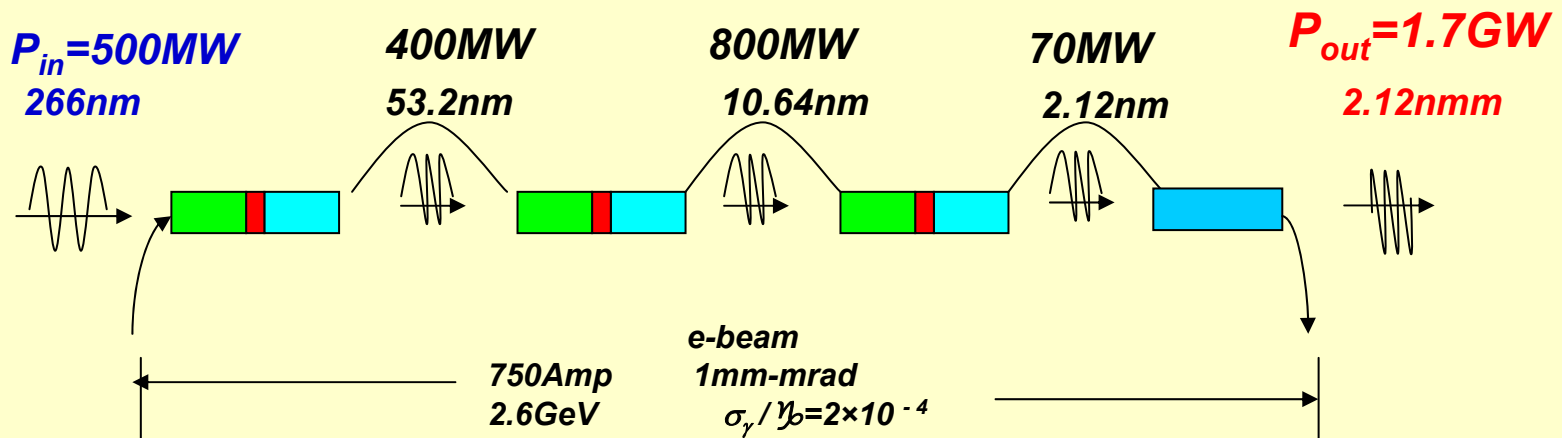
Improved beam properties by self-seeding



Li Hua Yu (Brookhaven National Lab)

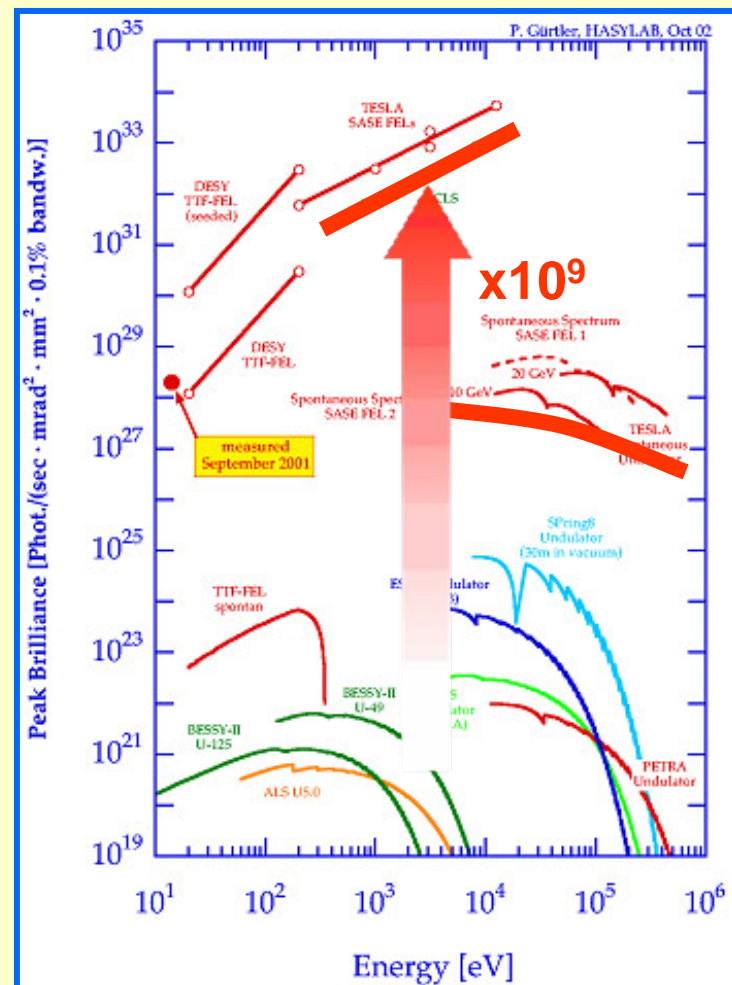
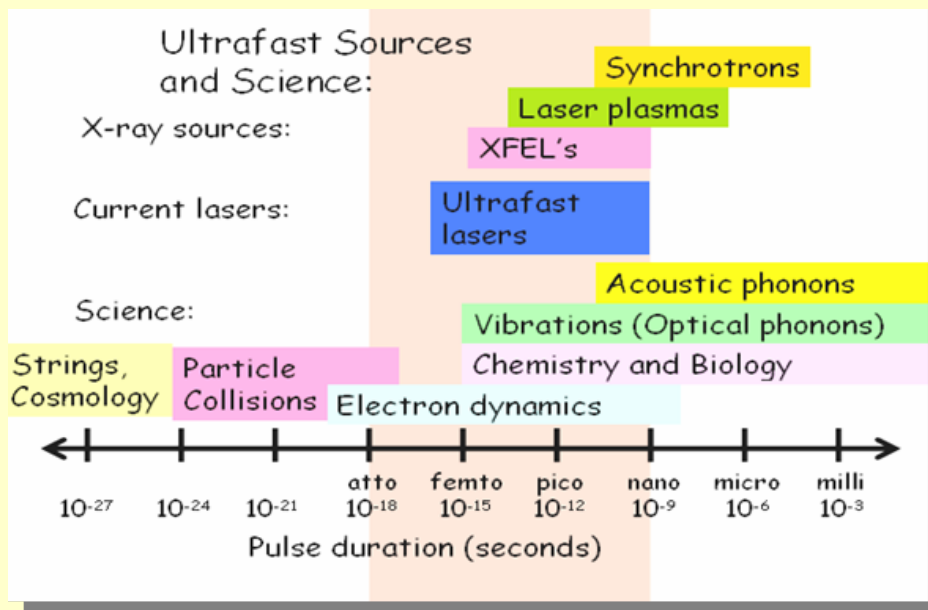


Cascading HGHG Stages to Generate Coherent Soft X-ray

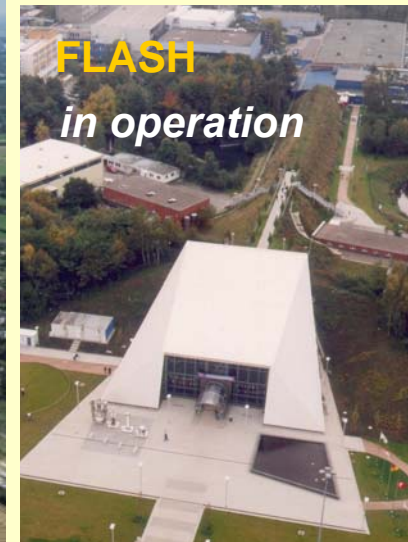
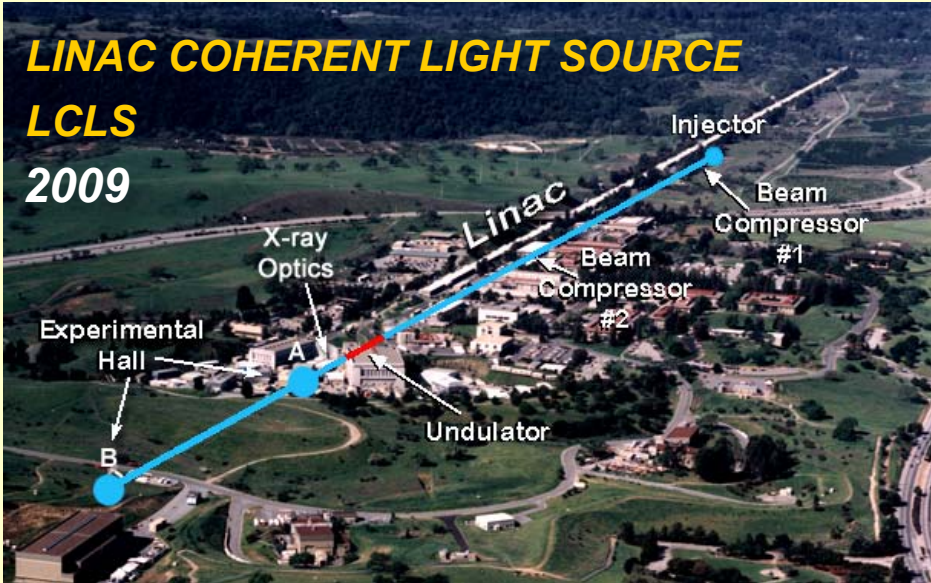


Compared to 3rd generation storage ring based synchrotron radiation facilities, the gain factors are:

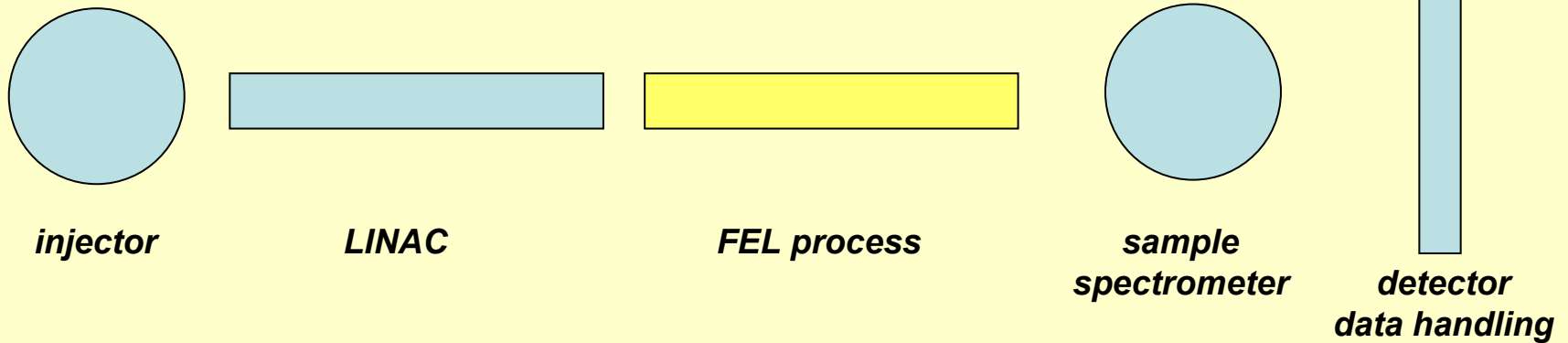
- **peak brilliance:** 10^9 at the FEL line
 10^4 spontaneous
- **average brilliance:** 10^4 at FEL line
- **coherence:** 10^9 at FEL line



Peak brilliance



Experiments at XFEL

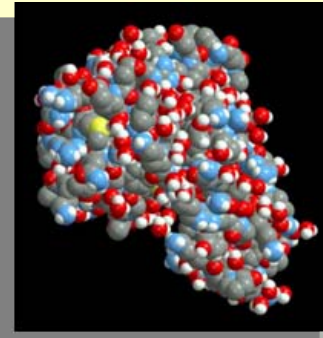
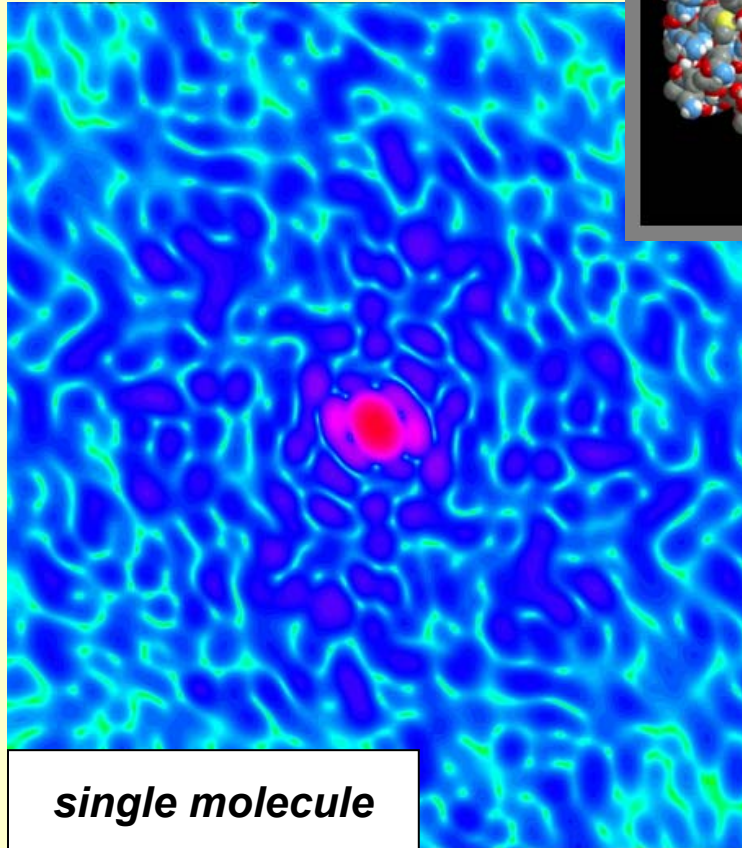


VUV-FEL
DESY

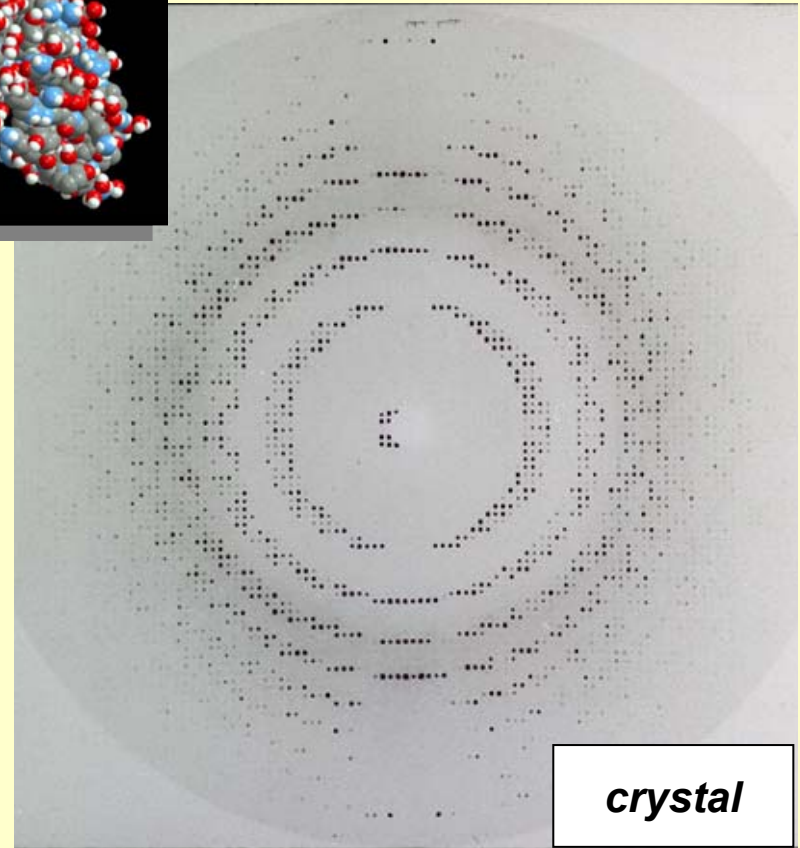
LCLS
Stanford

- *FEL process: pulse shaping*
- *e- and photon beam diagnostics, synchronization*
- *mechanical stability (10 fs ↔ 3 μm)*
- *interaction of FEL beam with matter*
- *sample preparation*
- *sample environment (pump lasers, synchronization)*
- *detector development*
- *data processing*
- *data analysis*

with atomic resolution



Lysozym

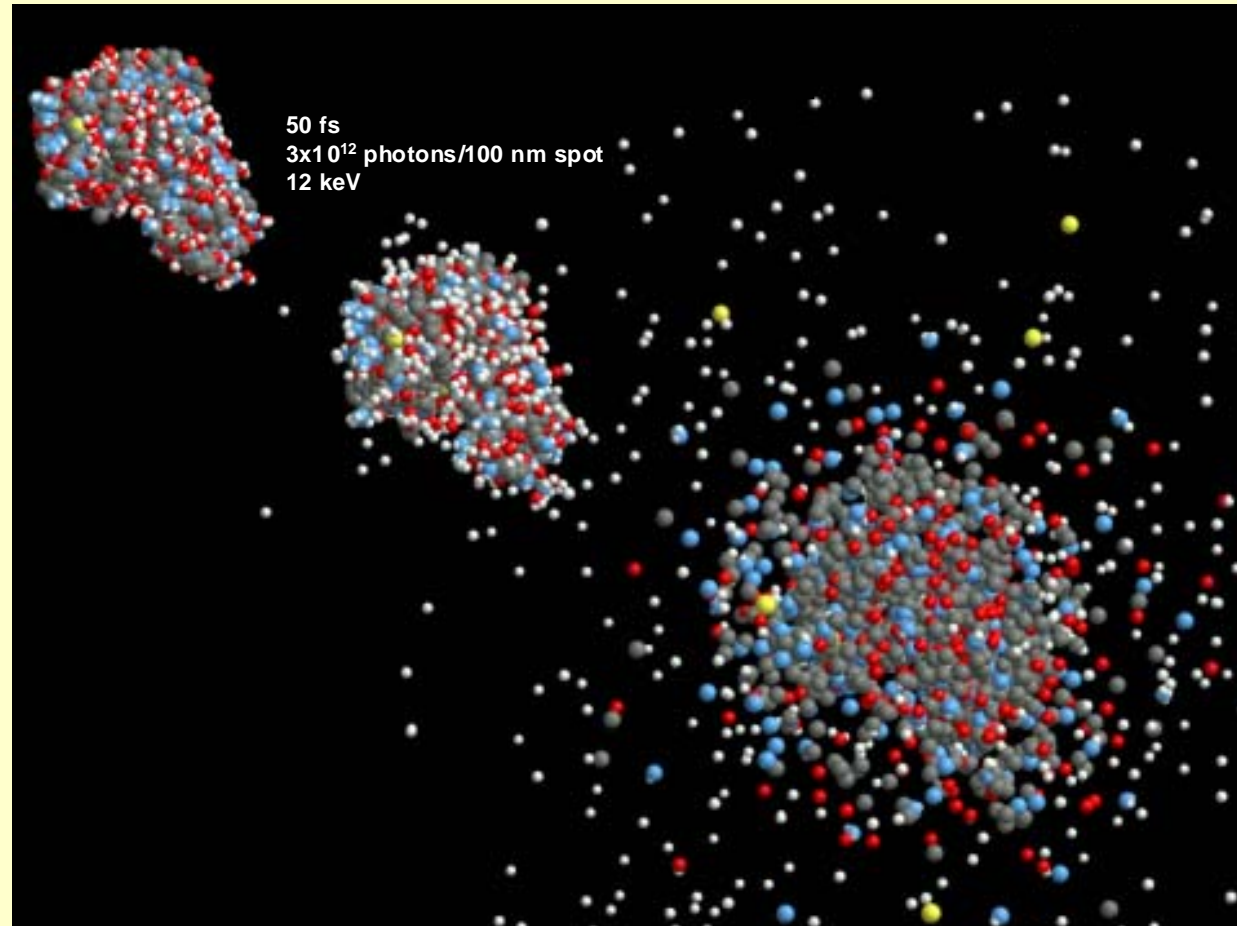


Oversampling: J. Miao, K.O. Hodgson and D. Sayre, PNAS 98 (2001) 6641-6645

$t=0$

$t=50 \text{ fsec}$

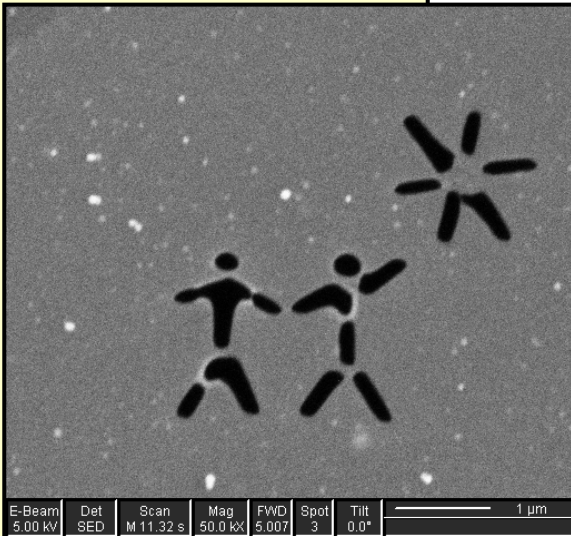
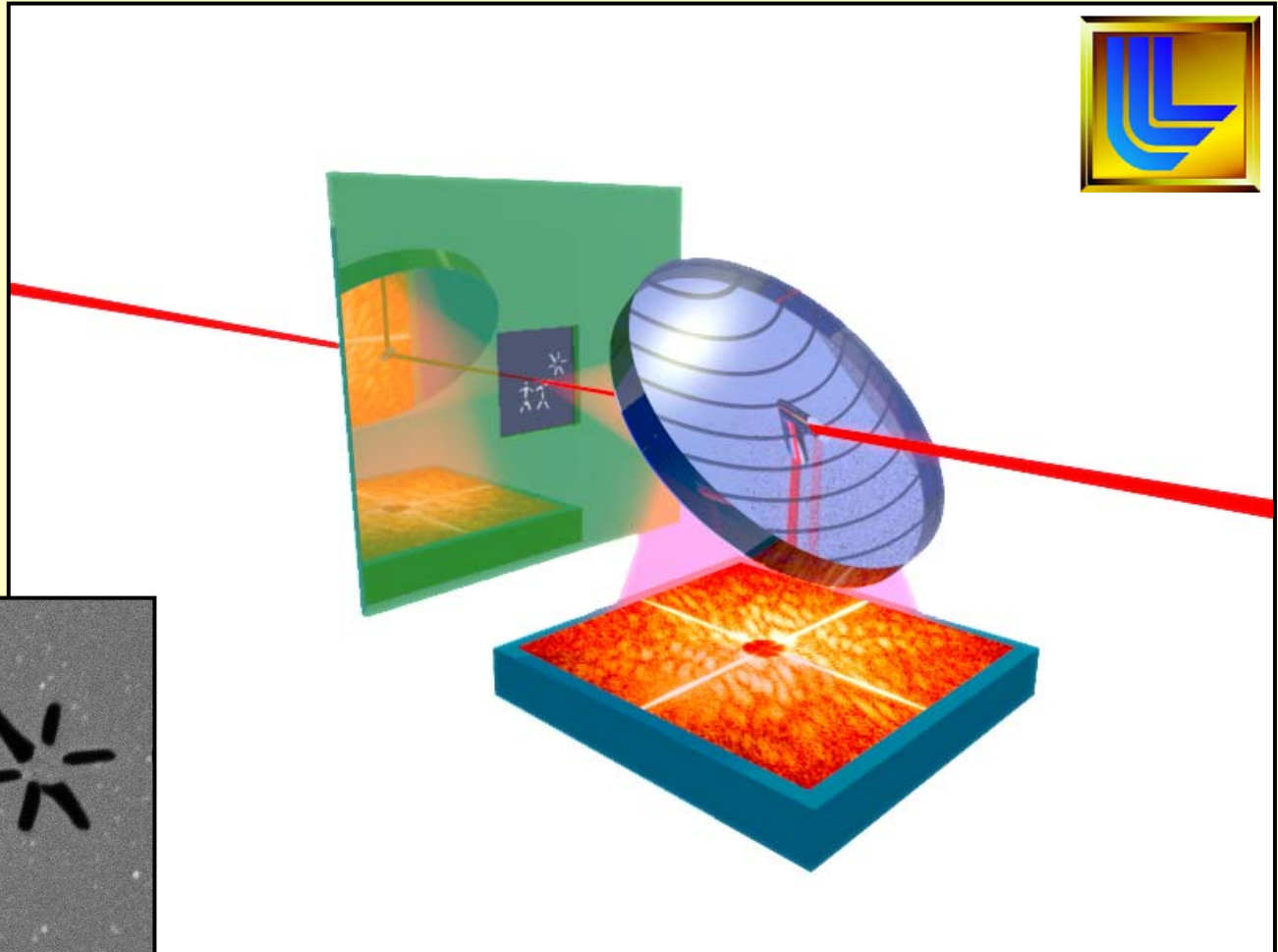
$t=100 \text{ fsec}$



R. Neutze, R. Wouts, D. van der Spoerl, E. Weckert, J. Hajdu: Nature 406 (2000) 752-757

FLASH

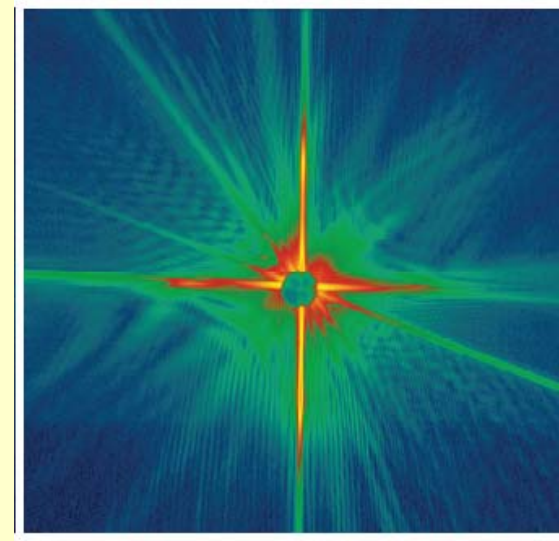
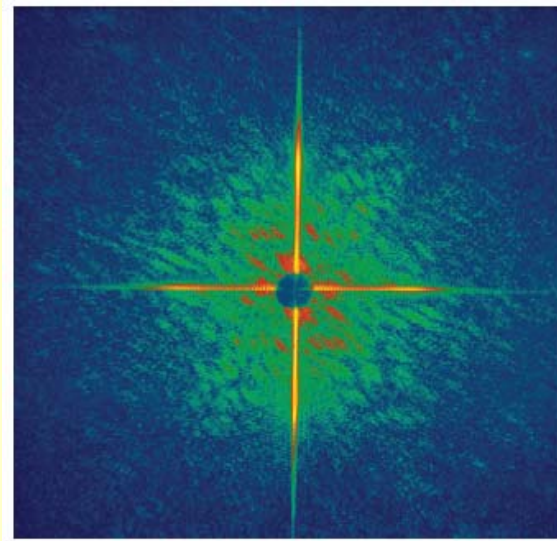
*Incident FEL pulse:
30 fs, 32 nm,
 $3 \times 10^{13} \text{ W cm}^{-2}$*



H. Chapman, J. Hajdu et al.

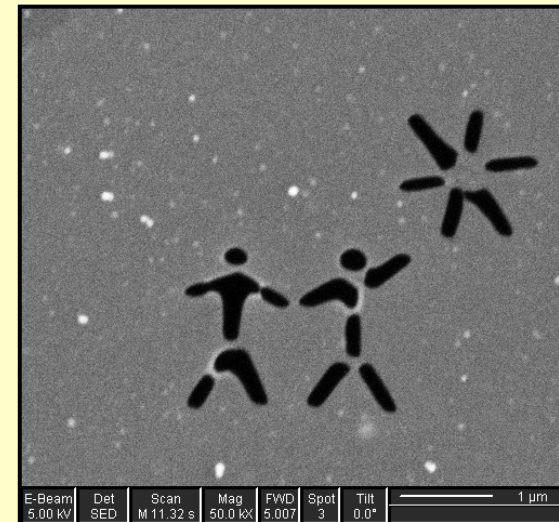
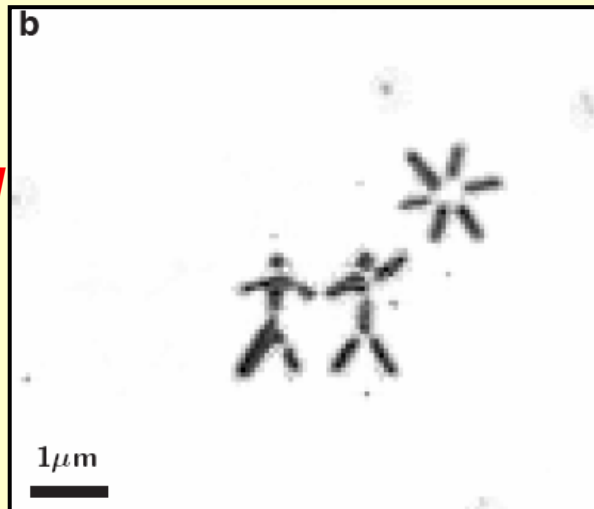
FLASH

diffraction pattern from first pulse



diffraction pattern from second pulse

reconstructed picture



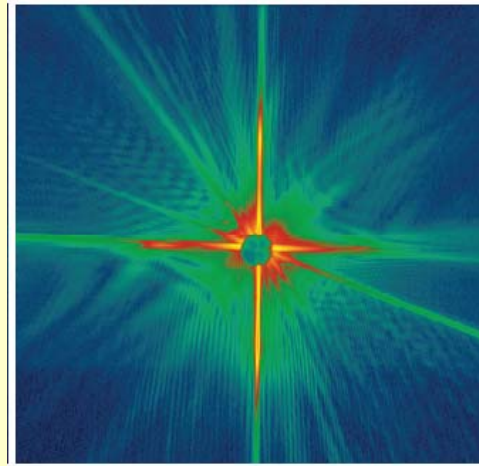
TEM picture from original structure



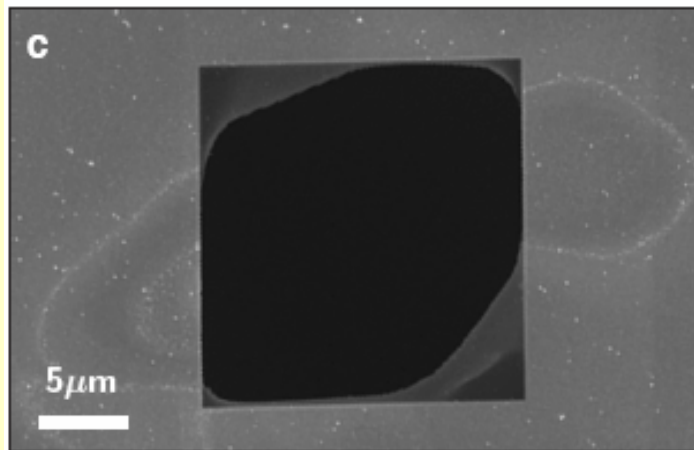
H. Chapman, J. Hajdu et al.

FLASH

H. Chapman, J. Hajdu et al.



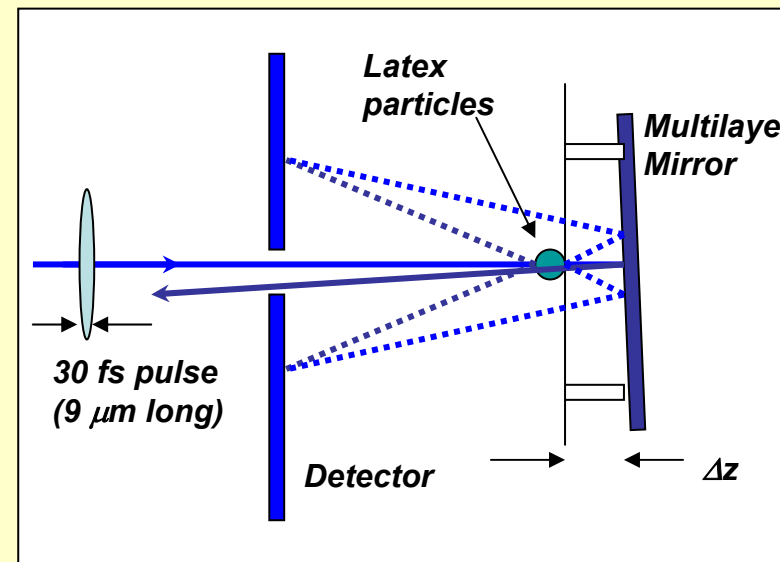
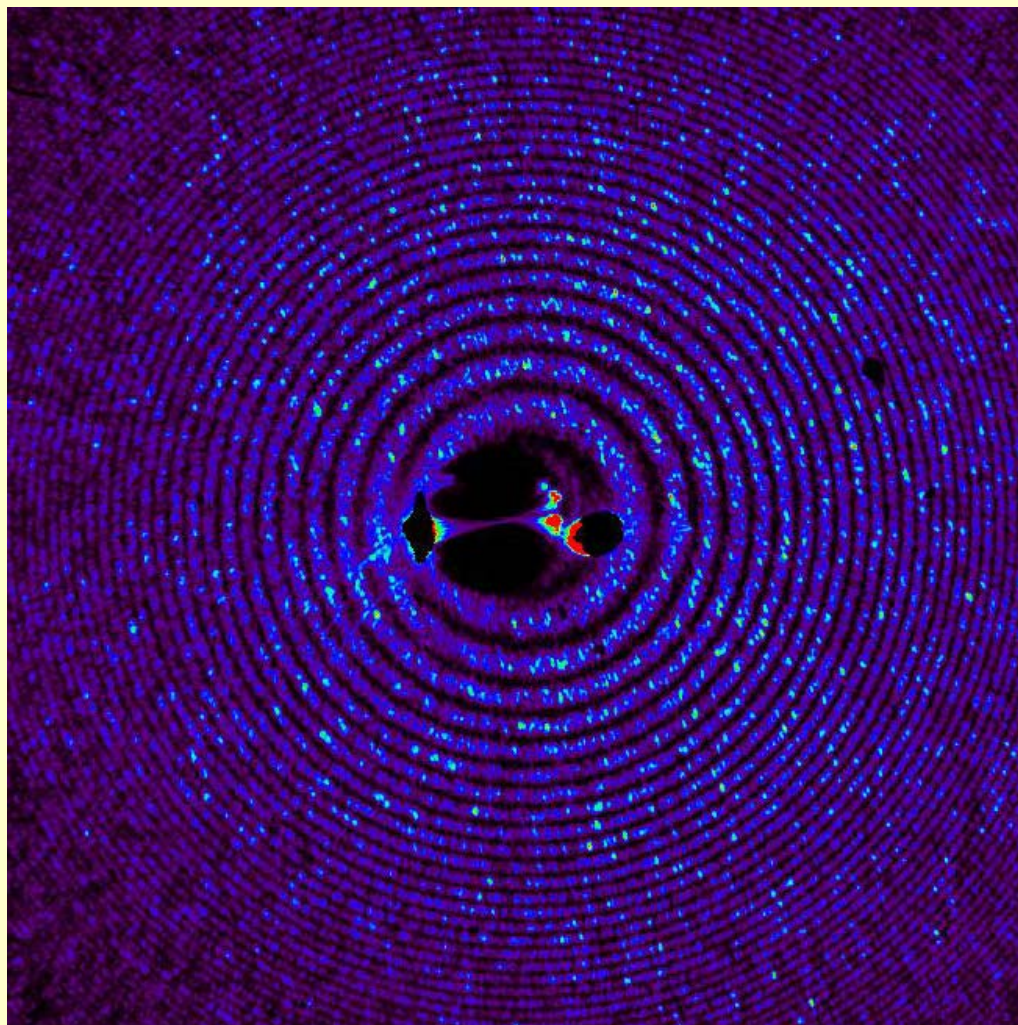
*diffraction
pattern from
second pulse*



photograph of Si frame



reconstructed picture including frame



- Prompt diffraction
- Delayed diffraction

$Time\ delay = 2\Delta z/c$

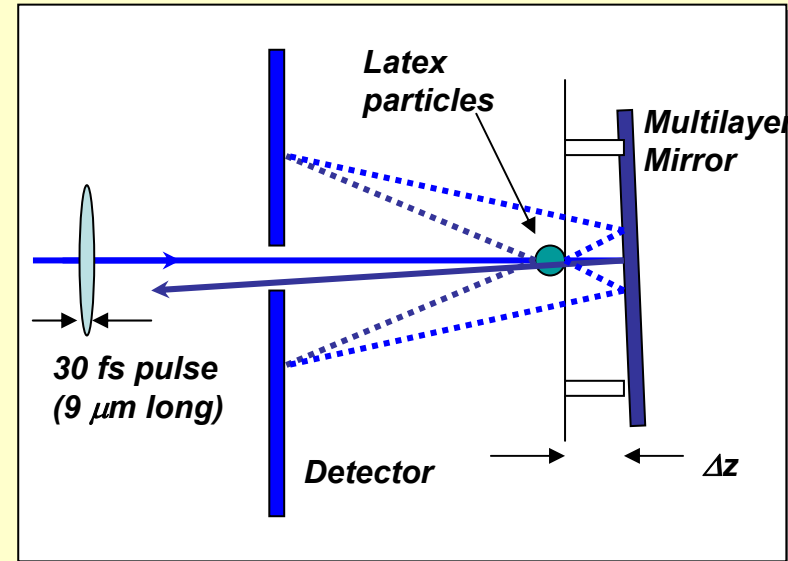
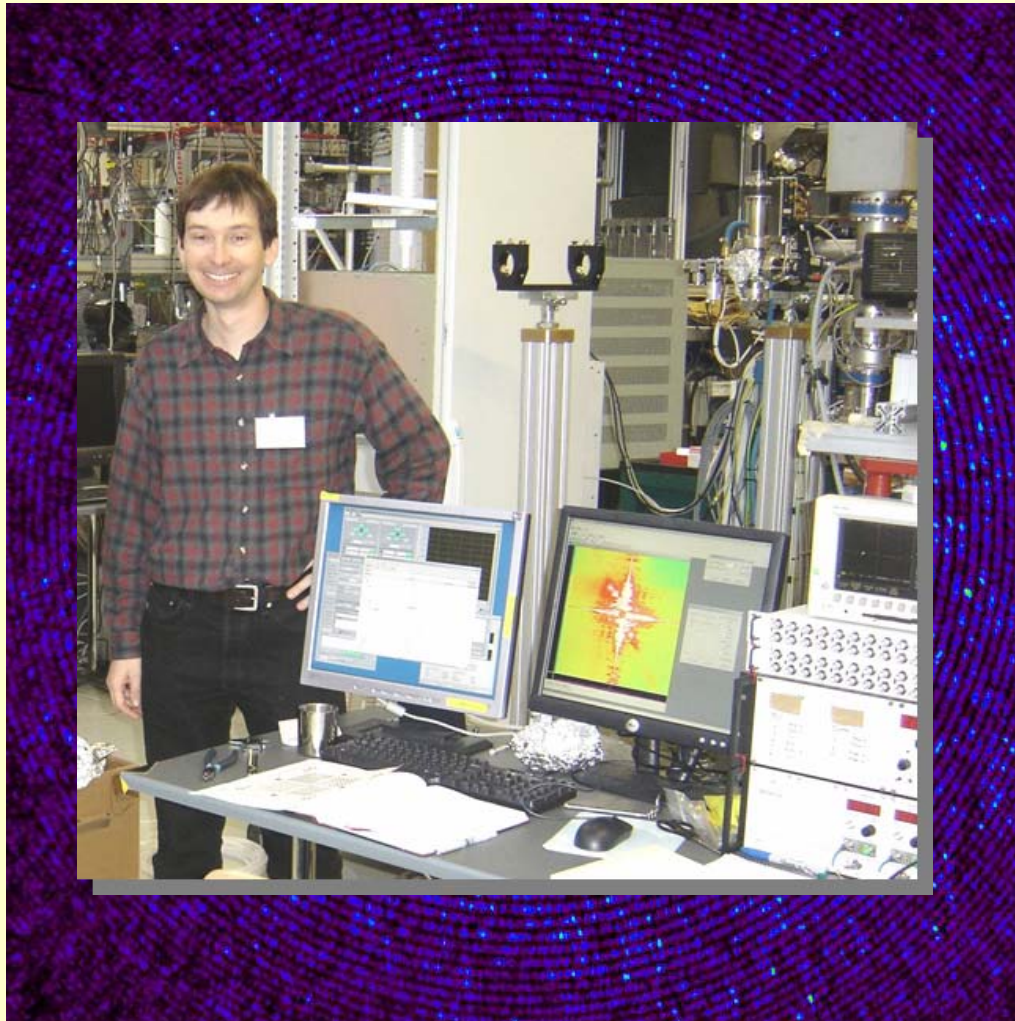
The pattern is the interference of the waves scattered from the unexploded particle (reference wave) and the same particle during explosion. Many particles generate speckle also.

Chapman, Hajdu and collaborators



FLASH

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



- Prompt diffraction
- Delayed diffraction

$$\text{Time delay} = 2\Delta z/c$$

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



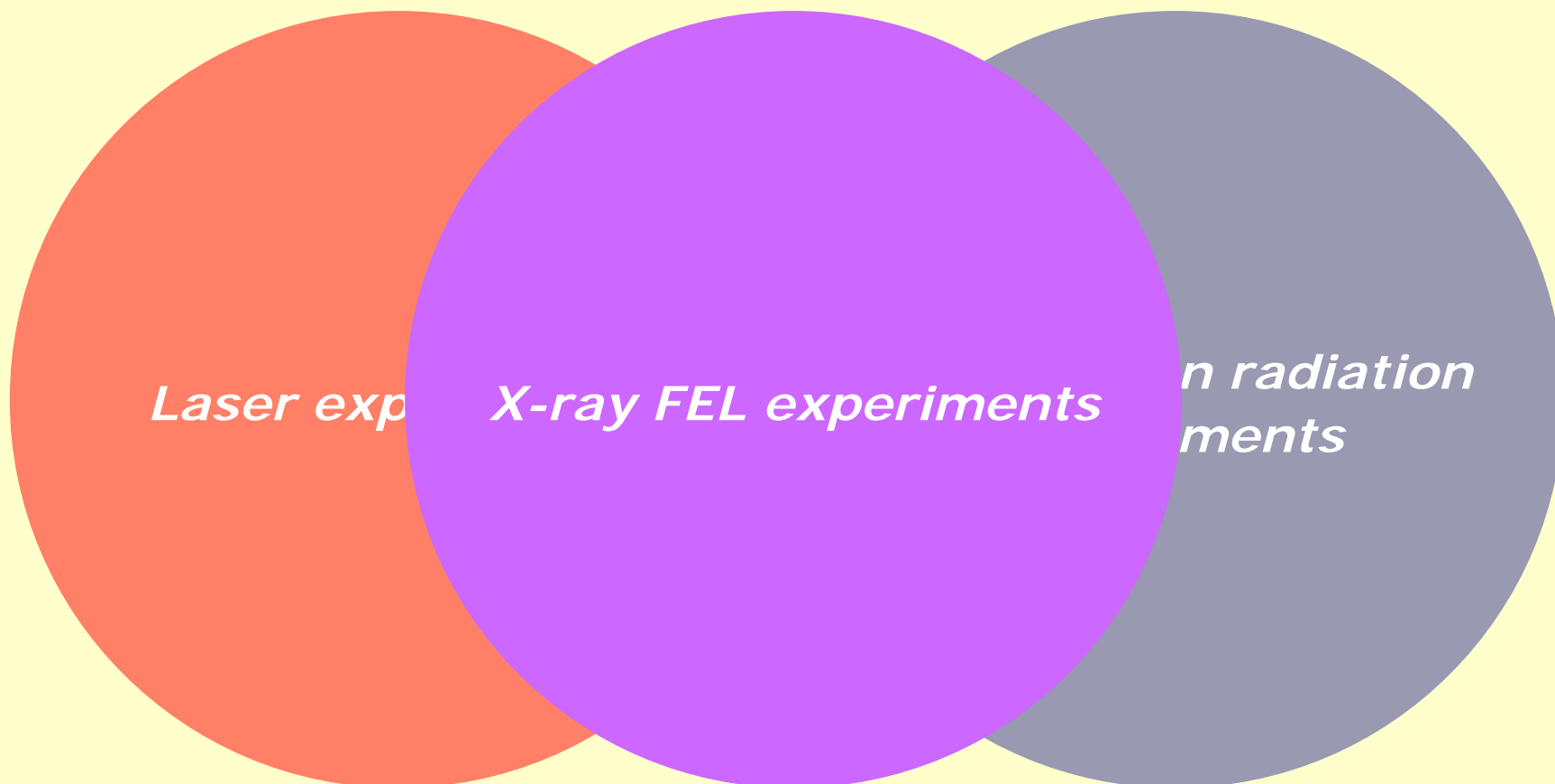
FLASH

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

Laser experiments

*Synchrotron radiation
experiments*

Accelerator Science & Particle Physics methodology



Accelerator Science & Particle Physics methodology