Ultrakurze Röntgenimpulse am PSI: vom FEMTO-Projekt zum SwissFEL

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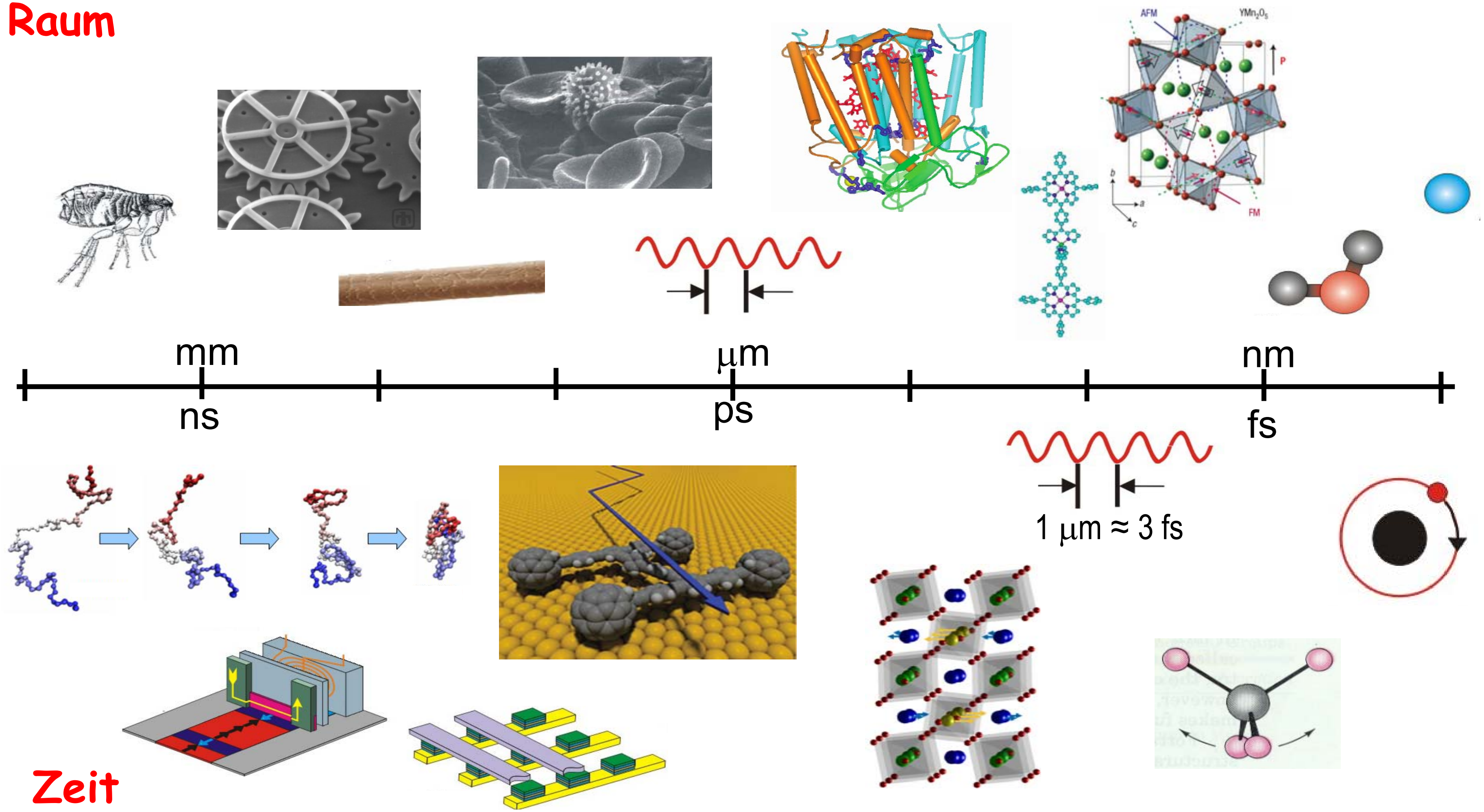
Warum ultrakurze Röntgenpulse?



Raum

mm

µm

nm

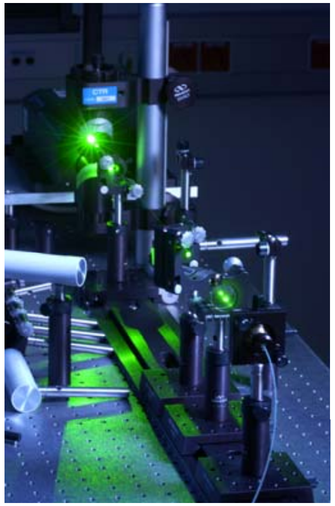
ns

ps

fs

1 µm ≈ 3 fs

Zeit



Optische Laser (HHG)

τ = 2 fs … (0.4 fs)

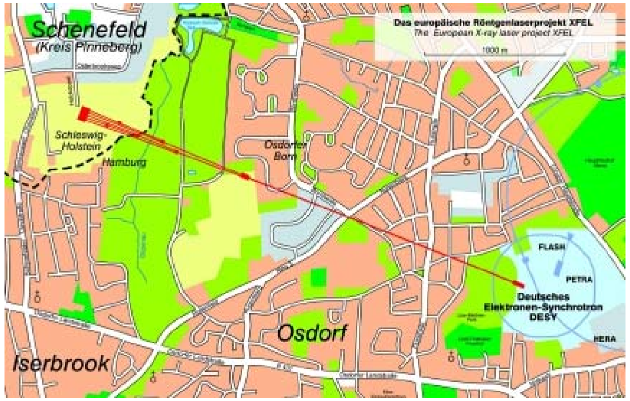
λ = 200 nm…(14 nm)

Synchrotron

λ = 0.1 – 10 nm, $\tau \approx$ 100 ps

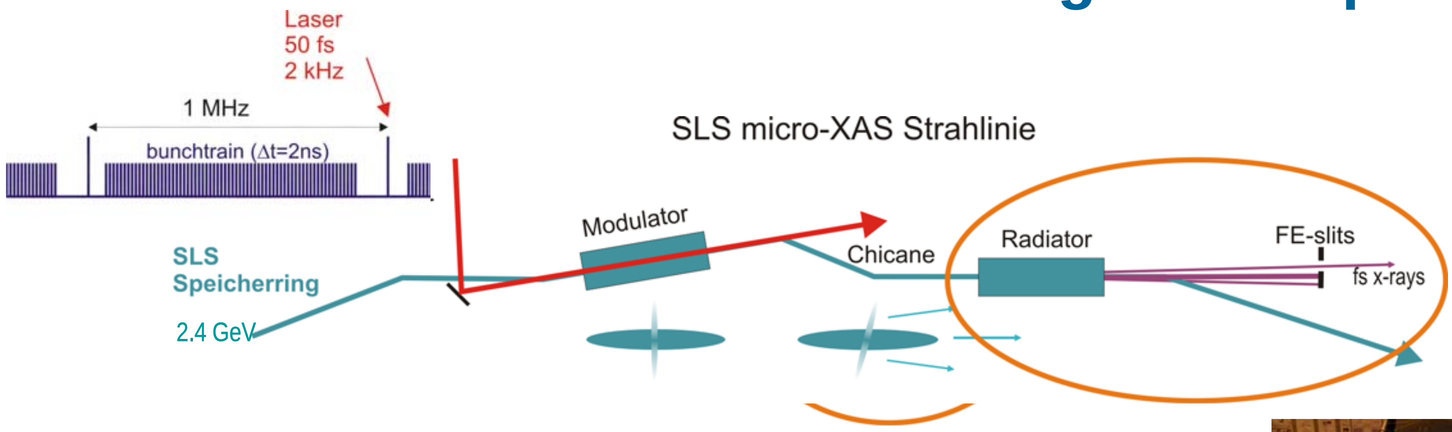
λ = 0.1 - 0.3 nm, $\tau \approx$ 100 fs

XFEL λ = 0.1 nm, $\tau \approx$ 10 fs



SCLC (Stanford)	2009
SCSS (Japan)	2011
XFEL (Hamburg)	2015
SwissFEL	2016

FEMTO: laser-electron beam ‘slicing’ technique



‚Slicing‘- Prozess in 3 Schritten:

1. Modulation der Elektronenenergie mit einem kurzen Laserpuls
2. Räumliche Trennung der modulierten Elektronen (Dispersion)
3. Trennung der von den modulierten Elektronen emittierten Strahlung in der Beamline

ineffizient

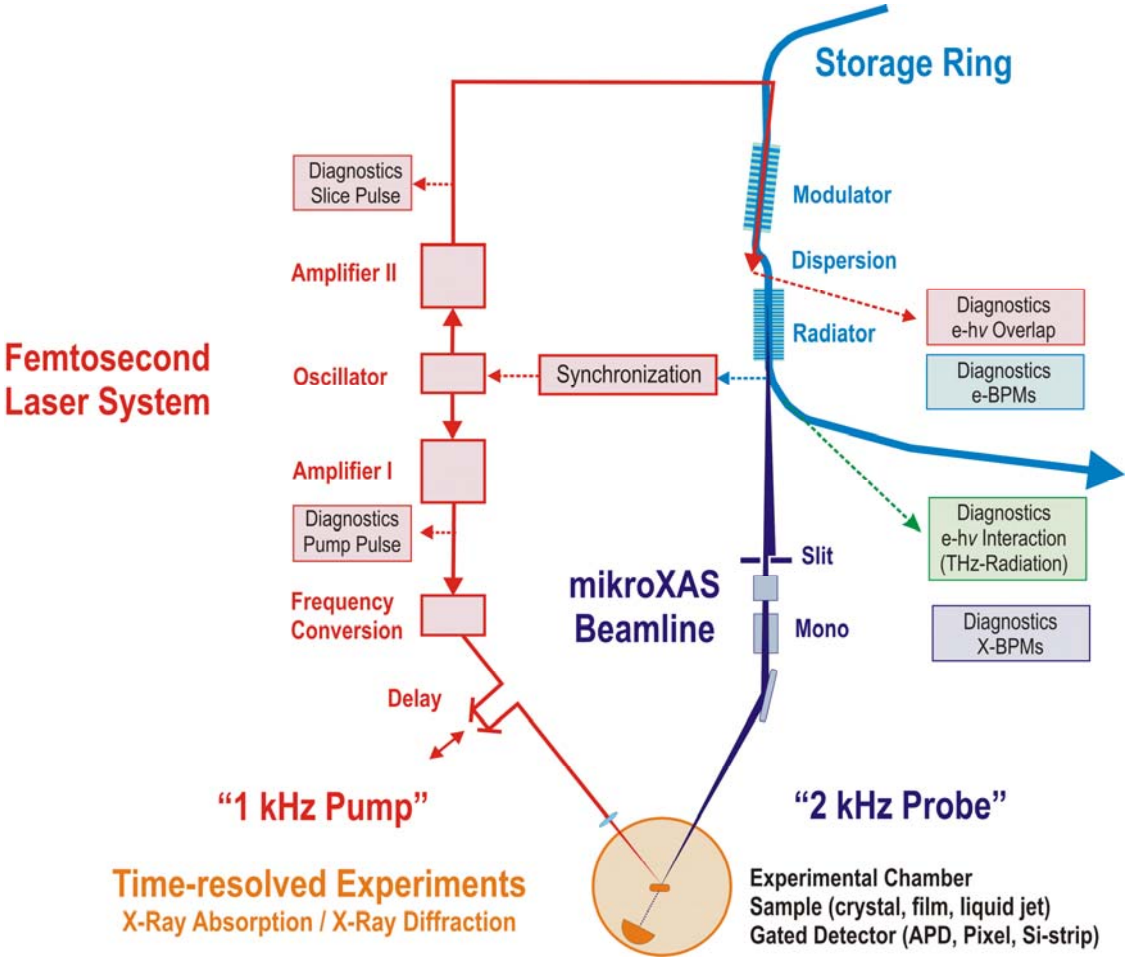
$$\boxed{\eta = \frac{f_L}{f_{el}}\frac{\tau_L}{\tau_{el}} \approx 10^{-8}}$$

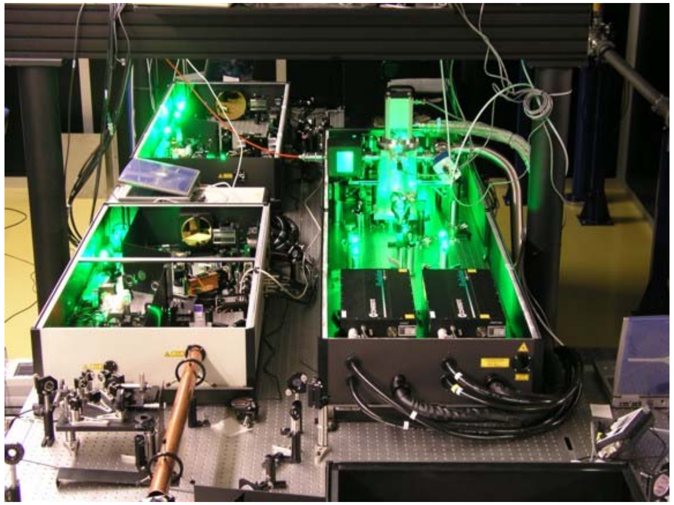
La

im pe

[Zholents and Zolotorev, *Phys. Rev. Lett.* **76**, 912, 1996; R. Schoenlein et al. *Science* **287**, 2237, 2000]

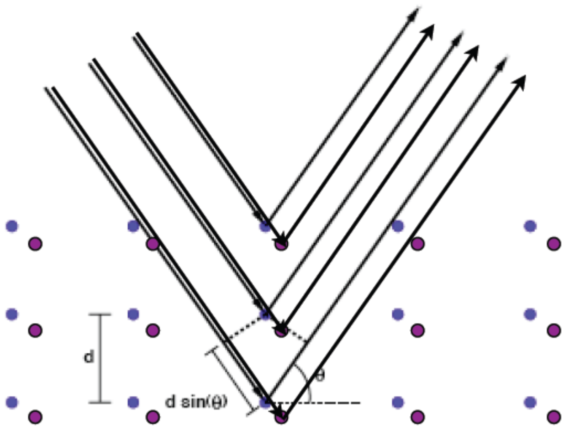
'Slicing' implementation at SLS

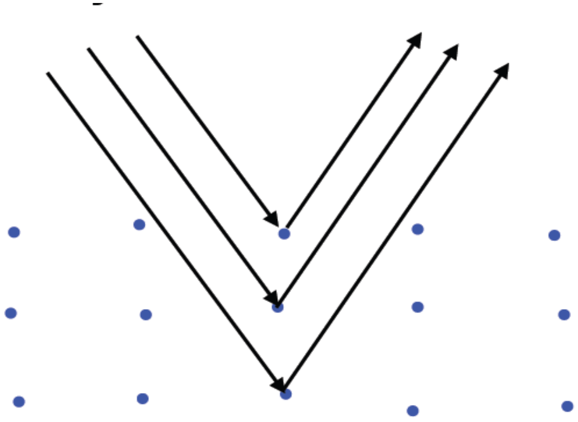




X-ray diffraction

Delivers Information on ‘long range’ electronic and atomic structure





Diffraction from a crystal with a non-trivial basis:

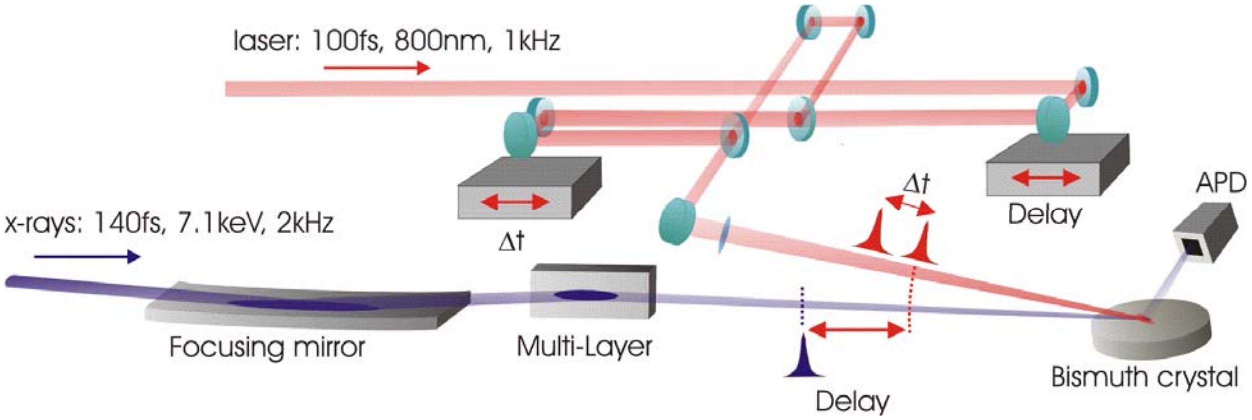
- Interference between “sublattices”
- Intensity of diffraction peaks → unit cell structure (structure factor)

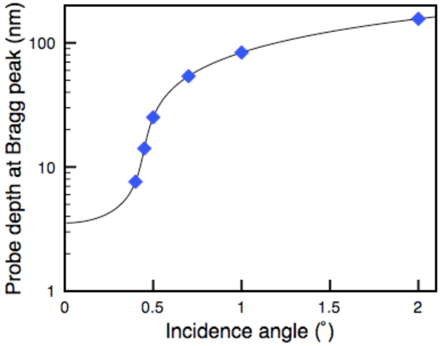
Diffraction from a disordered crystal:

- Debye Waller factor ~ $exp(-<(\mathbf{G}\cdot\mathbf{u})^2>)$
- Information on projected rms displacements

Femtosecond grazing incidence X-ray diffraction

Diffraction delivers Information on ‘long range’ electronic and atomic structure

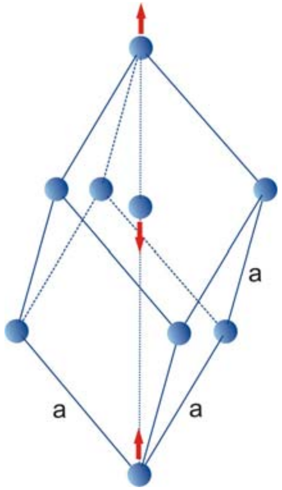




Simple structures → comparison to DFT

- Coherent optical phonon → source characterization [P. Beaud *et al.*, Phys. Rev. Lett. 99, 174801, 2007]
- Bi: electron-hole interaction, carrier diffusion [S.L. Johnson *et al.*, Phys. Rev. Lett. 100, 155501, 2008]
- InSb: energy transfer from excited carriers to the lattice [F.S. Krasniqi *et al*., Phys. Rev. B *72*, 174302, 2008]
- Phonon squeezing in Bi [S.L. Johnson *et al.*, Phys. Rev. Lett. 102, 175503, 2009]
- Te: Atomic movie [S.L. Johnson *et al.*, submitted]

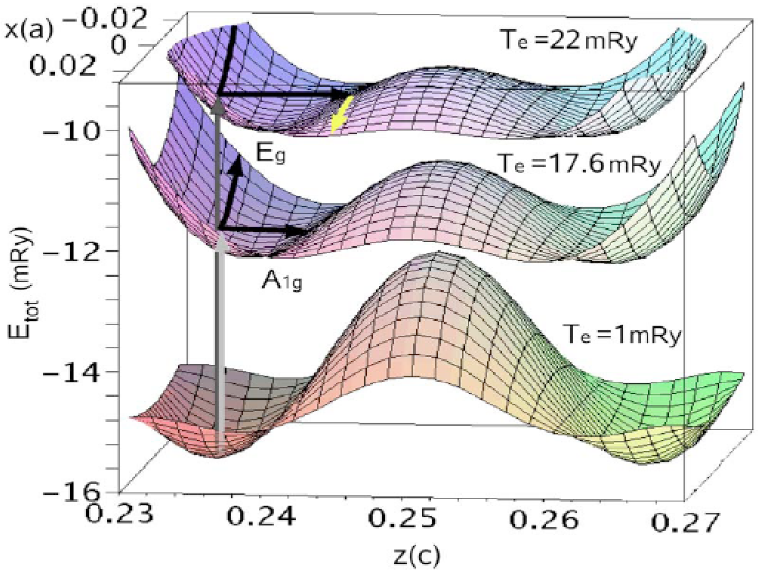
Ultrafast bond softening in Bi

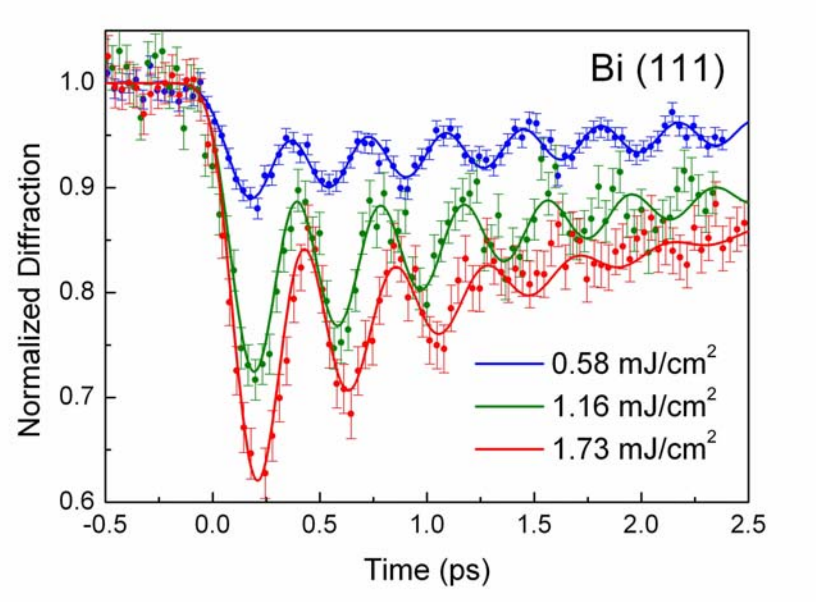


Semimetal, unit cell distorted by Jones-Peierls effect

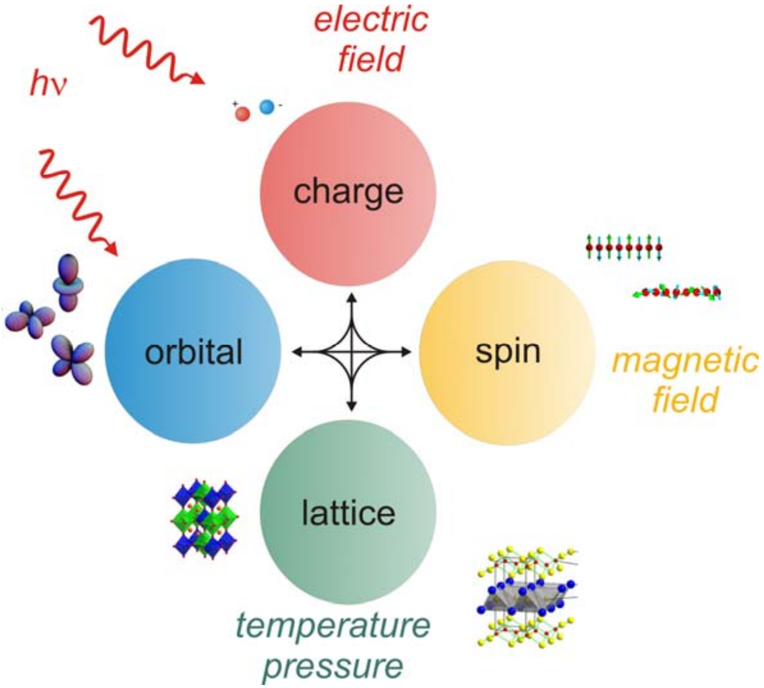
Displacive excitation of a coherent optical phonon:

- Structural information
- Mapping inter-atomic potential
- Direct comparison to theory





Ultrafast structural dynamics of photoexcited Strongly correlated electron systems



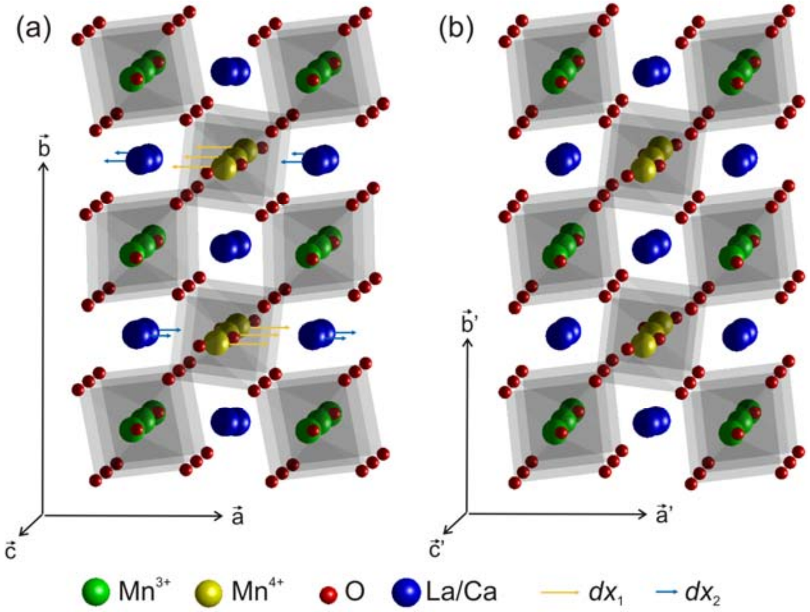
High-TC superconductivity

Colossal Magnetoresistance

Multiferroicity

Time-ordering will advance our understanding of underlying correlations

Structural response to ultrafast melting of charge and orbital order in a manganite



$La_{1-x}Ca_xMnO_3$ exhibits colossal magnetoresistance for x<0.5

Ground state charge and orbitally ordered (x>0.5)

<2 mJ/cm^2: displacive excitation of optical phonon (no PT)

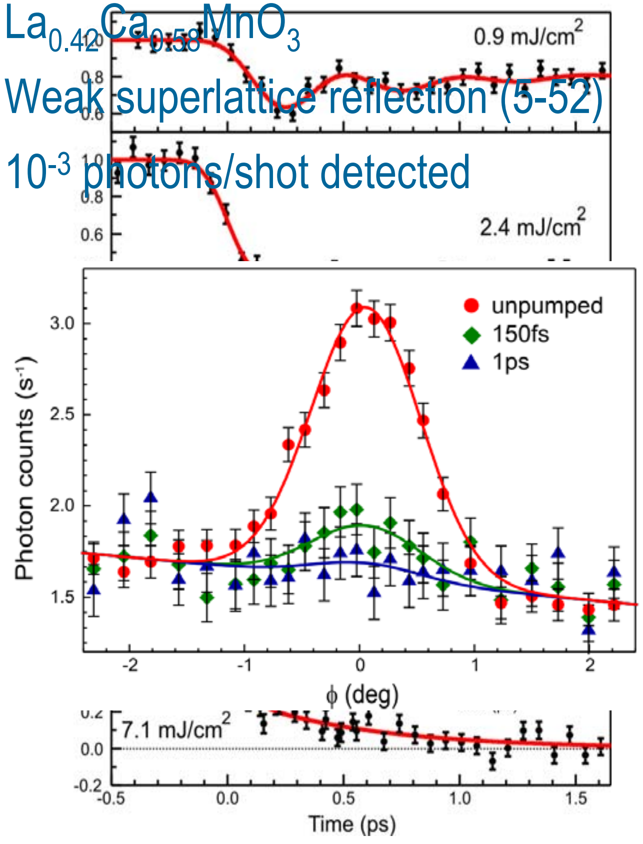
>2 mJ/cm^2: immediate release of Jahn-Teller distortion

→ complete structural phase transition within 1 ps

$La_{0.42}Ca_{0.58}MnO_3$

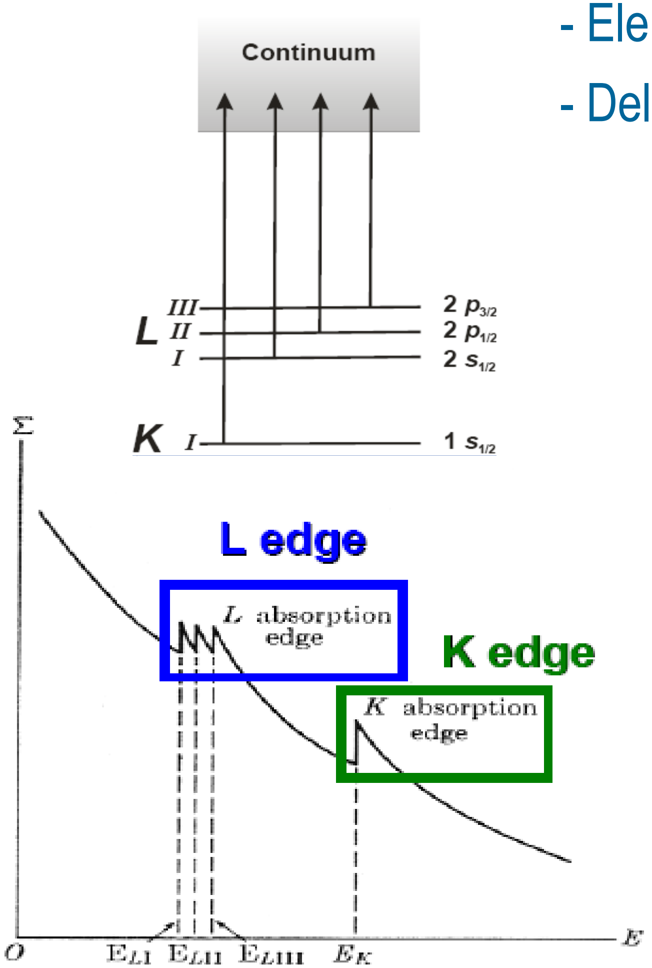
Weak superlattice reflection (5-52)

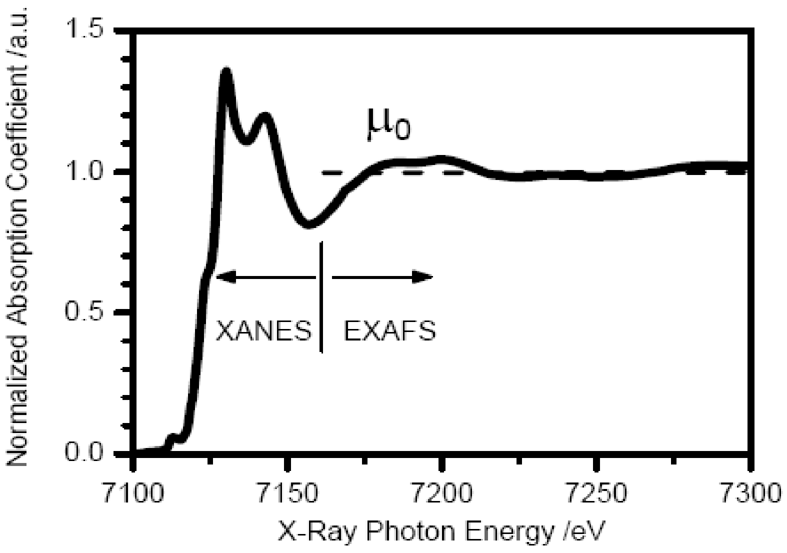
10^{-3} photons/shot detected



X-ray absorption spectroscopy

- Element specific
- Delivers Information on **'local'** electronic and atomic structure

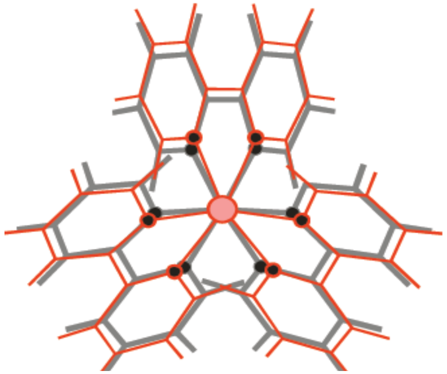




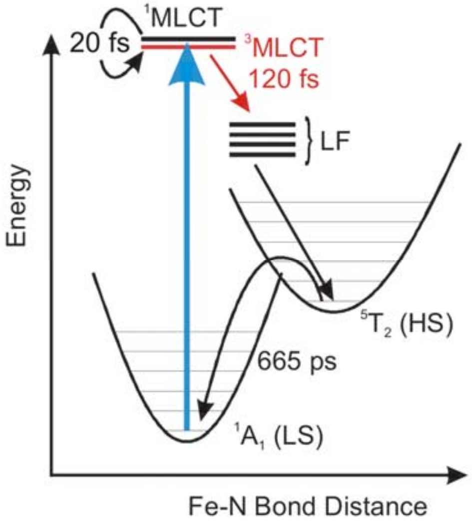
XANES: X-ray Absorption Near Edge Structure

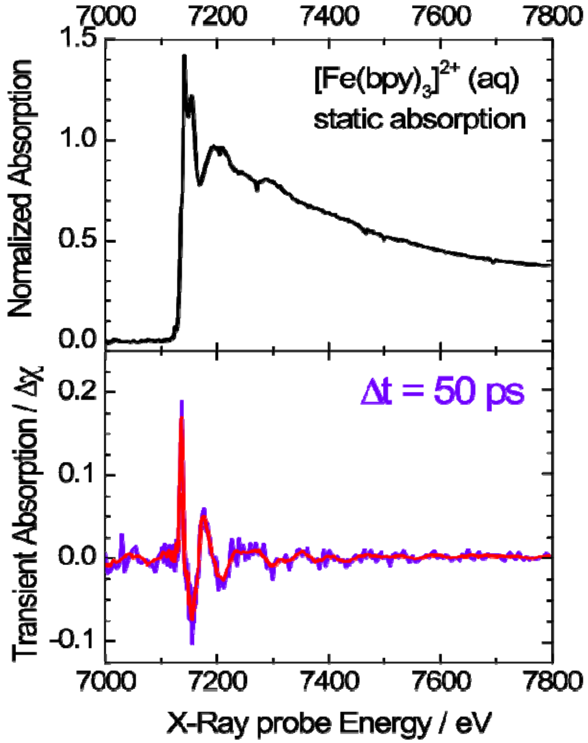
EXAFS: Extended X-ray Absorption Fine Structure

Picosecond XANES of the light-induced spin crossover in an Iron(II)-complex (Collaboration with M. Chergui, EPFL)



$[Fe(bpy)_3]^{2+}$ in water

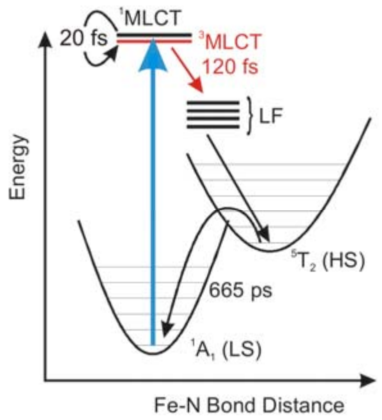


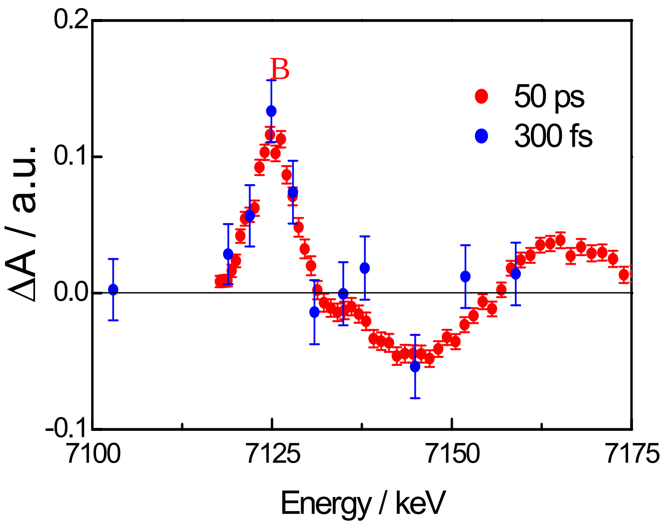


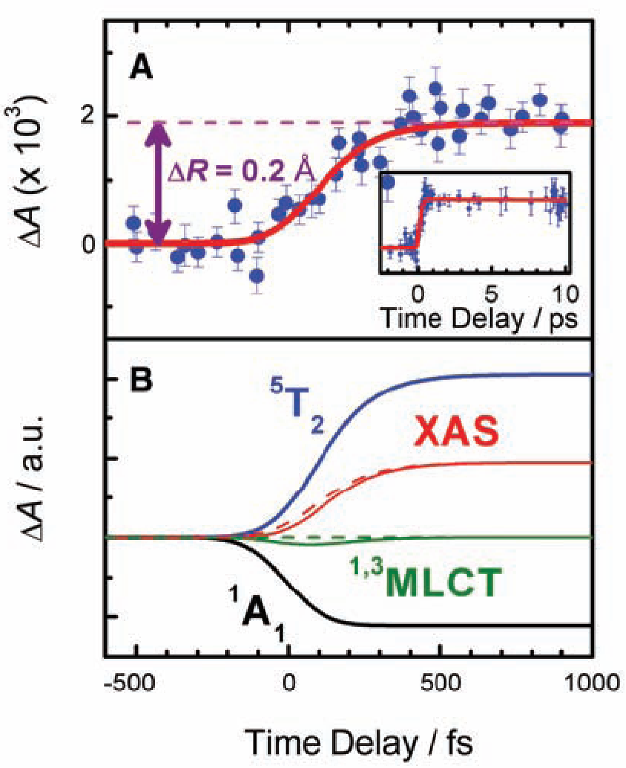
Elongation of Fe-N bond distance by 0.19 ± 0.03Å in quintet state
[W. Gawelda, et al., Physical Review Letters 98, 057401, 2007]

Results of femtosecond XANES

[C. Bressler *et al.*, Science 323, 489, 2009]

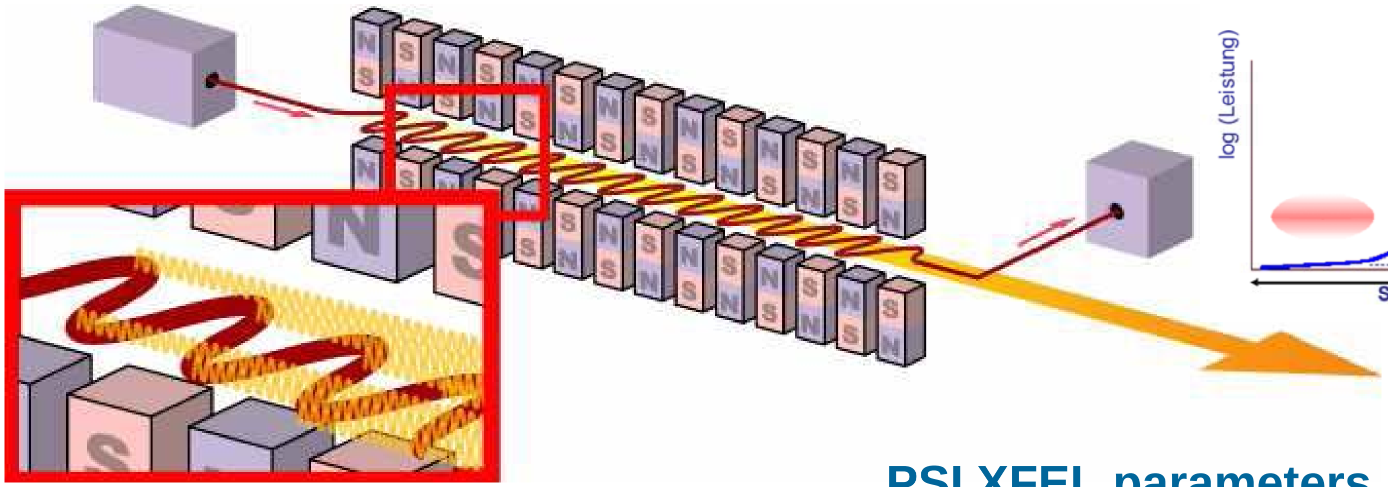




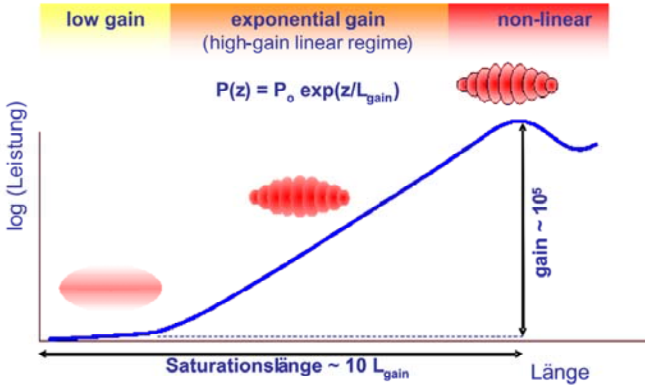


Quintet state populated within ~150 fs !

SwissFEL, the next large facility at PSI



„self-amplified spontaneous emission“ (SASE).



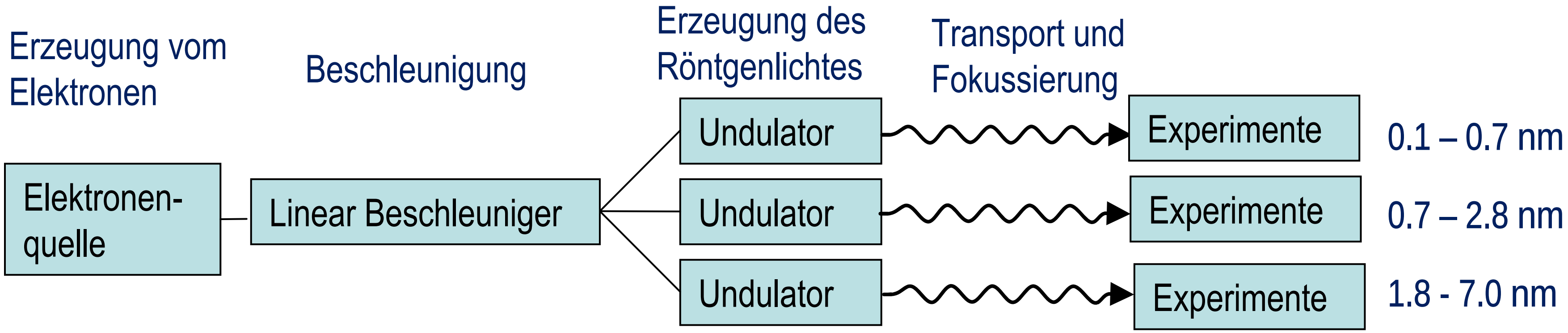
FEL principle

Electrons interact with periodic magnetic field of undulator magnets to build up an extremely short and intense X-ray pulse.

PSI XFEL parameters

- Wavelength tunable from 10^{-10} to 10^{-8} m
- Pulse duration 10^{-14} to 10^{-15} s
- Pulse energy 2 – 50 μJ
- Repetition rate 100 – 400 Hz

„Bausteine“ eines FELs



Erzeugung vom Elektronen

Beschleunigung

Erzeugung des Röntgenlichtes

Transport und Fokussierung

Elektronen-quelle

Linear Beschleuniger

Undulator

Undulator

Undulator

Experimente

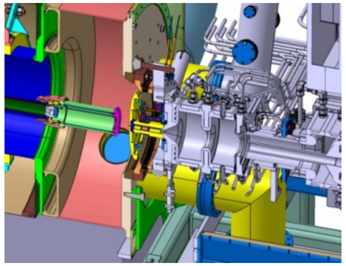
Experimente

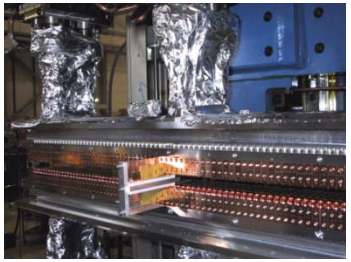
Experimente

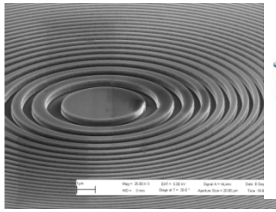
0.1 – 0.7 nm

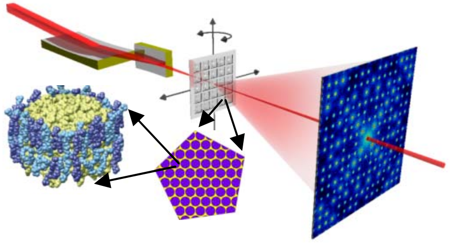
0.7 – 2.8 nm

1.8 - 7.0 nm



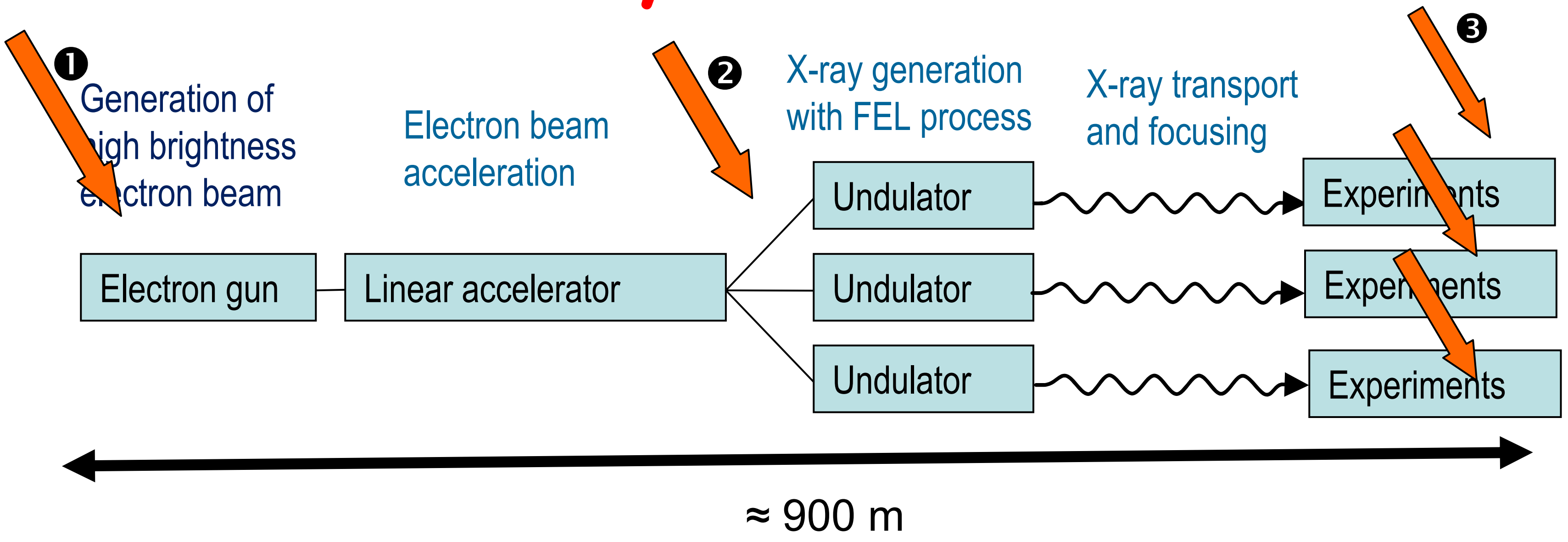






Laser Systeme

Synchronization ?



❶ Generation of high brightness electron beam

Electron beam acceleration

❷

X-ray generation with FEL process

X-ray transport and focusing

❸

Electron gun

Linear accelerator

Undulator

Undulator

Undulator

Experiments

Experiments

Experiments

≈ 900 m

❶

gun laser
for electron generation
(C. Hauri, R. Ganter)

❷

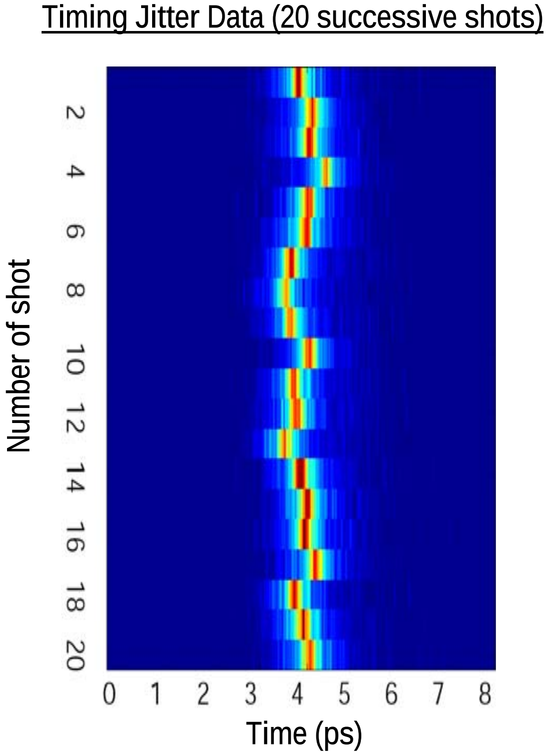
seed
high-order harmonic generation

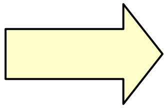
❸

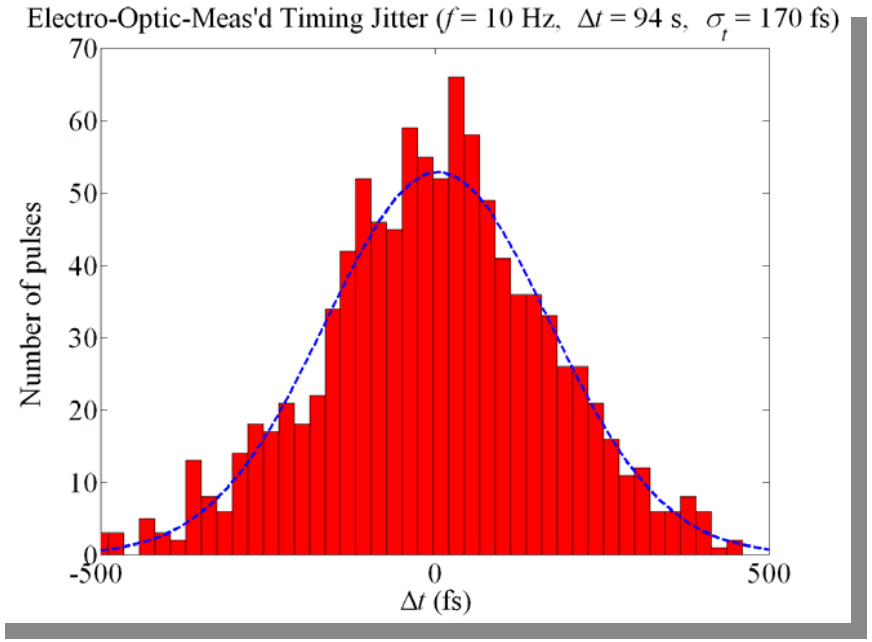
various lasers
at experimental stations

SPPS: Electron Beam-Laser Arrival Time Measurements

EO cross-correlation-measurements performed by A.L.Cavalieri et al. @ SPPS, SLAC

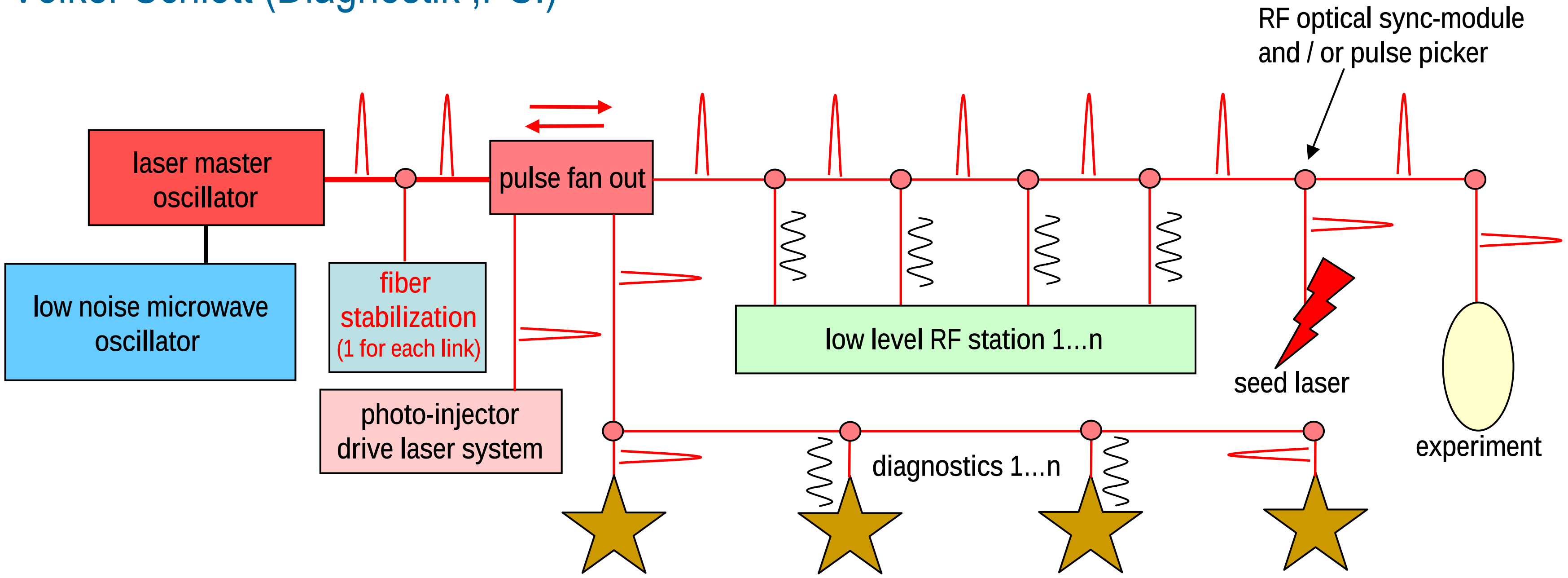






Layout Optical Synchronization System

Volker Schlott (Diagnostik ,PSI)



- mode-locked lasers as “new” optical master oscillator (fiber or solid state lasers)
- optical fiber distribution: <10 fs stabilization demonstrated

FEL science

Atomic physics: Auger processes, hollow atoms

Nanoscale dynamics

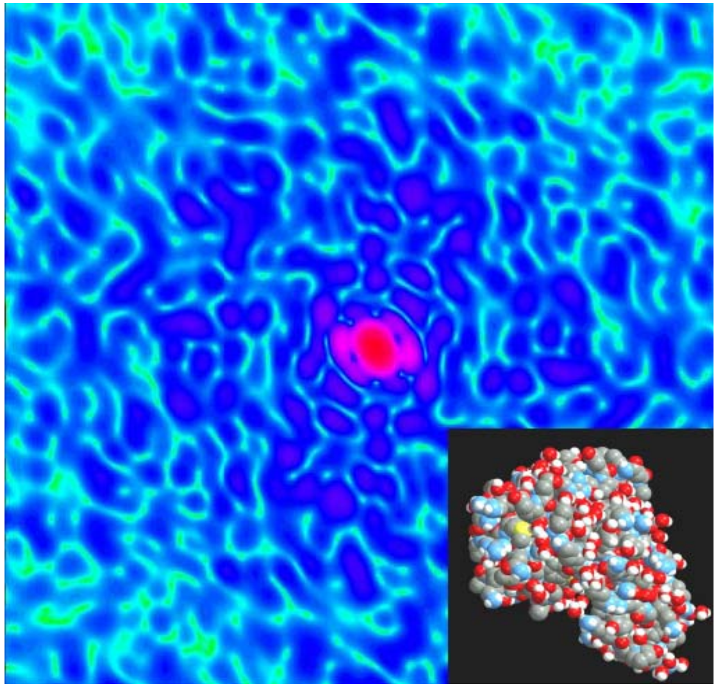
Material Science

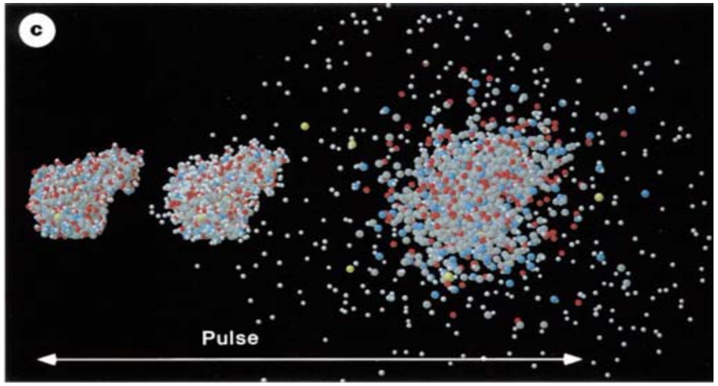
Femtochemistry

Biology:

  3D structure of a single molecule

  in a single shot





Neutze R, Wouts R, van der Spoel D, Weckert E, Hajdu J, NATURE **406**, 752-757 (2000)

‘High-Power green’ Laser am PSI ?

Zumeist diodengepumpte Festkörperlaser im Einsatz
→ hervorragende Stabilität

SwissFEL, ein grüner, Hochleistungslaser?

Output power	~5 mW
Energieverbrauch	~5 MW

Aber: Materialforschung in Grossforschungsanlagen mit Röntgenstrahlen oder Neutronen haben einen grossen Beitrag zur Entwicklung heutiger Technologien beigetragen.

Herzlichen Dank für Ihre Aufmerksamkeit!