X-ray Free Electron Lasers
&
ultrafast x-ray science

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Muggia, Italy, 21 September – 1 October 2026

Outline

Break @ 17h10-17h20

- What is an X-ray Free Electron Laser and how does it work ?
- Ultrafast science and ultrafast experiments
- X-ray Free Electron Lasers around the world
- What are the new science opportunities ? Examples of recent results
- Ongoing developments: Where are we heading to ? What new science ?
- Outlook

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Different types of lightsources

Storage rings (SR)

- High perf. x-ray source
- Very stable; highly efficient
- Many user installations for large variety of applications

→ X-ray scattering, microscopy, spectroscopy

X-ray FEL radiation

- Peak brightness x-ray source
- Single-pass; few sources
- So far only few user installations; applications u. study

→ X-ray ultrafast methods using scattering, microscopy, spectroscopy; non-linear methods

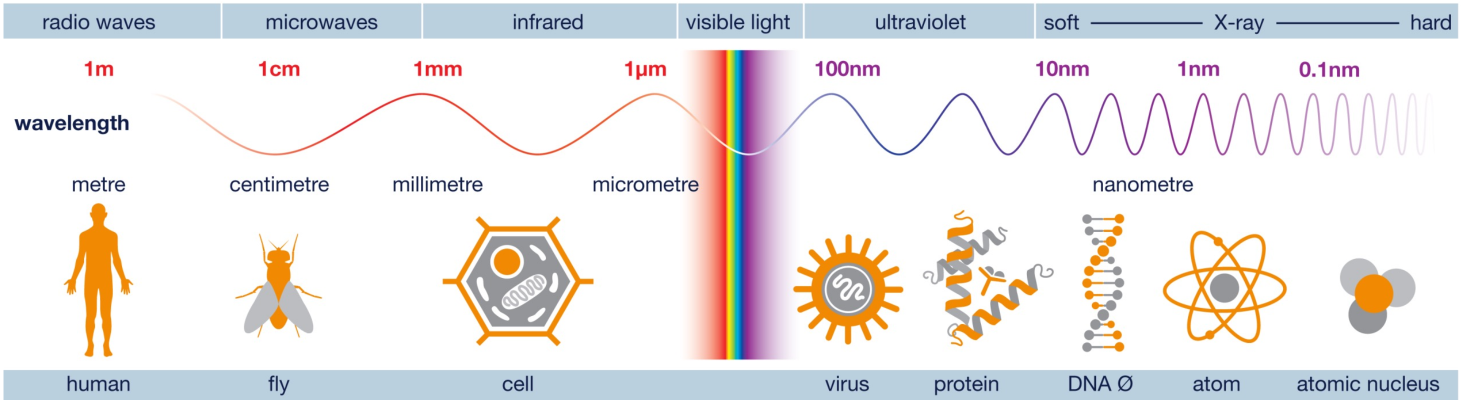
Visible Laser radiation

- Commercial or home-built systems widely distributed, large facilities
- Huge community
- Attosecond & non-linear techn.

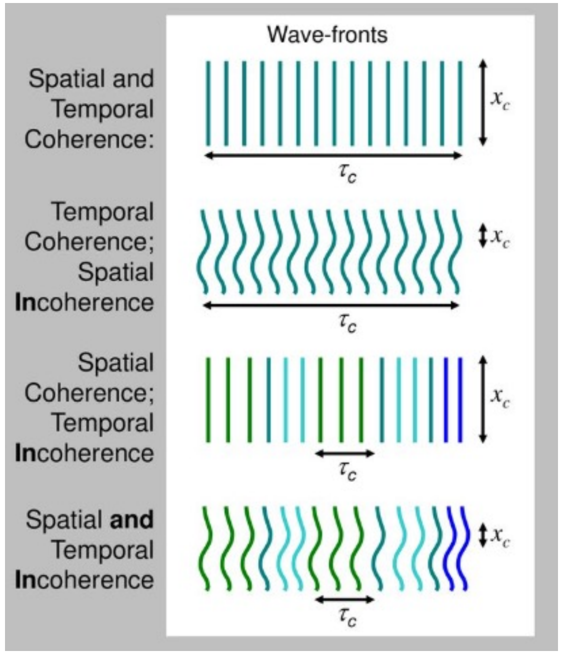
→ Light ultrafast and non-linear methods using microscopy or spectroscopy

XFEL radiation is very different from Laser radiation …

Wavelength
- orders of magnitude smaller

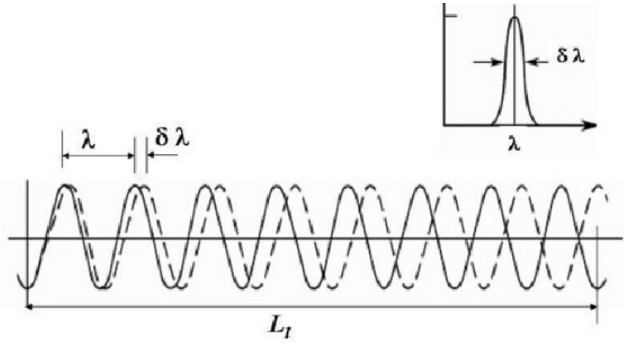


Coherence
- spatial coherence: similar
- temporal coherence: much lower

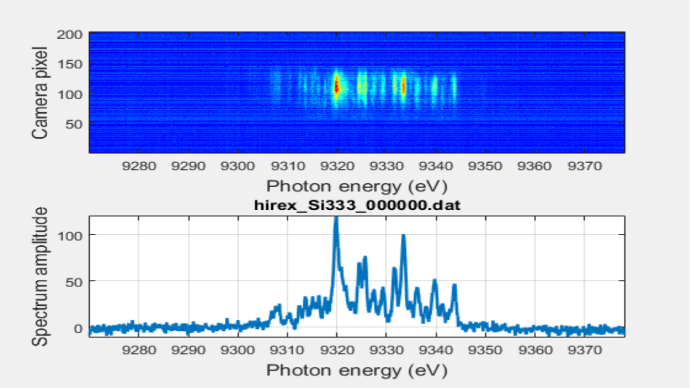


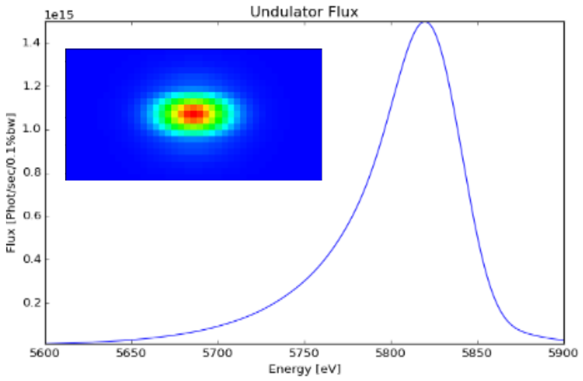
LASER

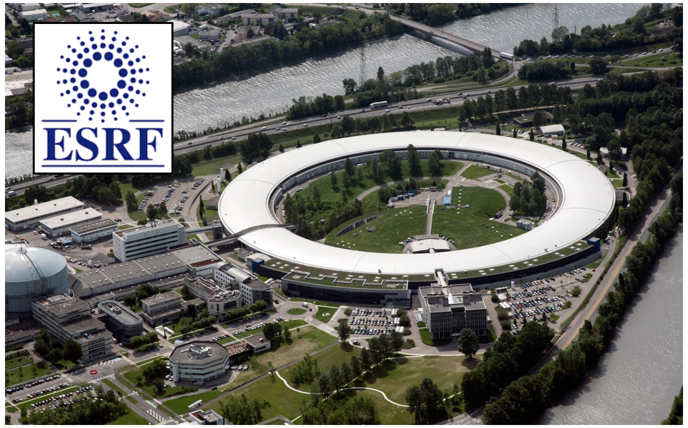
XFEL

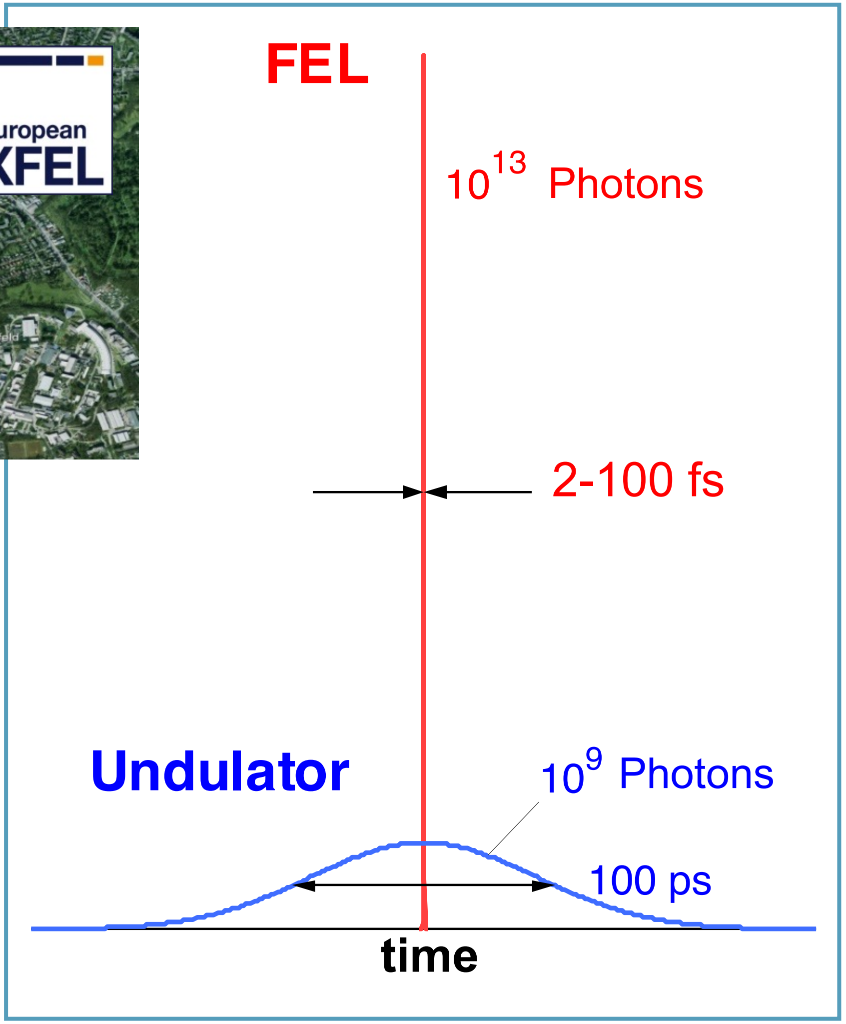


XFEL radiation is very different from Synchrotron radiation …

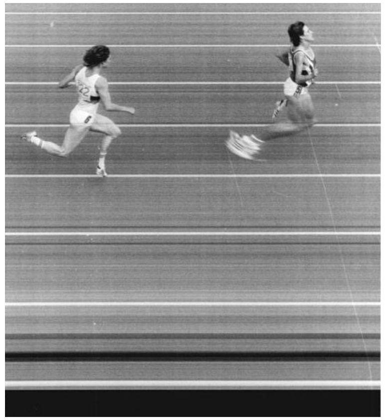


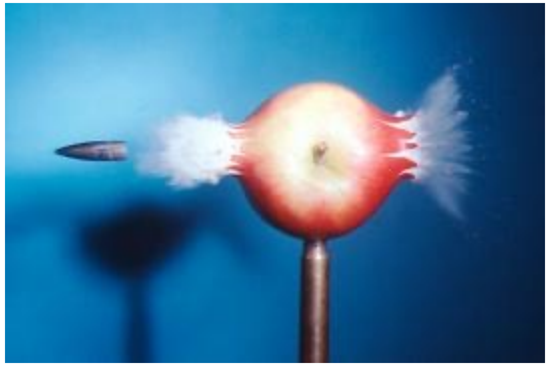




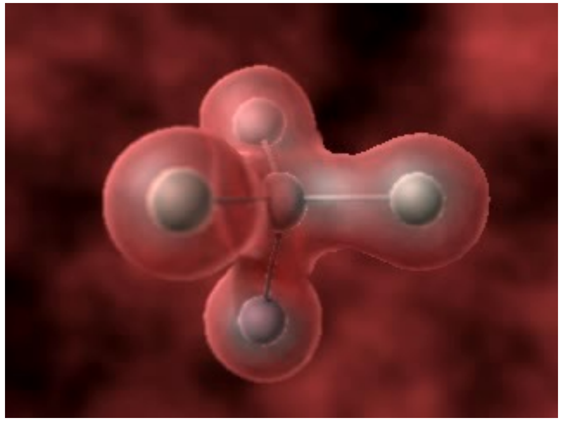


XFELs can take snapshots of atomic movements ...





© MIT Museum



Speed of subject	10 m/s	1000 m/s	1000 m/s (rattling speed of atoms)
Picture resolution	10 mm	1 mm	1/10 000 000 mm
Time resolution	1/1000 s	1/1 000 000 s	1/10 000 000 000 000 s (or 100 femtoseconds)

- fs pulse: a probe of atomic motion (100fs) …. and charge migration (fs)
- hard X-rays: atomic resolution, chemical selectivity, bulk sensitivity

Acoustic vibration

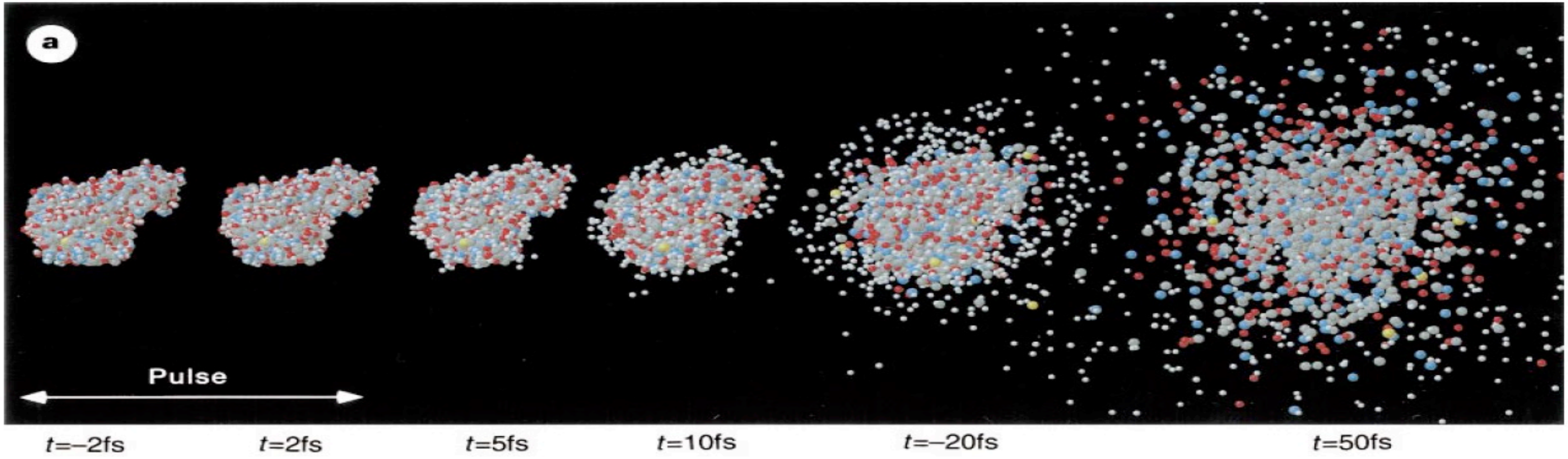
Speed of sound: $v = 3000\, m/s\ ,\ a = 3\text{Å} \quad \Rightarrow \delta t \leq 10^{-13}\, s = 100\, fs$

- Can we measure phonon dynamics in the time domain ?
- Can we see how charge migrates from one atom to another ?

Diffract before destruction: a totally new approach to structural determination with X-rays

Free Electron Lasers : The exploding protein

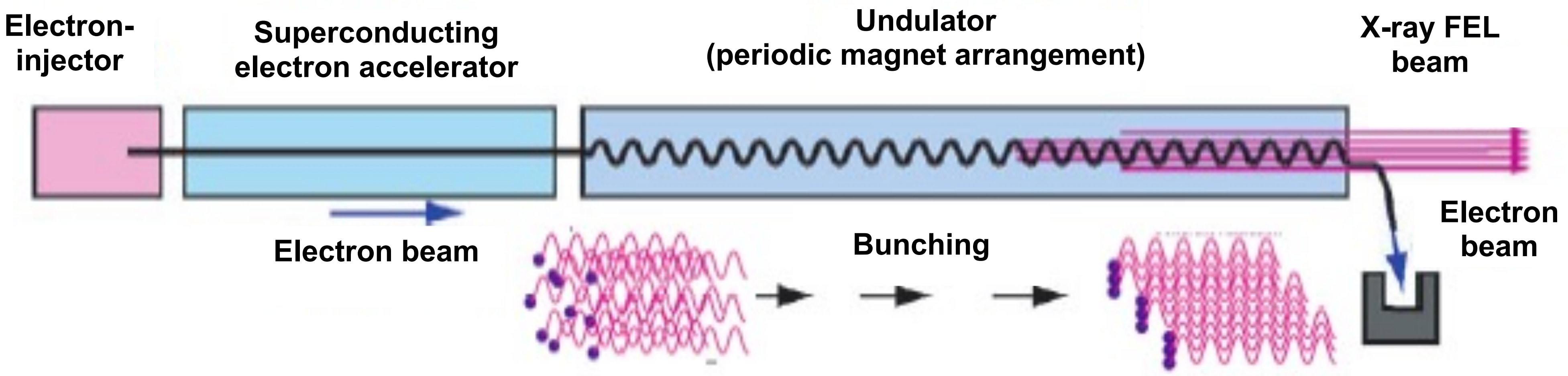
R. Neutze et al, Nature 406, 752 (2000)

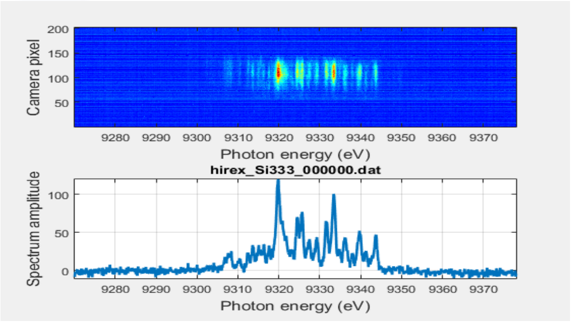


- Can we beat radiation damage ?
- Can we measure at room temperature ?
- Can we make movies of proteins at work ?

X-ray Free-Electron Laser: SASE radiation

Self-Amplified Spontaneous Emission (SASE)





Each e- in the bunch emits spontaneously and incoherently (($P \sim N_{el}$)

Electrons interact with EM field → micro-bunching → coherent emission ($P \sim N_{el}^2$)

- Properties of SASE X-ray FEL radiation
  - **Ultrashort duration (fs – 200 fs)**
  - **Very high pulse energies (0.1 – 1 mJ); 10^{12} (10^{13}) photons at 0.1 (1) nm**
  - **Almost full spatial coherence (<10 keV); Limited temporal coherence**
  - **Single pass generation / fluctuations**

FEL concept : J.M.J. Madey, J. Appl. Phys. 42, 1906(1971)
SASE FEL radiation: High Gain Single Pass regime: A.M. Kondratenko, E.L. Saldin, Part. Accel. 10, 207 (1980);
Collective instability and self-organization: R. Bonifacio, C. Pellegrini, L.M. Narducci, Opt. Comm. 50, 373 (1984)

Differences with respect to undulator/synchrotron radiation

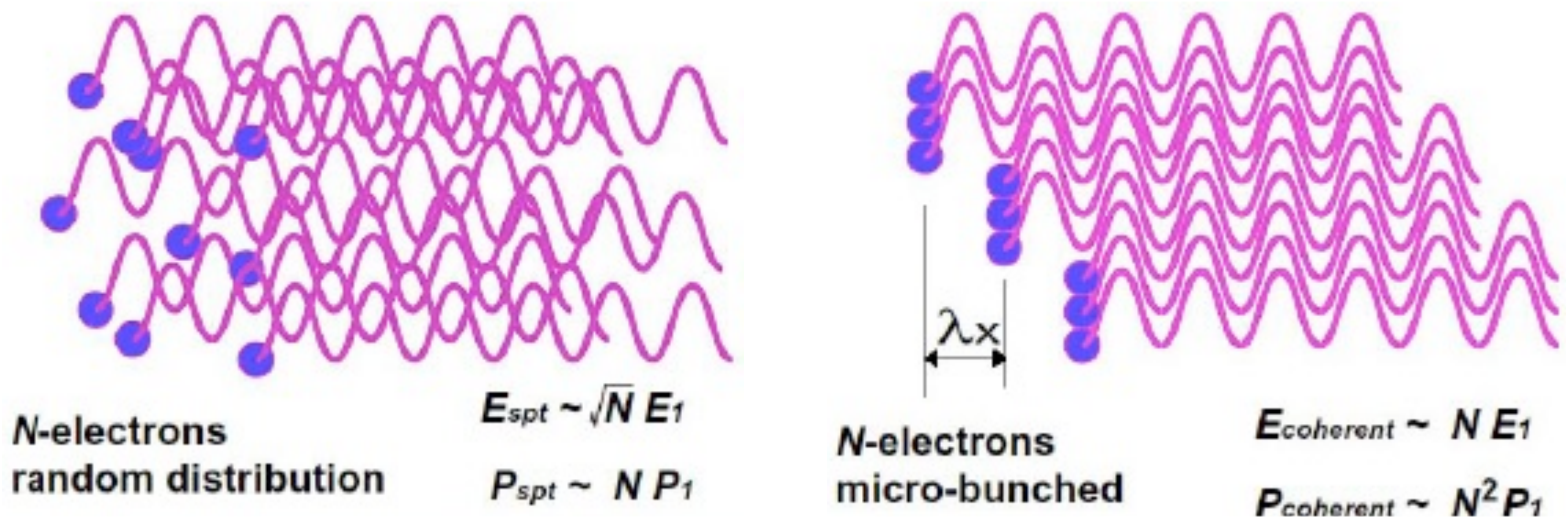
- Resonance condition is equal

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad K = 0.934\lambda_u B_0$$

- Much tighter electron phase space parameters
  - **Extremely small emittance**
  - **Bunch compression**

Parameter	SR	FEL	factor
Transverse emittance	1 nm (x) (→ 0.1(x,y))	0.015 nm (x,y)	40 (7)
Longitudinal e^- density	10 nC / 30 mm	1 nC / 30 μm	100

- Coherent emission process



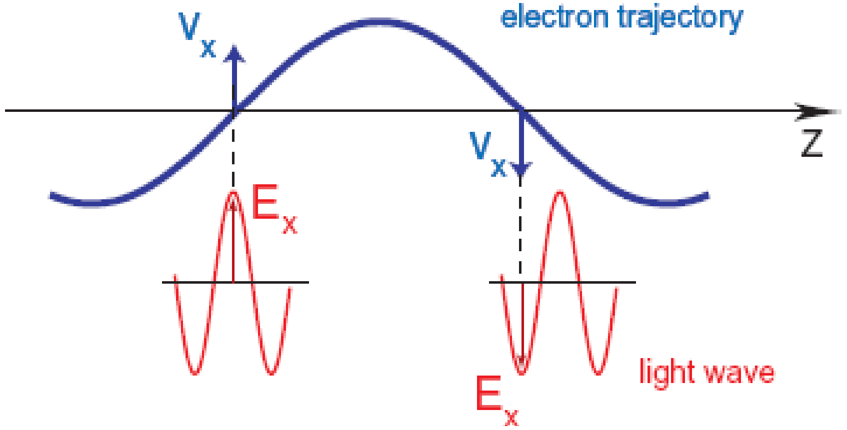
Bunching the electrons

- By electro-magnetic forces arising from interaction with the co-propagating radiation field
  - **Energy change due to x-ray field:**

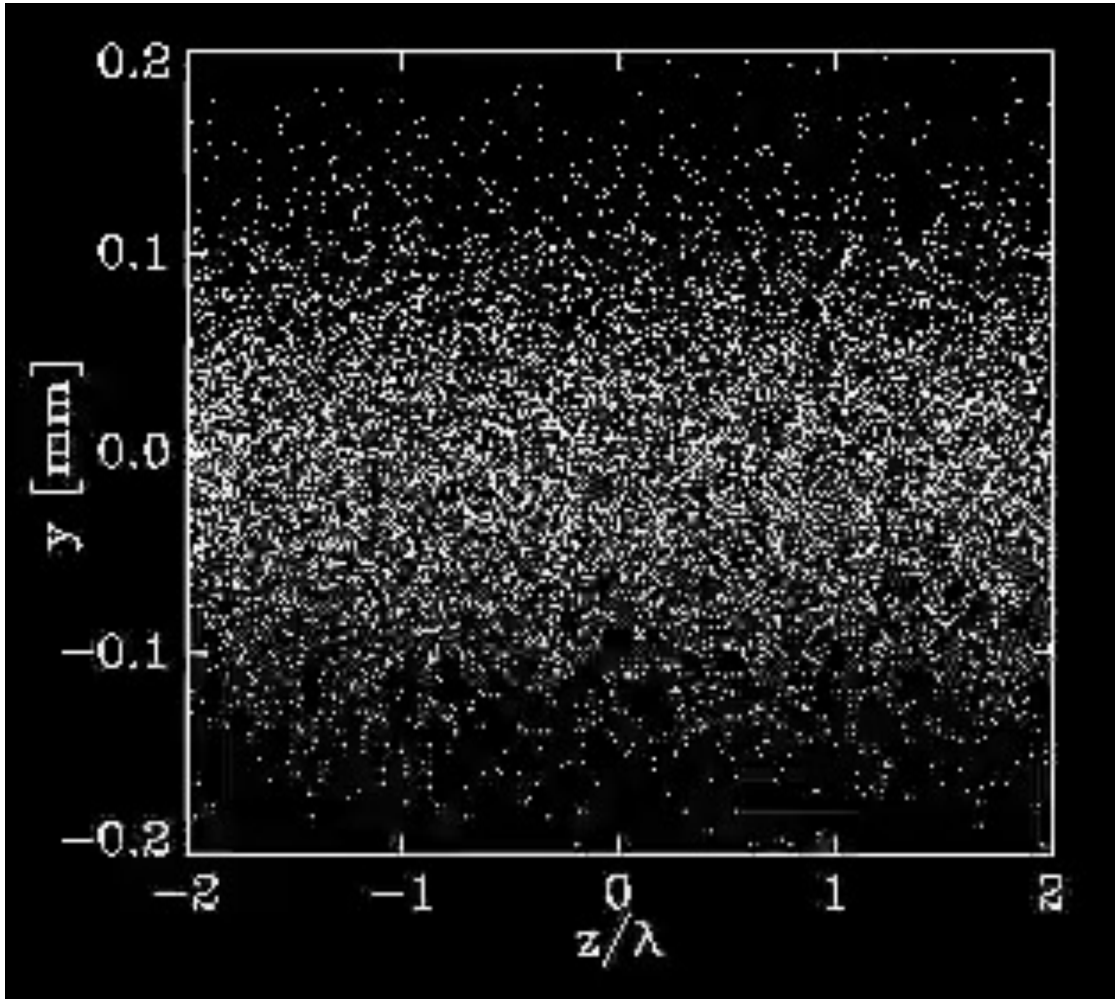
$$dE = -e\, v_x(t) \times E_x(t)\, dt$$

  - **SASE resonance condition:**

Keep phase between $v_x(t)$ and $E_x(t)$ const.



GENESIS -
simulation for TTF parameters
Courtesy - Sven Reiche (DESY, now PSI)



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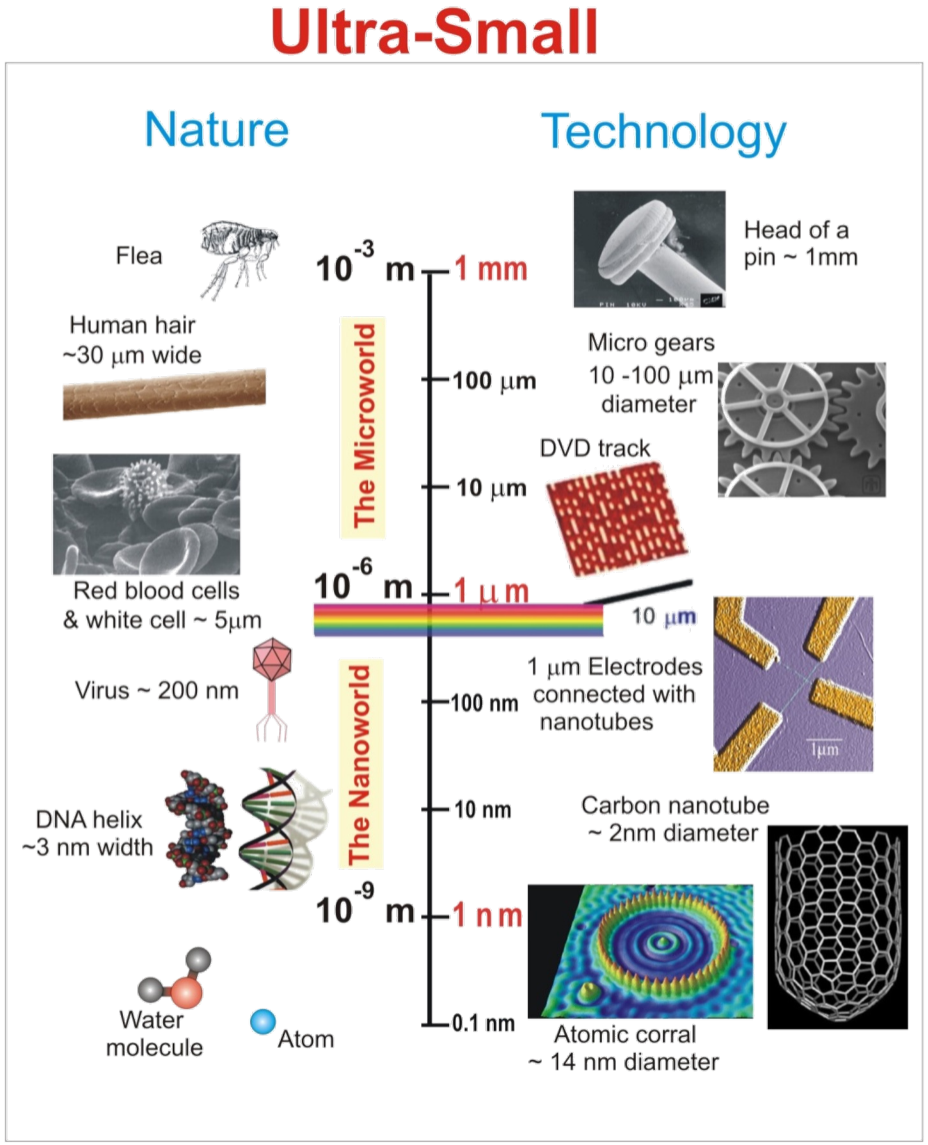
Ultrafast x-ray science

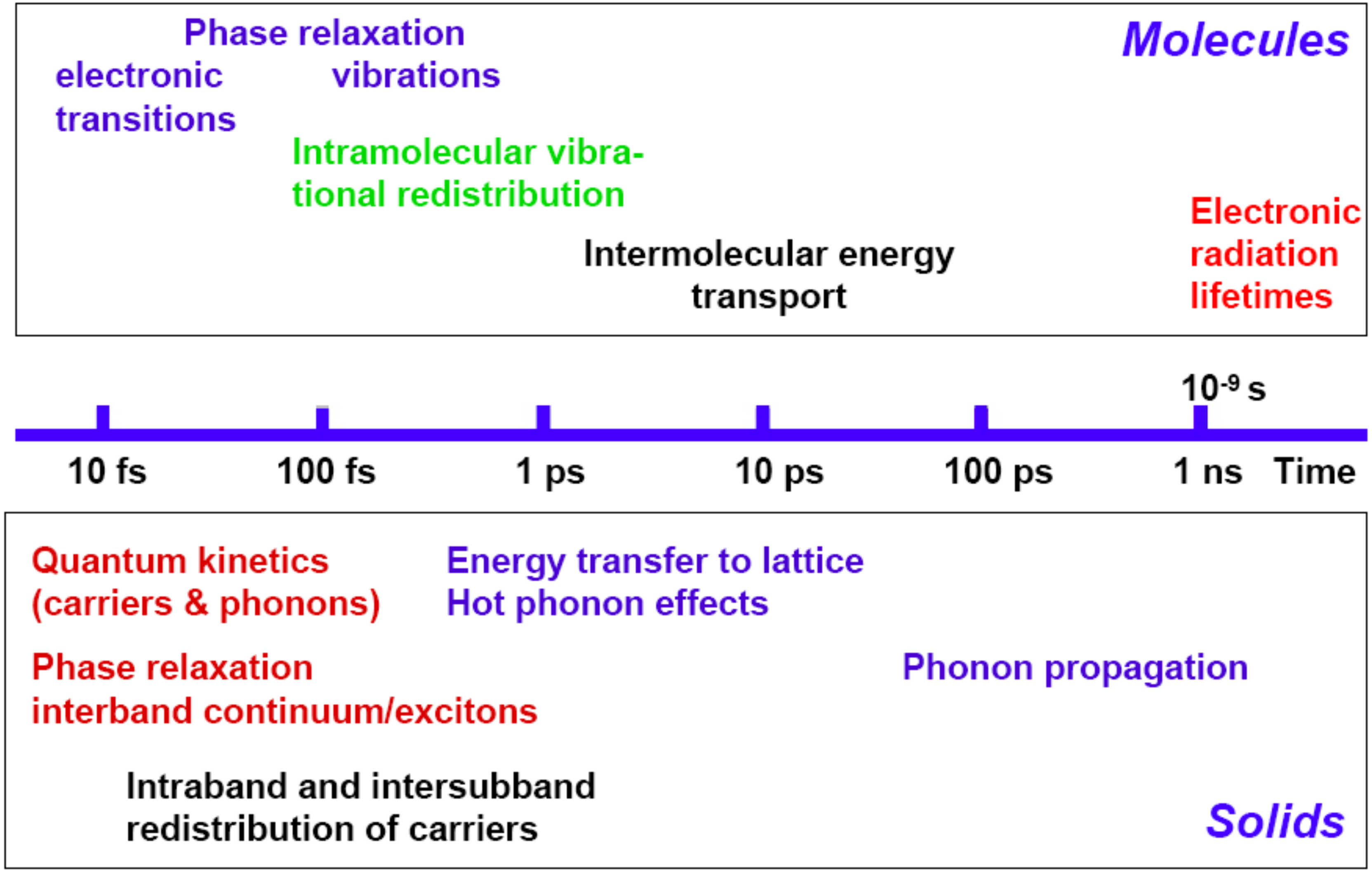
- Connection of length and time scales



Courtesy: SLAC

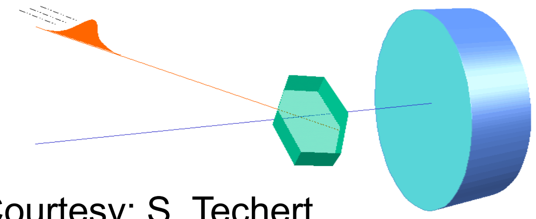
Investigations of structural dynamics

- Atoms, molecules, clusters
- Solids, materials
- Complex matter
- Extreme states



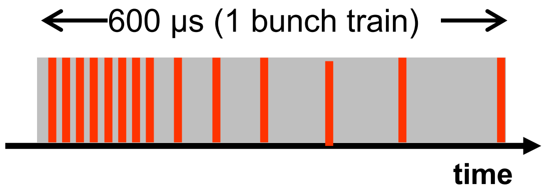
Performing ultrafast x-ray experiments using FELs

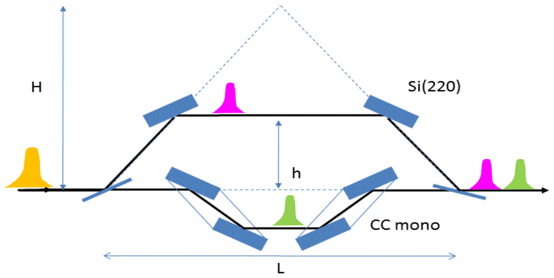
- Usually performed in pump-probe mode
  - **Lack of ultrafast detection schemes**
- Resolution elements
  - **Exciting pump pulse: Optical laser, x-ray, others**
  - **Probe pulse: typ. x-ray**
  - **Precision of time-difference (jitter)**
- Synchronization of different light sources
- Application range down to ~ 50 fs → 10 fs → 1 fs

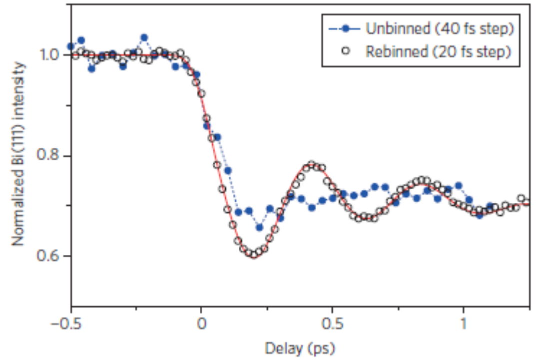


Courtesy: S. Techert

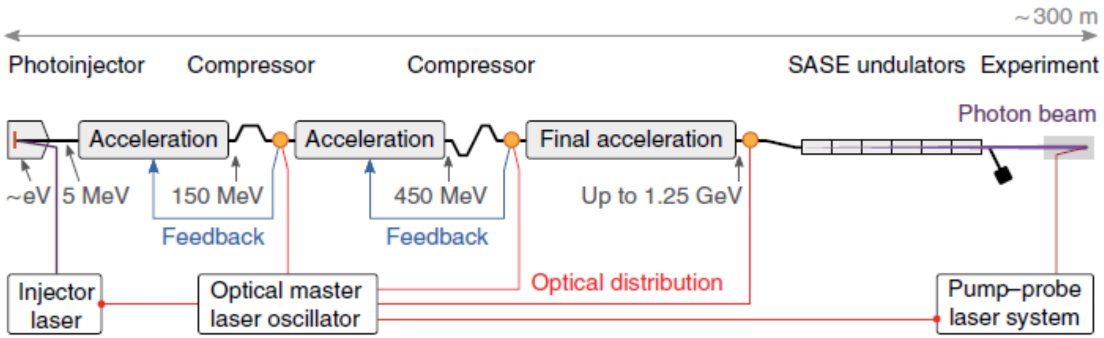
European XFEL pulse train





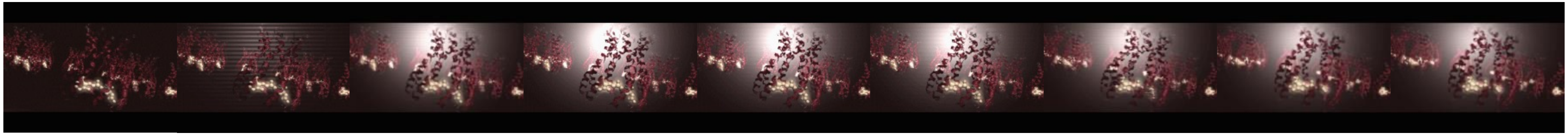


M. Harmand et al., Nature Phot. 7, 215 (2013)

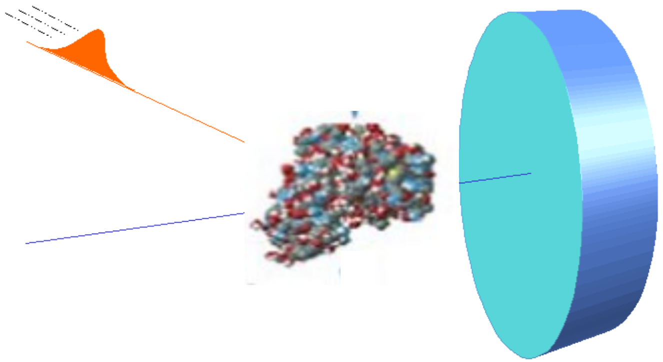


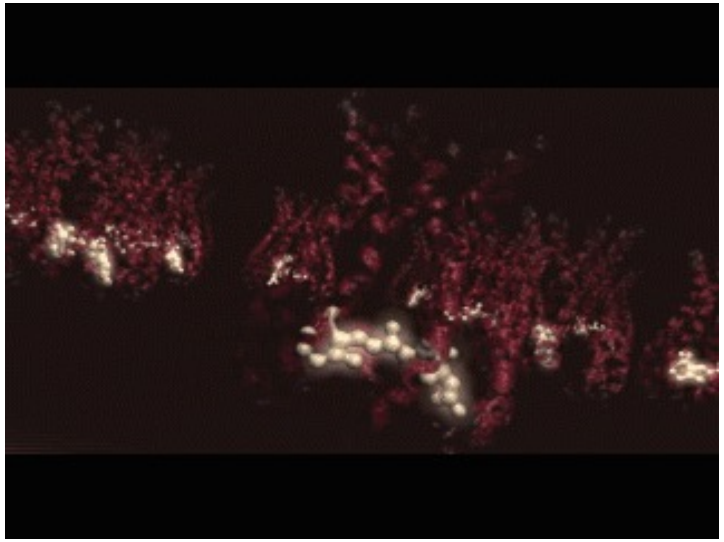
S. Schulz et al., Nat. Comm. 6, 5938 (2015)

Example: Real time molecular dynamics in native state & transient structures of proteins



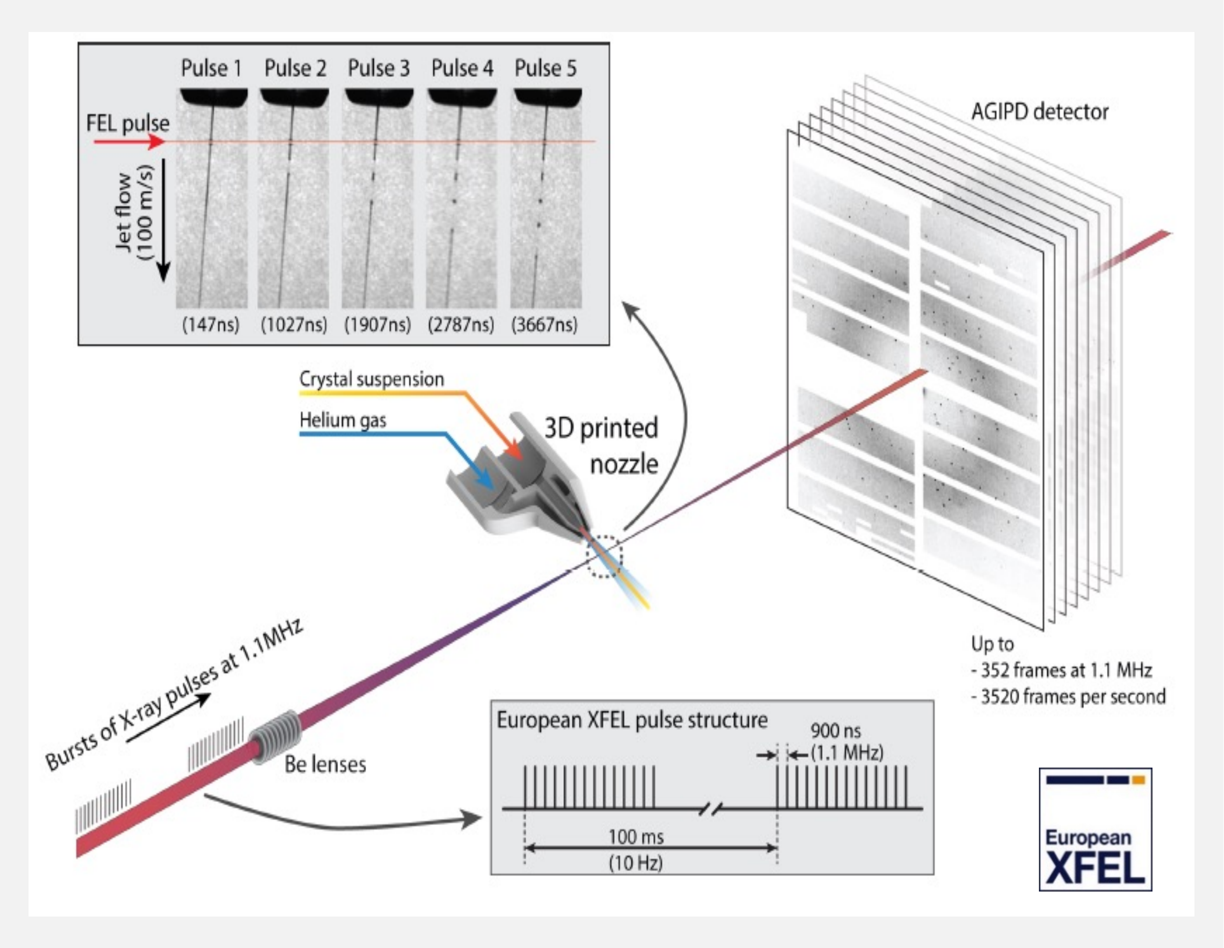
- Making molecular movies



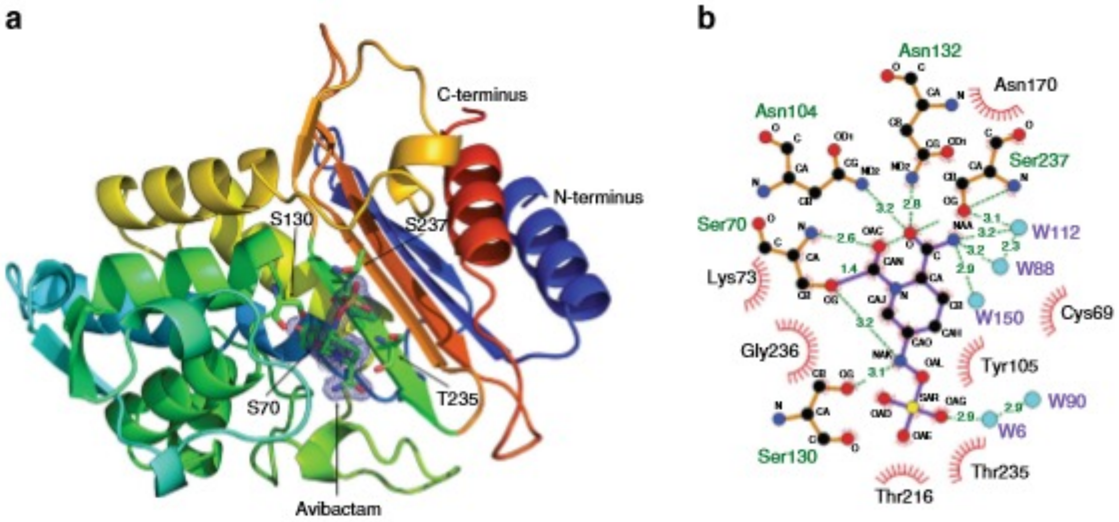


Ad-hoc sample delivery methods have been developed

- MHz Serial Femtosecond Crystallography (SFX)



- High resolution structure determination from very small, "radiation sensitive" or "dynamic" crystals



~ 10^5 good patterns per structure

M.O. Wiedorn, Nature Comm 9, 4025 (2018)

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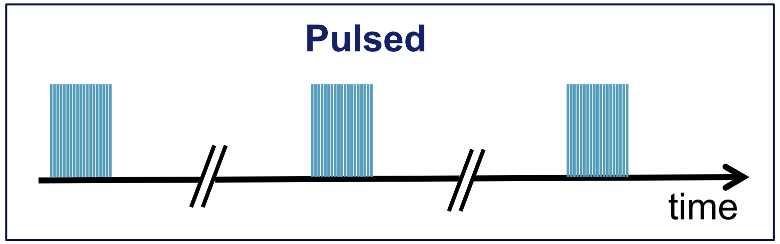
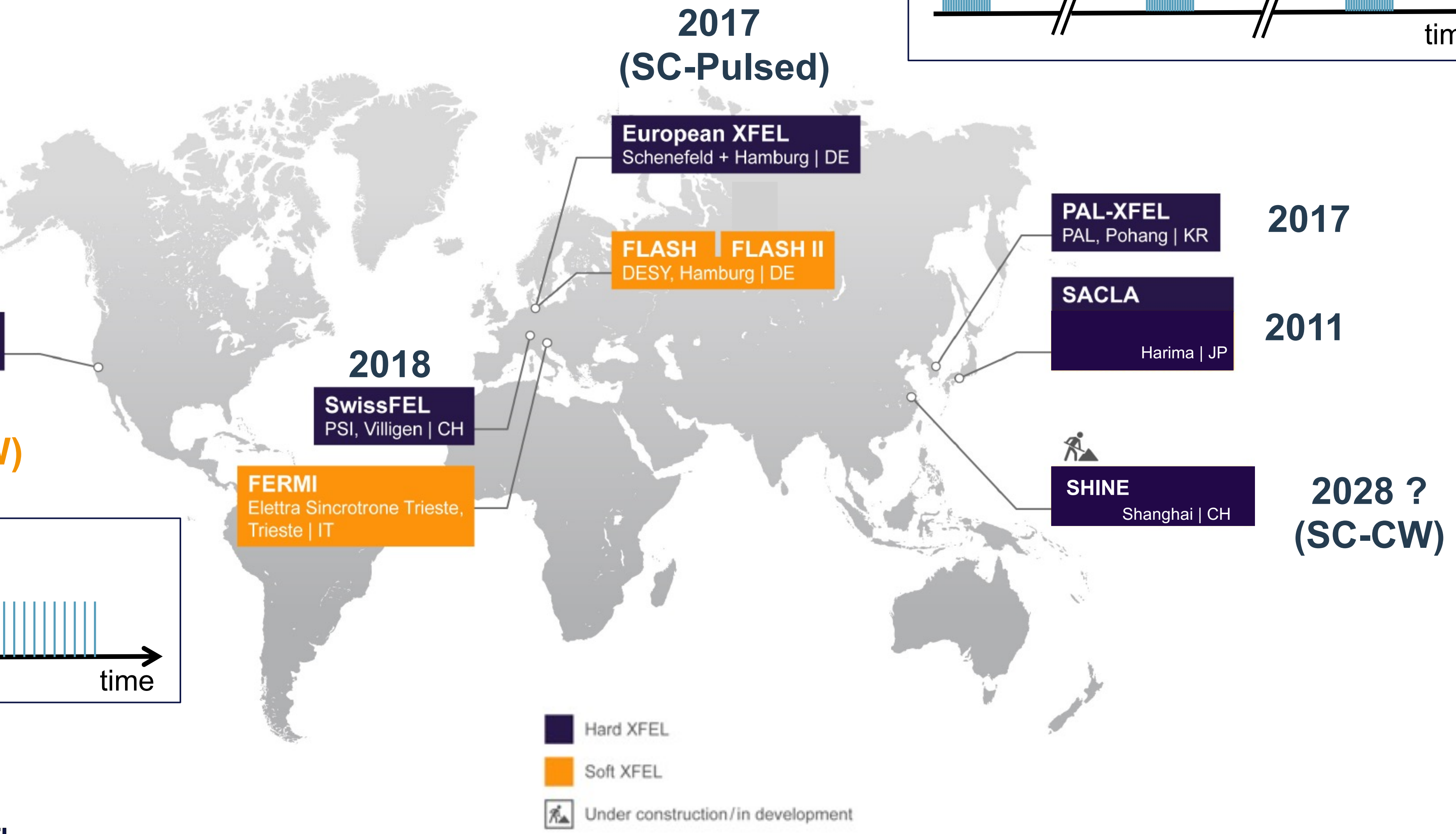
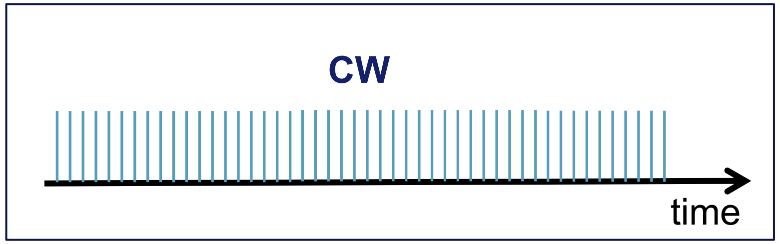
X-ray free-electron lasers worldwide







Some specifics about FEL facilities

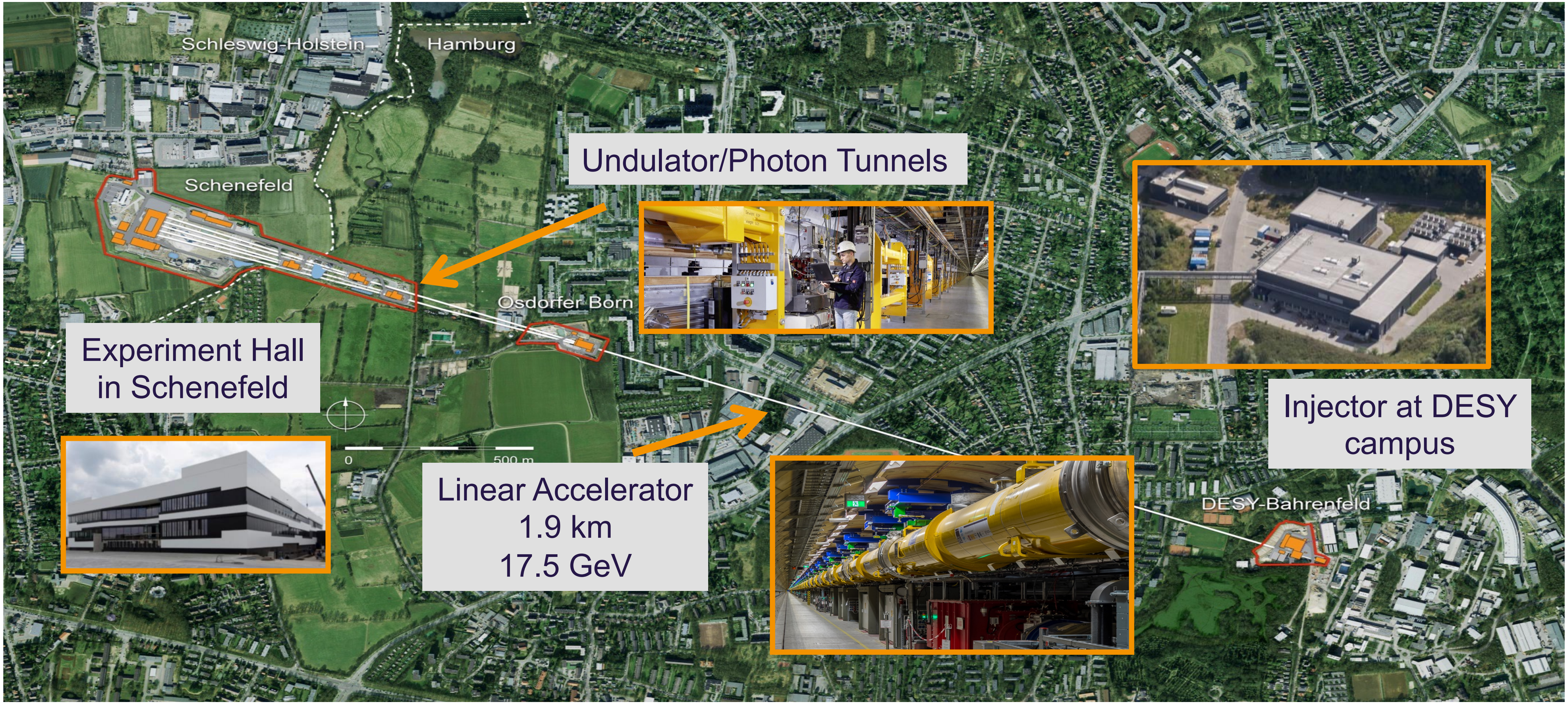
- FLASH – first user facility (2005) for XUV and soft x-ray FEL radiation
- FERMI – first user facility to successfully employ laser seeding (XUV to soft x-rays)
- LCLS – first user facility (2009) for hard x-ray FEL radiation and later self-seeding
- SACLA, PAL, SwissFEL – compact hard x-ray FELs
- European XFEL – First international user facility (2017) for soft and hard x-ray FEL radiation

- LCLS-II(-HE), SHINE – first CW-type soft and hard x-ray FELs

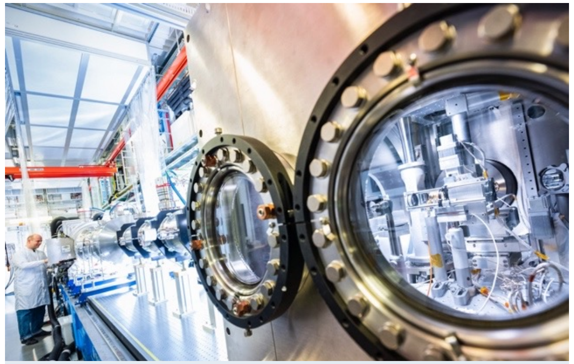
About the European XFEL

- International user facility for FEL research
  - **Providing soft & hard X-ray FEL radiation**
  - **Photon energy 300 eV to ≥ 20 keV**
  - **High pulse energies**
  - **MHz repetition rates**
- Multi-disciplinary science community
  - **Physics**
  - **Chemistry**
  - **Biology**
  - **Geosciences**
  - **Materials**
- Status
  - **Construction 2009-2017**
  - **First experiments 2017**
  - **6 instruments operating since 2019 (+ 1 in 2023)**

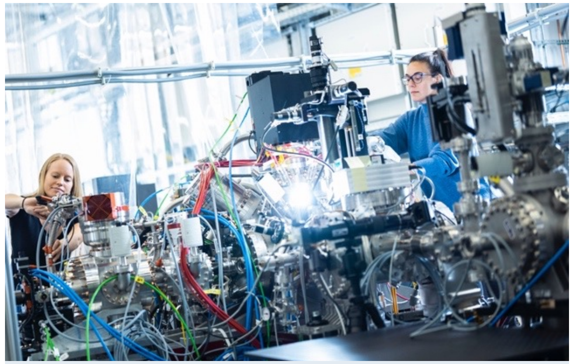
Layout of the European XFEL

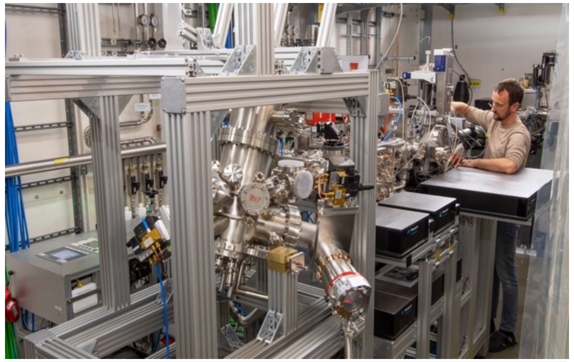


Seven scientific instruments

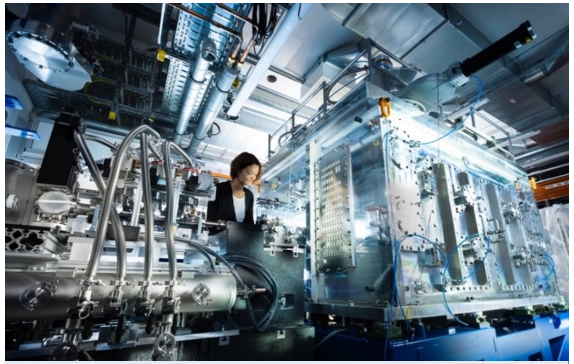

SPB/SFX (start Sep 2017)


MID (start Apr 2019)


SQS (start Nov 2018)


SXP (start summer 2023)


FXE (start Sep 2017)


HED (start May 2019)


SCS (start Nov 2018)

Scientific instruments

SASE1

FXE (Femtosecond X-ray Experiments)

- Ultrafast dynamics of liquids and solid matter
- Combination of spec. & scat. techniques

SPB/SFX (Single Part., Bioimaging, & SFX)

- Coherent diffraction imaging from single part.
- Serial fs nano-crystallography

SASE2

MID (Materials Imaging & Dynamics)

- CDI from nano-structured samples
- XPCS of nanoscale dynamics

HED (High Energy Density science)

- Ultrafast dynamics of highly excited matter
- Combinations of scattering, diff. & spectroscopy

SASE3

SQS (Small Quantum Systems)

- Ultrafast dynamics of atoms, ions & clusters
- Combination of spec. & coh. scat. techniques

SCS (Spectroscopy & Coherent Scattering)

- Ultrafast dynamics of complex solids
- Combination of hr-inelastic spec. & coh.scattering

SXP (Soft X-ray Port)

- Time-resolved X-ray photoelectron spectroscopy

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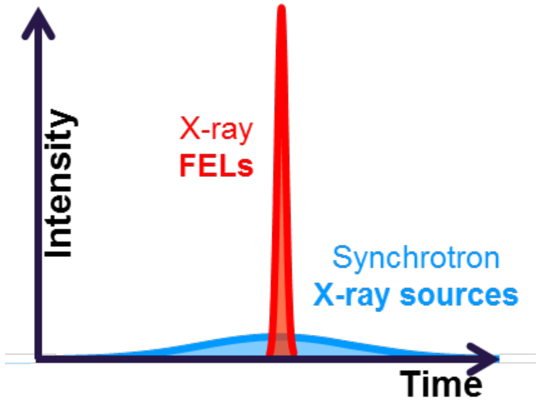
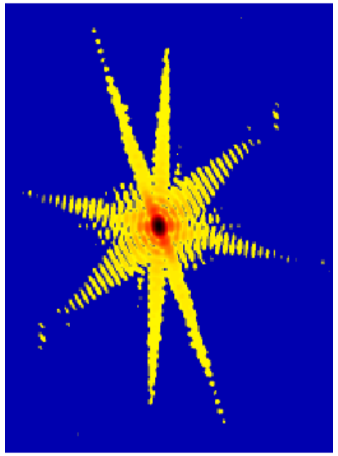
New opportunities offered by X-ray FELs





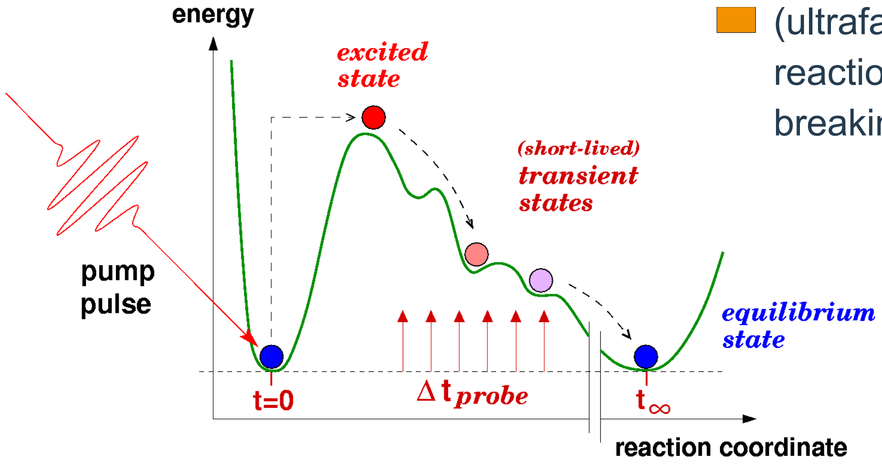
Ultrashort pulses
1 – 100 fs

Coherence
Almost full transverse
Partially temporal

Intensity/power
up to few mJ
up to >10^{20} W/cm^2

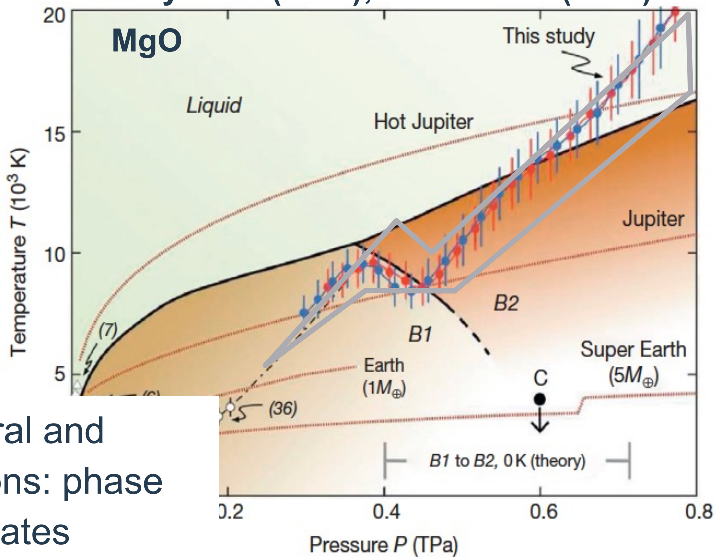
- Structural dynamics
  - **Measurement of atomic and electron dynamics with high spatial [0.1 nm] and temporal [10 fs] res.**
  - **physics, materials sciences, chemistry, life science**
- Imaging at the nanoscale
  - **Imaging experiments on confined and extended objects with atomic to mesoscale resolution [0.1–1000 nm]**
  - **physics, materials sciences, chemistry, life science**
- Non-linear x-ray science
  - **Start using non-linear techniques to obtain hidden information (off-diagonal elements in reaction matrices)**
  - **physics, chemistry**

Open science problems

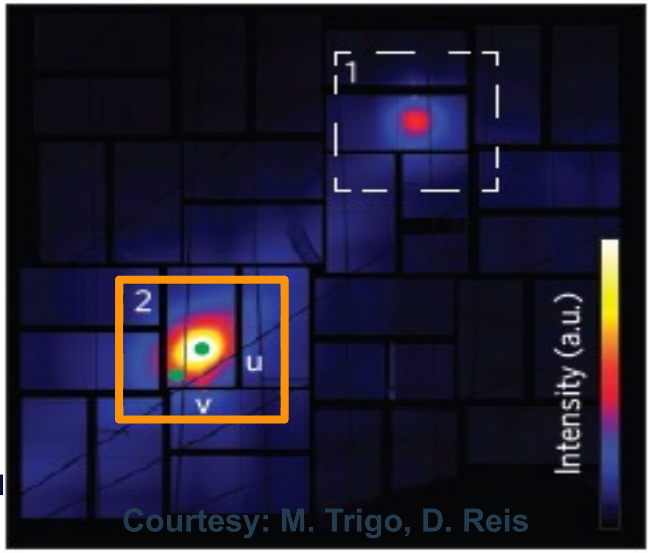


- (ultrafast) (bio-)chemical processes: reactions, phase transitions, bond breaking & forming

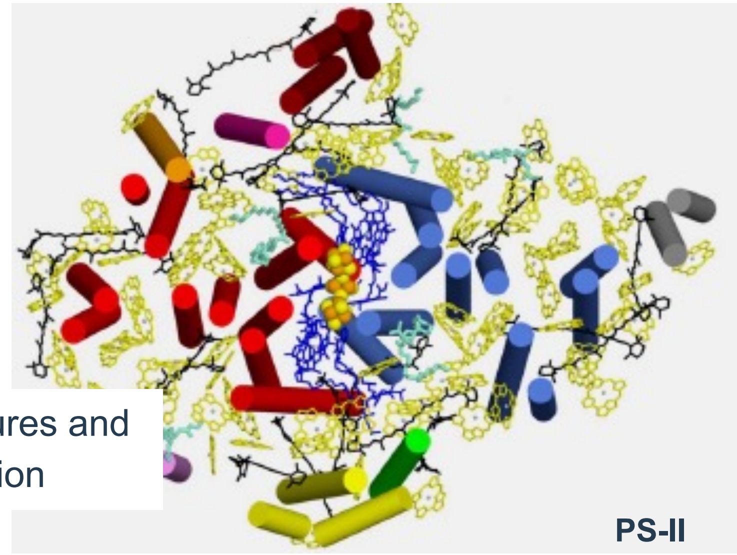
Duffy et al. (2015); Bollis et al. (2016)



- (ultrafast) structural and electronic transitions: phase transitions, new states



- Systems ‚in function‘: excited states, non-reversible processes



- complex (bio-)structures and their temporal evolution

Research at the European XFEL

Digitalization

Structural dynamics of functional and quantum materials

- Magnetism at nm/fs scales
- Promotion of AI/data technologies

Climate & Energy

Structural dynamics of new materials, processes, and molecular reactions

- Photocatalysis
- Microphysics of Fusion

Environment & Sustainability

Properties of durable materials, sustainable agriculture, and planetary processes

- Structure of natural insecticides
- Hard materials under load

Health

Structural dynamics and reaction pathways of biomolecules, viruses, and cells

- Structure & dynamics of biomolecules
- New therapies and diagnostics

Research at the European XFEL

Climate & Energy

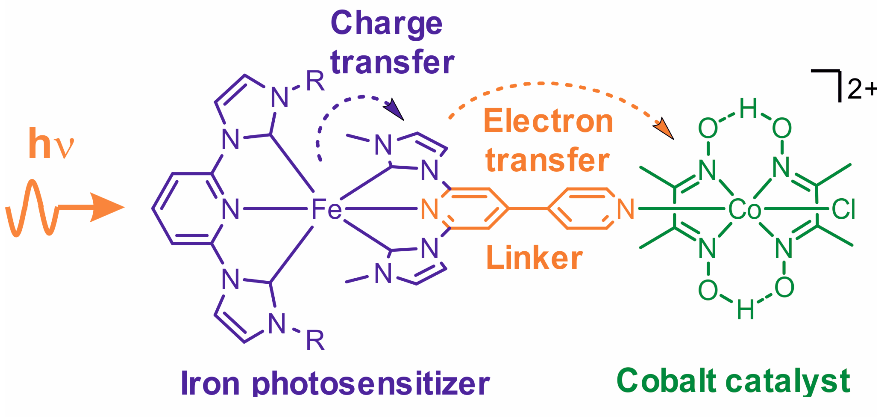
Structural dynamics of new materials, processes, and molecular reactions

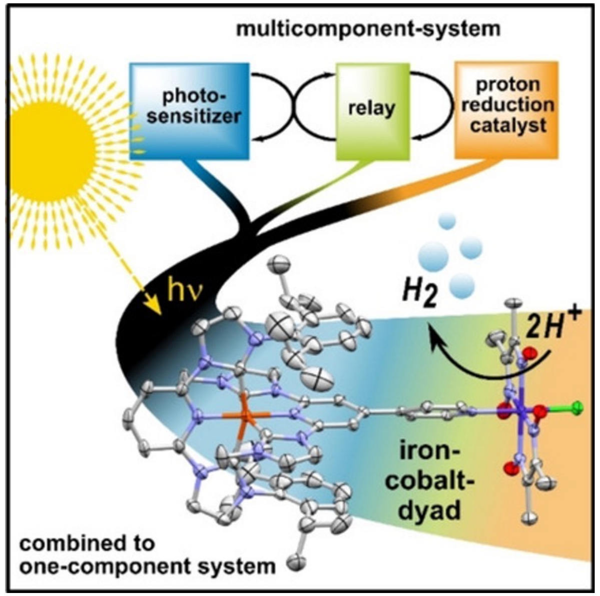
- Photocatalysis
- Microphysics of Fusion

Excited State Landscape in a Base Metal Dyad

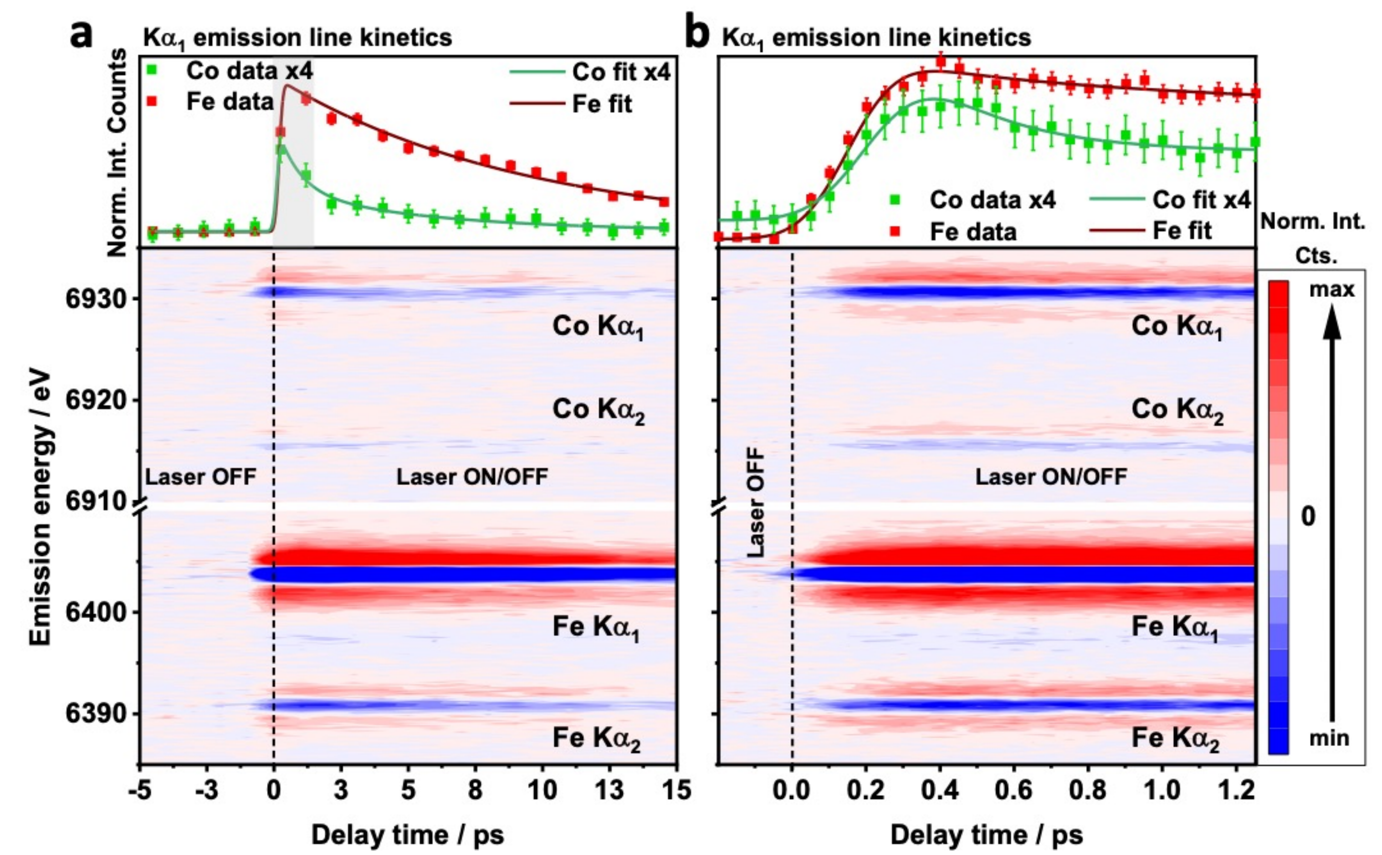
Universität Paderborn
UAM Universidad Autónoma de Madrid
Adam Mickiewicz University Poznań
FXE

Using light for a sustainable production of molecular hydrogen





Ultrafast Two-Color X-Ray Emission Spectroscopy



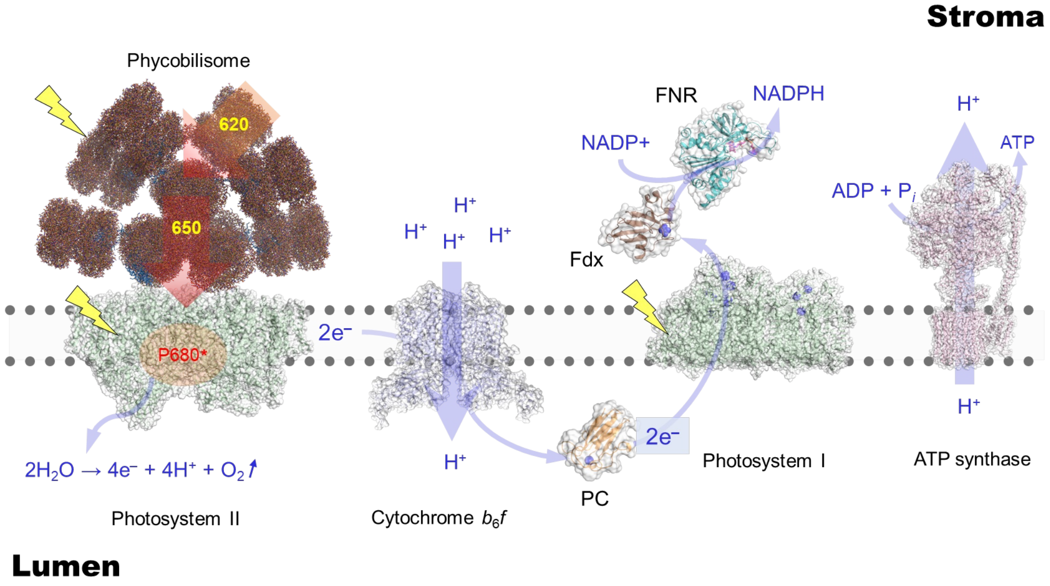
M. Nowakowski… & M. Bauer, Adv. Sci. 11, 2404348 (2024)

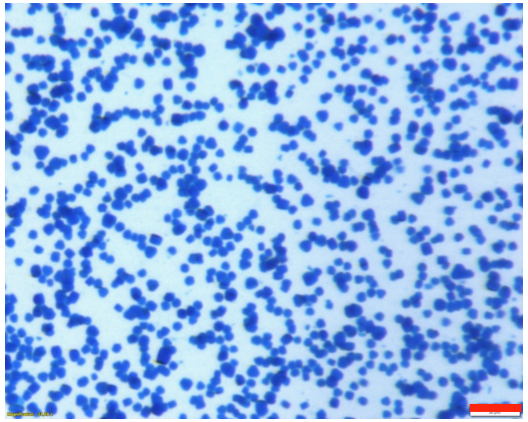
SPB/SFX

Energy transfer mechanism in cyanobacteria

Towards more efficient photosynthetic light-harvesting

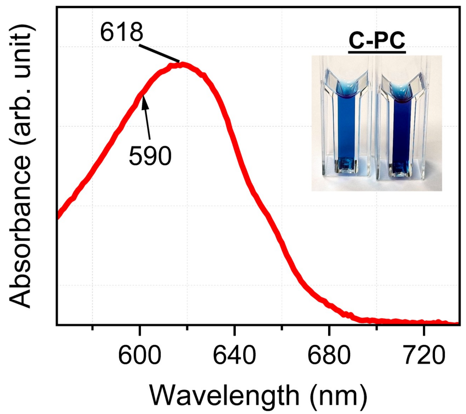
- Specialized bacteria which use photosynthetic energy generation
- Light absorbing-molecules (Phycocyanobilin "PCB") channel high energy photons and convert to lower energy photons suitable for photosystem II
- Funnels energy to photosynthetic reaction center (unidirectional down-hill energy transfer) through 3 chromophores
- Our study investigates the energy transfer mechanism via time resolved SFX of the Phycobilisome complex





Crystals for SFX

Wavelength response



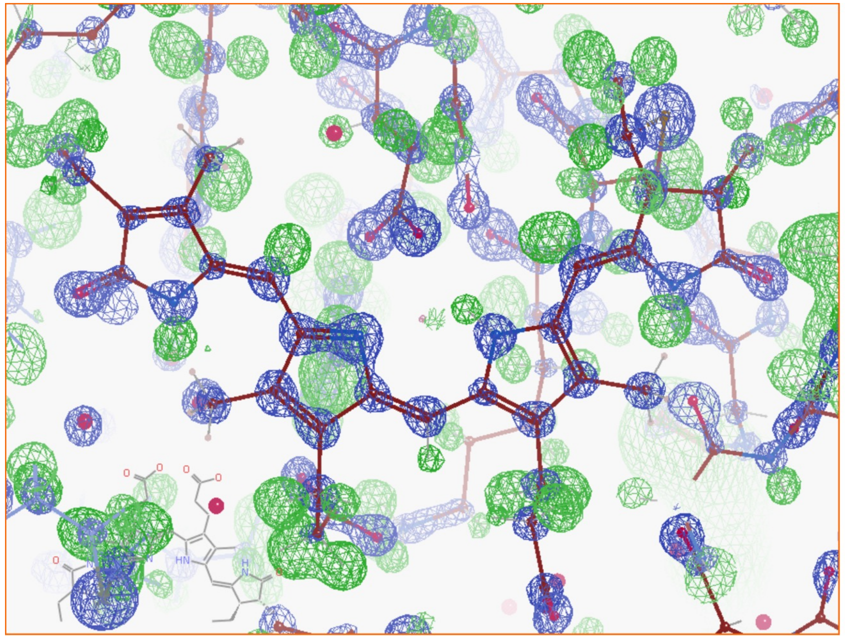
Faisal Koua et al., in preparation

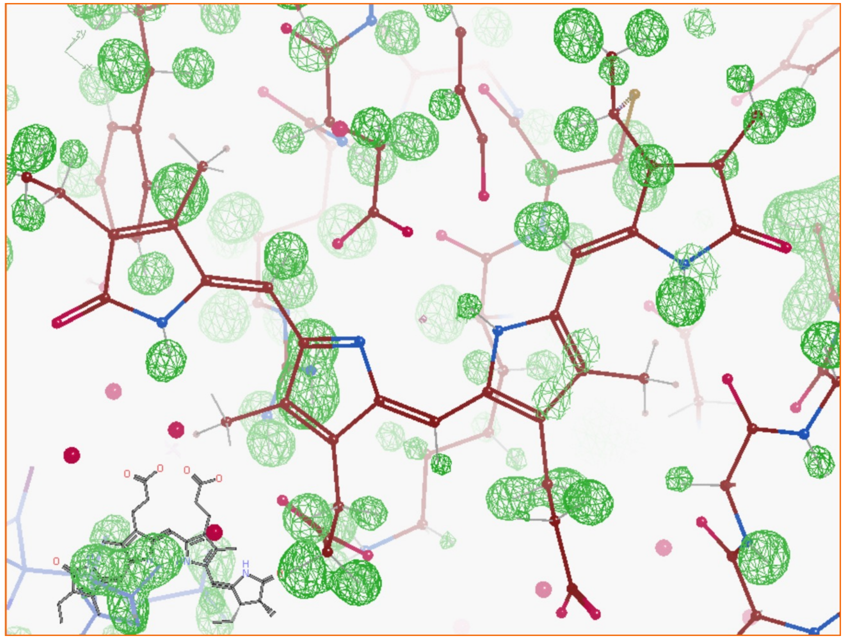
SPB/SFX

Energy transfer mechanism in cyanobacteria

Towards more efficient photosynthetic light-harvesting

- High resolution structures allow accurate attribution of hydrogens (green mesh) in the structural model
- Observed change in chromophore electron densities (pentomer ring structures) and hydrogens over time sheds light on the energy transfer pathway through the harvesting molecule.

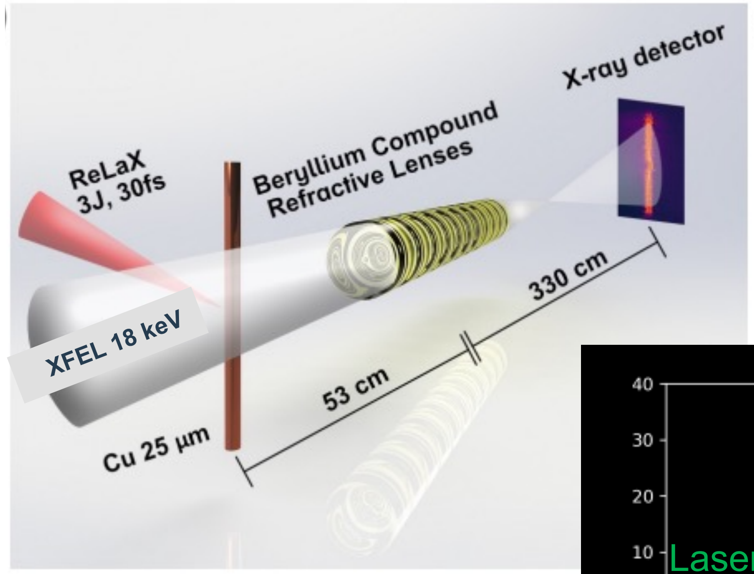


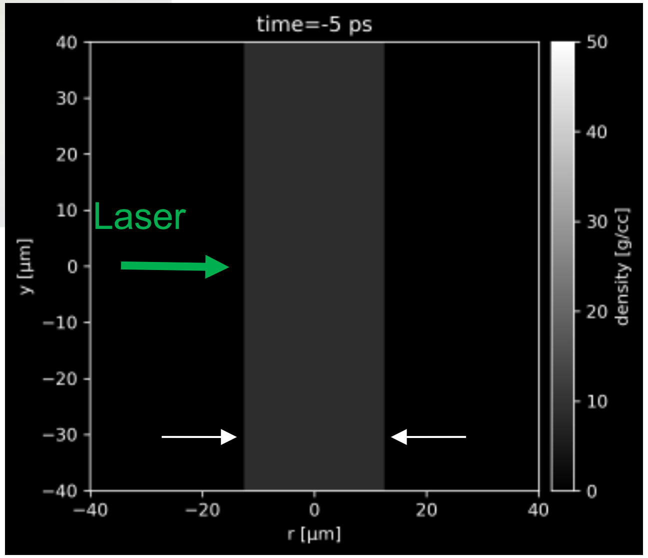


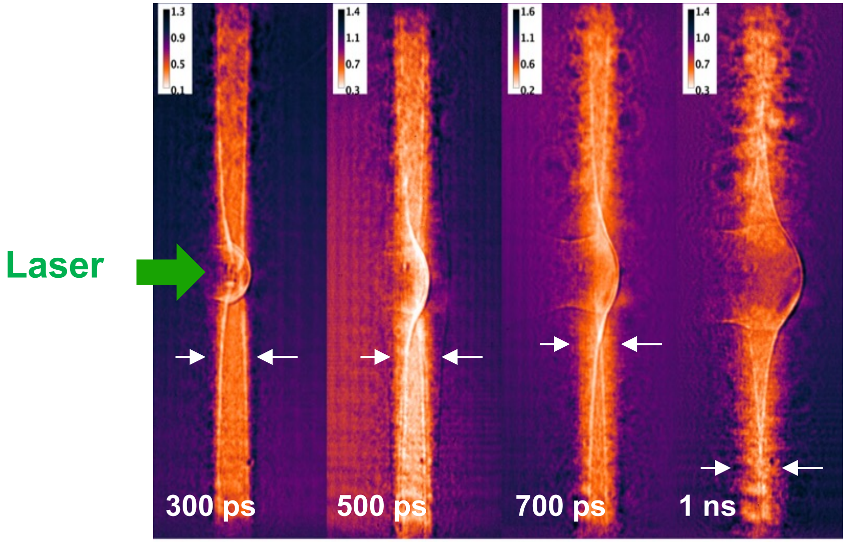
Faisal Koua et al., in preparation

Phase contrast imaging of cylindrical ablation-driven compression

Developing high resolution imaging of dense plasma







HED

- Relativistic laser drives 200 kA surface return current
- Surface heating to ~400 eV → ablative compression
- Cu compressed ~ 10 x ρ_0 ~ 800 Mbar
- New technique to reach stellar conditions with 1000-fold lower laser energy than with direct laser compression

A. Laso Garcia et al., Nature Comm. 15, 7896 (2024)

Research at the European XFEL

Health

Structural dynamics and reaction pathways of biomolecules, viruses, and cells

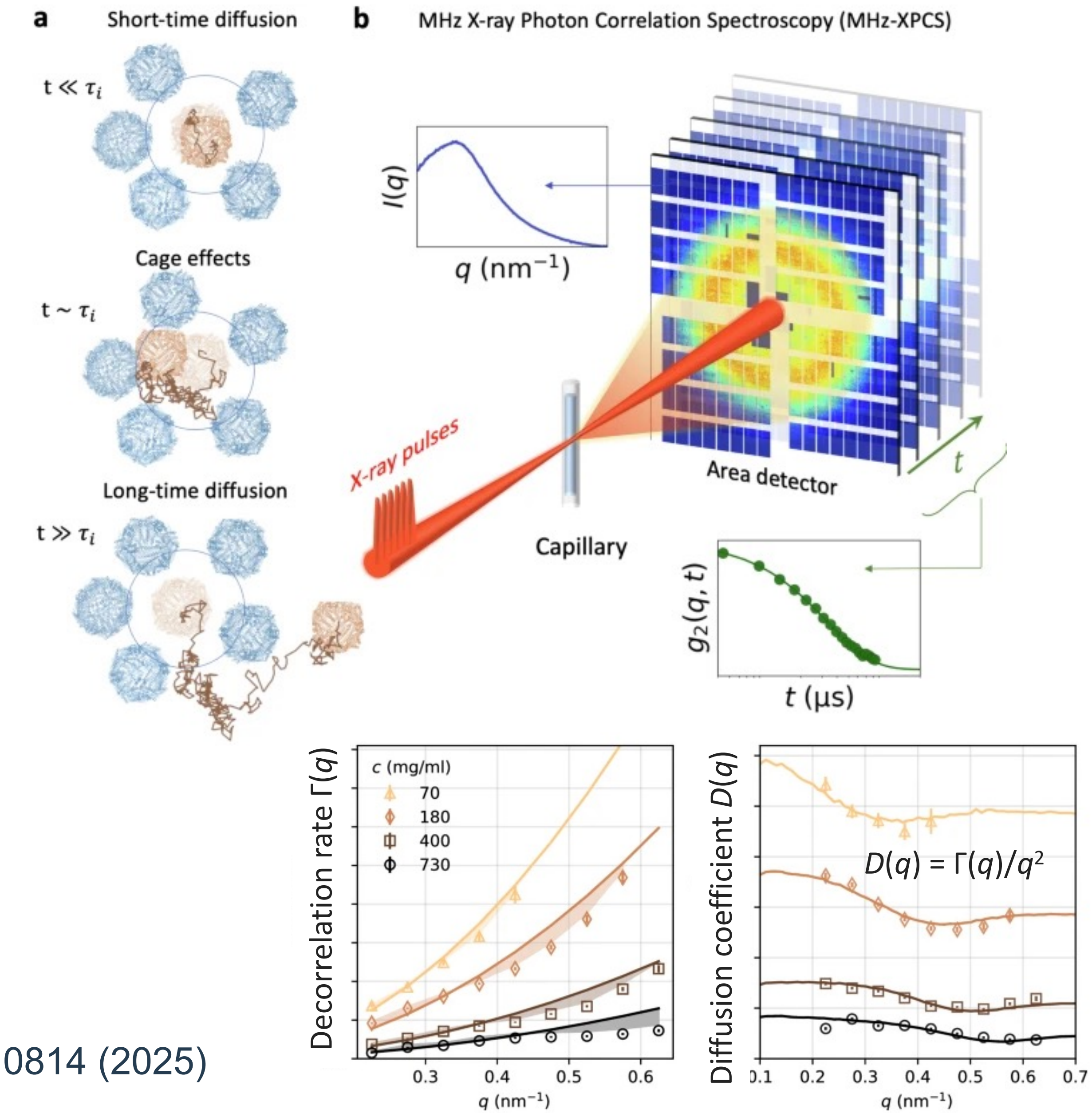
- Structure & dynamics of biomolecules
- New therapies and diagnostics

MID

Anomalous molecular diffusion in crowded protein solutions

Optimizing protein-based drug delivery

- Understanding protein motion within the cell is crucial for predicting reaction rates and macromolecular transport in the cytoplasm
- How do crowded environments, like inside the cell, affect protein dynamics ?
- The results reveal anomalous diffusion on microsecond time scales
- Behaviour consistent with the presence of cage-trapping in-between the short- and long-time protein diffusion regimes.



European XFEL

A. Girelli et al., Nature Comm 16, 10814 (2025)

Research at the European XFEL

Environment & Sustainability

Properties of durable materials, sustainable agriculture, and planetary processes

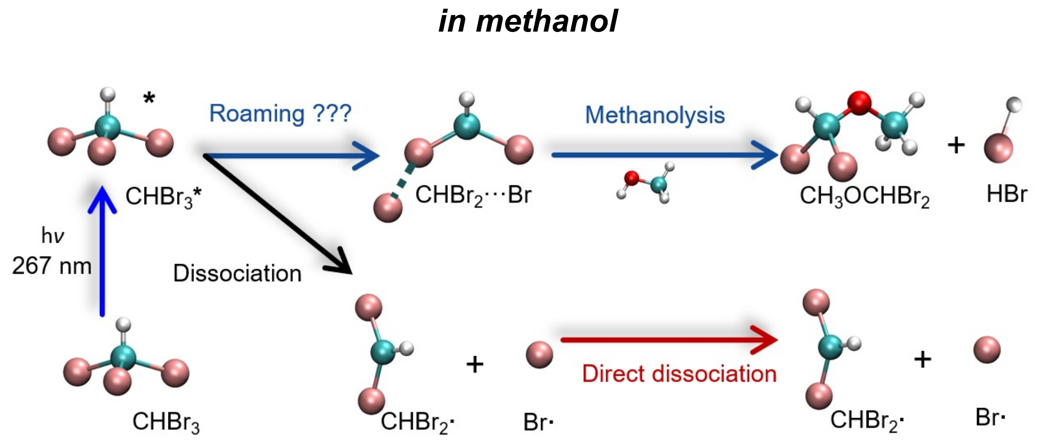
- Structure of natural insecticides
- Hard materials under load

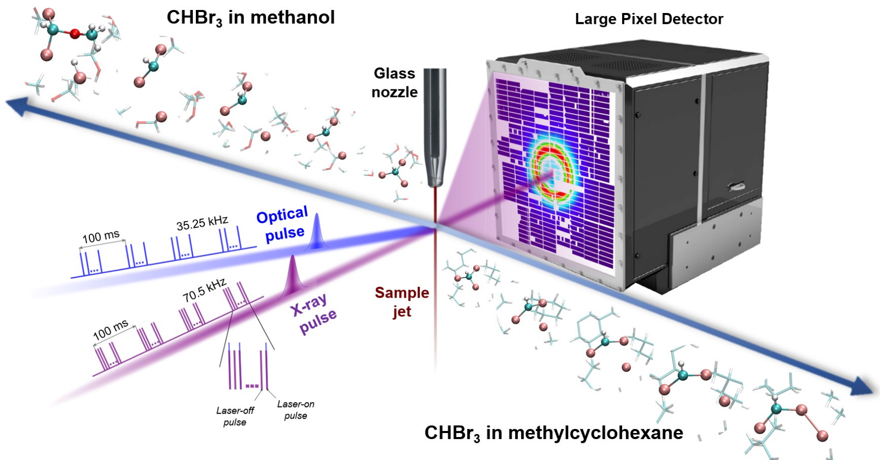
Ultrafast solvent-modulated roaming mechanism in bromoform

How small molecules in the atmosphere dissociate under the effect of UV irradiation

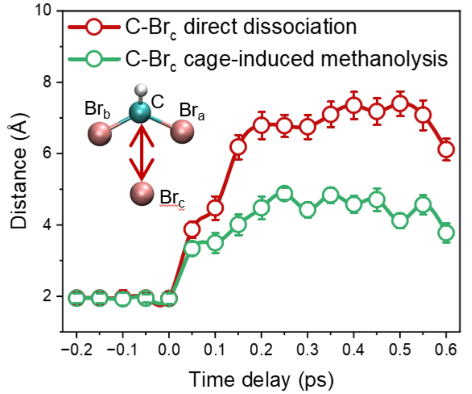
FXE

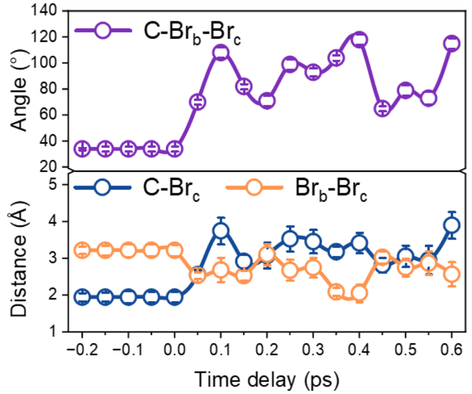
- UV irradiation of poly-halomethanes releases reactive halogens, driving catalytic ozone depletion in the atmosphere
- Bromoform ($CHBr_3$) is the most abundant natural source of bromine (Br_2), >100 times more destructive to ozone than other halogens.
- Solvent-dependent reaction pathways of very short-lived roaming intermediates remain poorly understood, especially for environmentally relevant compounds involved in ozone depletion.

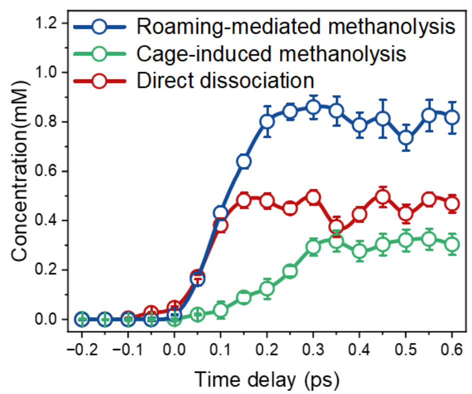




fs-resolved X-ray solution scattering







Peiyuan Su, … & Quingyu Kong, Nature Comm 17, 2514 (2026)

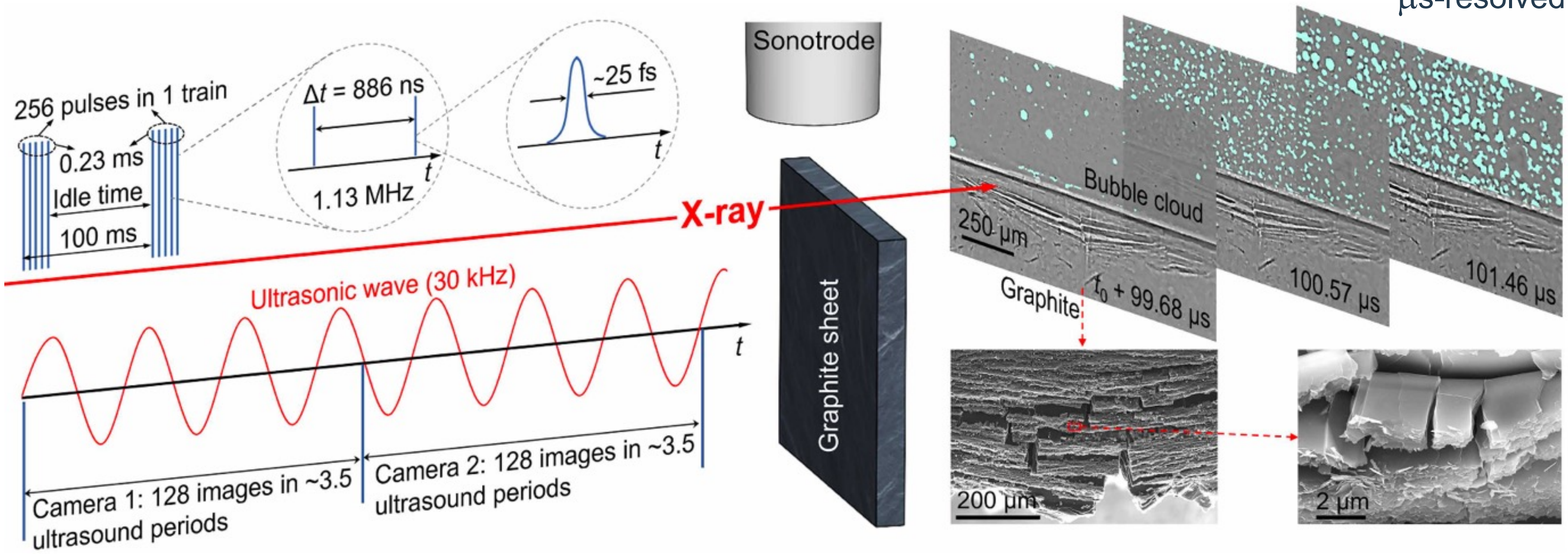
Ultrasonic exfoliation of graphene

SPB/SFX

Environmentally friendly processes to produce large surfaces of 2D functional materials

- Ultrasound Liquid Phase Exfoliation has been identified as a promising low cost and environmentally friendly technical route for producing large size multilayers from bulk materials.
- Investigation of the dynamics of cavitation bubbles and the subsequent exfoliation of graphene layers from graphite provides important insights for tuning the technique for commercial processes

μs-resolved phase contrast imaging



Kang Xiang … & Xiawei Mi, Science Advances (2025)

Research at the European XFEL

Digitalization

Structural dynamics of functional and quantum materials

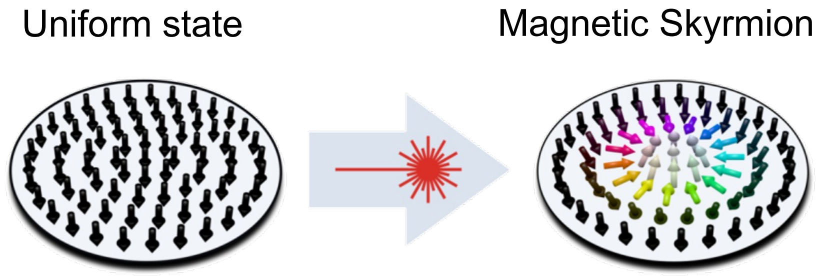
- Magnetism at nm/fs scales
- Promotion of AI/data technologies

Picosecond localization dynamics following ultrafast nanoscale topological phase transition

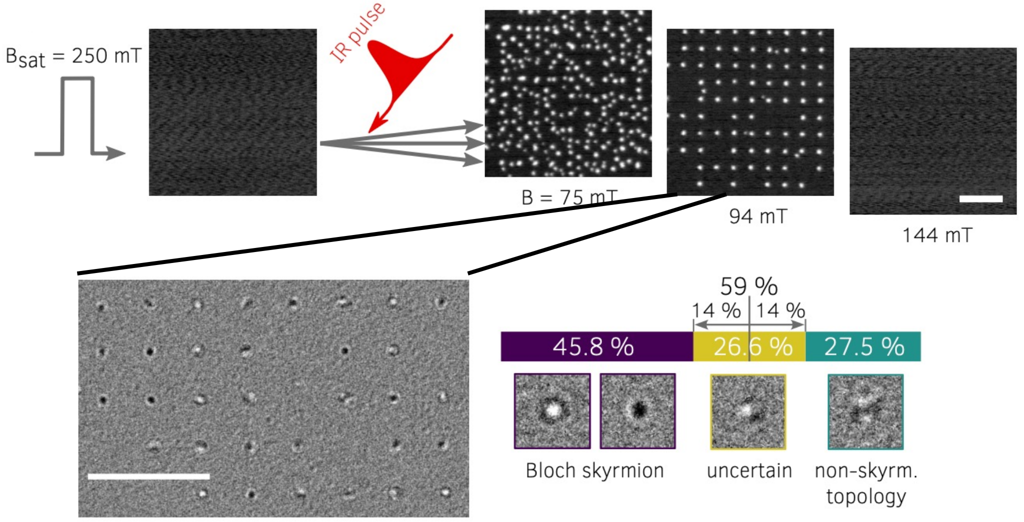
Advancing ultrafast control in nanoscale technologies

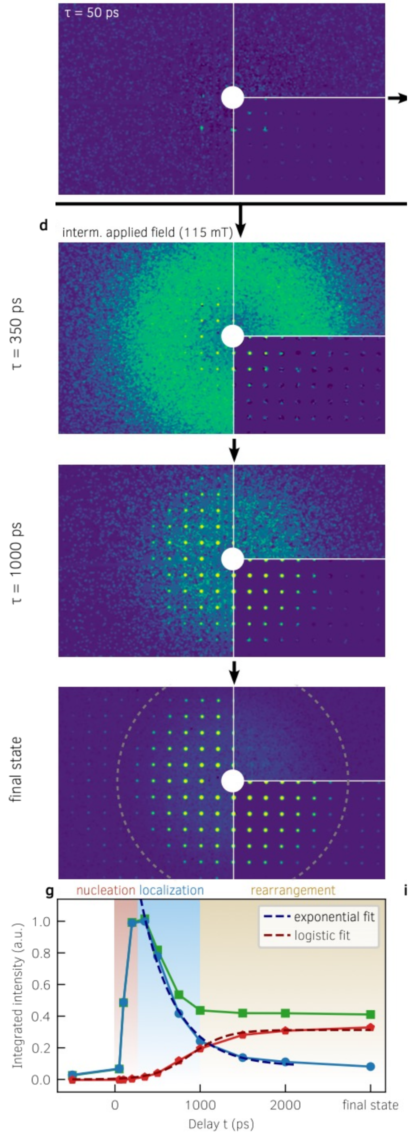
Shot-resolved resonant X-ray scattering

- Track, in real time, the laser-driven nucleation and localization of nm-scale spin textures
- Deterministic spatial control of skyrmion formation after laser excitation through ion-beam patterning of the underlying magnetic anisotropy



- Experiment reveals that nucleation and localization are two distinct processes, occur on different timescales
- Ultrafast phase-transition dynamics fundamentally differ from conventional transitions





Metternich,… , F. Büttner, arXiv:2512.17643 (2025)

Outline

Break @ 17h10-17h20

- What is an X-ray Free Electron Laser and how does it work ?
- Ultrafast science and ultrafast experiments
- X-ray Free Electron Lasers around the world
- What are the new science opportunities ? Examples of recent results
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Infrastructure: developments, challenges and strategy

Accelerator

- Operation and development of superconducting accelerator
- Enabling technologies (e.g. RF)
- Superconducting gun

X-ray Sources

- X-ray cavity
- Superconducting undulators
- Polarization and angular momentum control

Advanced Operation Modes

- Hard X-ray Self Seeding (HXRSS)
- Attosecond pulses
- High photon energies

Detectors and Data Science

- Detectors: CW & hard X-ray compatible
- Data reduction, processing, analysis
- Machine learning, artificial intelligence
- High-performance computing

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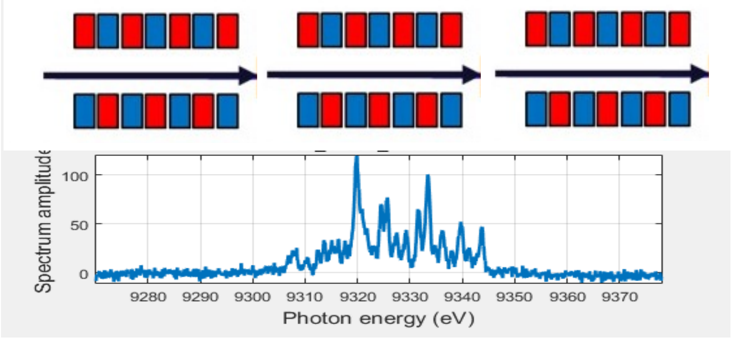
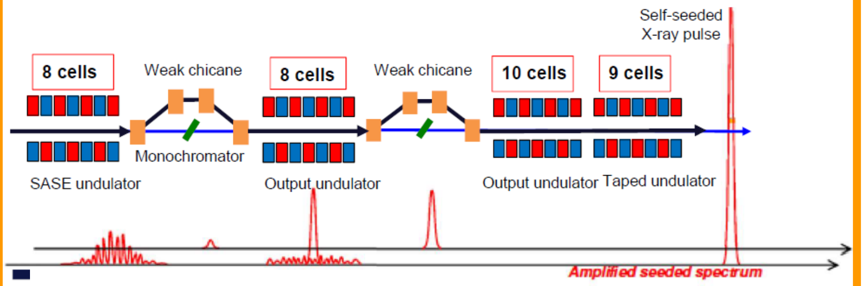
Increasing spectral brilliance, reducing shot-shot instability

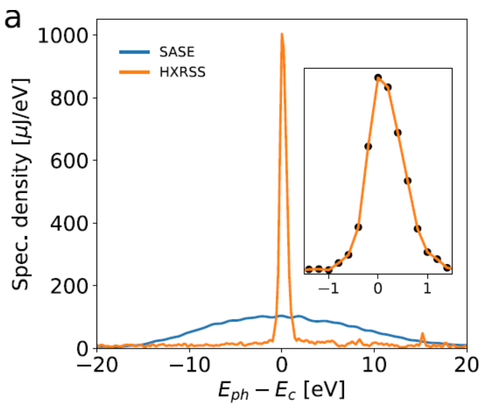
SELF AMPLIFIED SPONTANEOUS EMISSION (SASE)



Photon Energy	9 keV
Pulse energy	2.2 mJ/pulse
BW (FWHM)	20 eV
Spectral density	**100 uJ/eV**

HARD X-RAY SELF SEEDING (HXRSS)





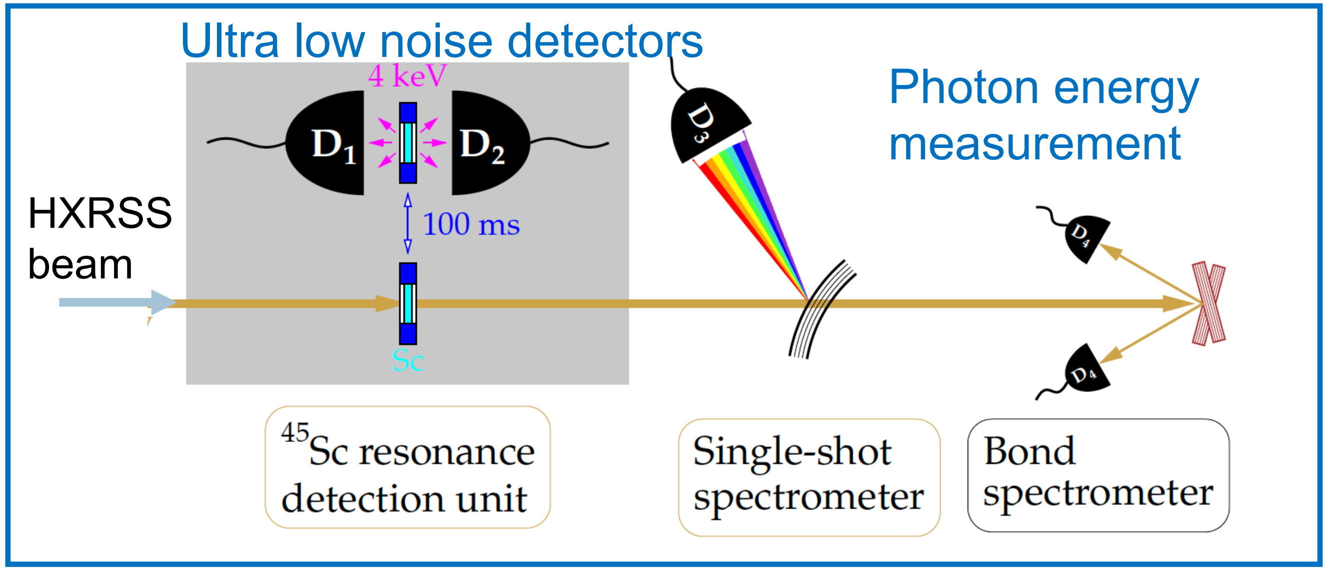
Photon Energy	9 keV
Pulse energy	1.2 mJ (bkg 0.4 mJ)
BW (FWHM)	0.8 eV
Spectral density	**1000 uJ/eV**

Liu et al., Nature Photonics 17, 984 (2023)

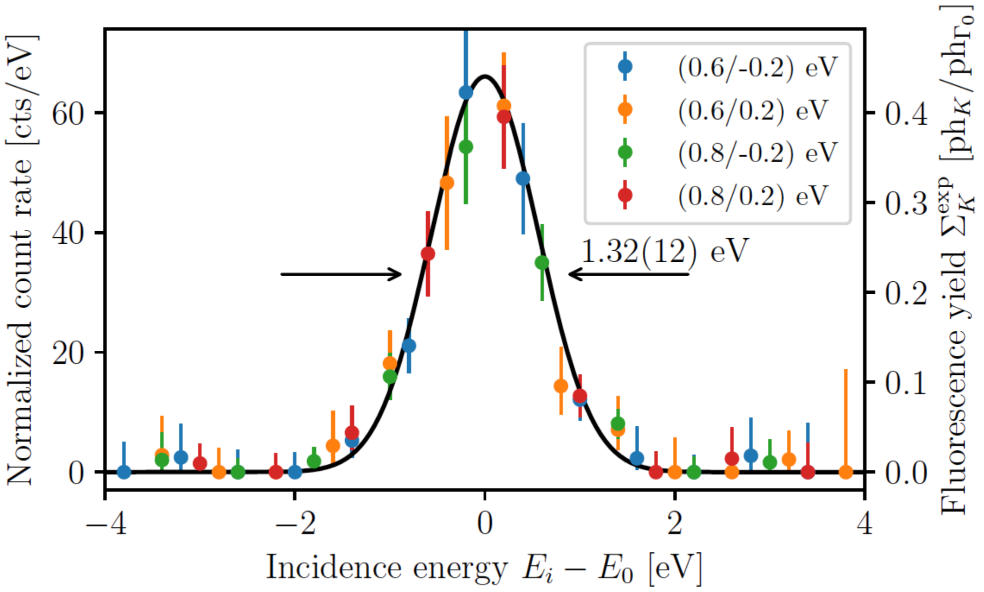
Resonant excitation of the nuclear clock isomer ^{45}Sc

MID

- Resonant oscillators with stable frequencies and large quality factors determine our ability to keep track of time with high precision
- Nuclear oscillators surpass their atomic counterparts by their naturally higher quality factors and higher resilience against external perturbations
- The 12.4 keV nuclear transition in ^{45}Sc
  - Ultranarrow transition linewidth: 1.4 femto-eV
  - Extreme metrology and ultraprecise frequency standards



$$E_0 = 12{,}389.59^{\pm 0.15(\text{stat})}_{+0.12(\text{syst})}\ \text{eV}$$



Yu. Shvydko *et al.*, Nature 622 (2023)

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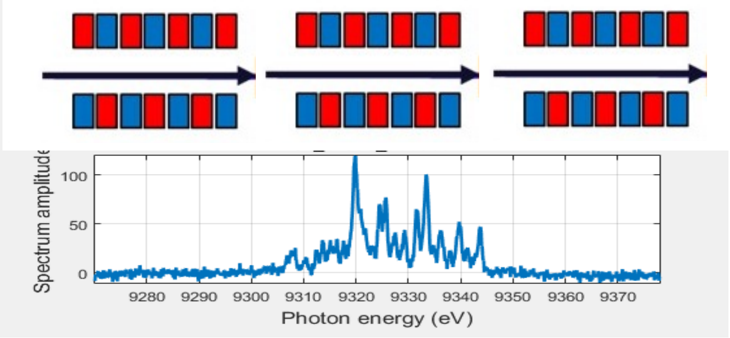

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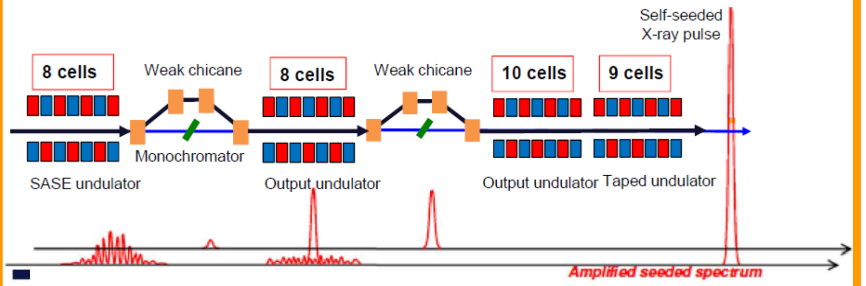
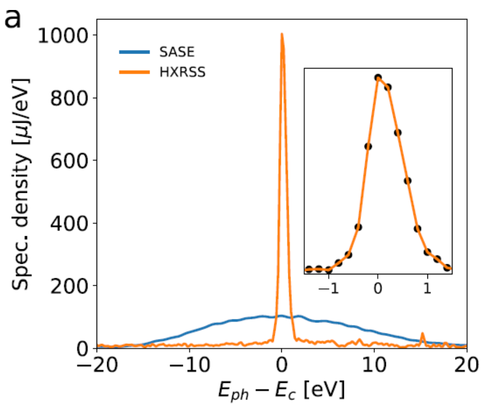
HARD X-RAY SELF SEEDING (HXRSS)





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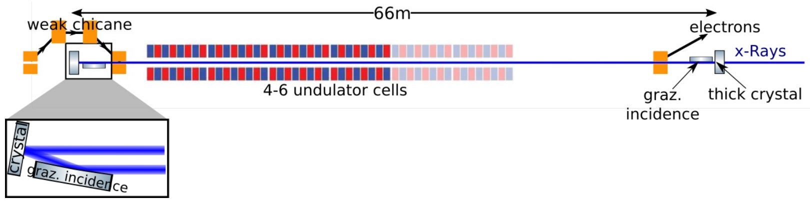
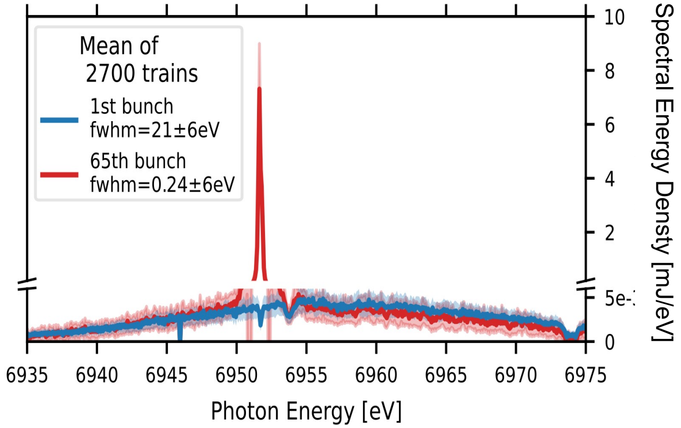
Spectral density	**1000 uJ/eV**

Liu et al., Nature Photonics 17, 984 (2023)

CAVITY BASED X-RAY SOURCE



Sunday 18 May 2025



Photon Energy	7 keV
Pulse energy - th	800 uJ/pulse
BW (FWHM) - th	20 meV
Spectral density - th	**40000 uJ/eV**

Rauer et al., Nature 650, 93 (2026)

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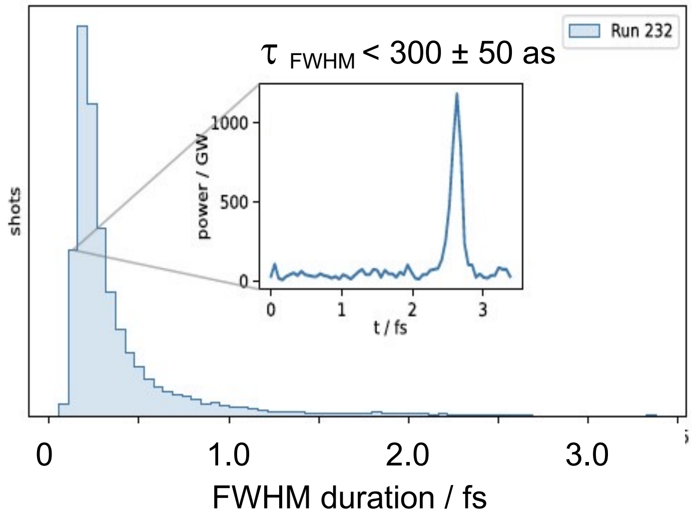
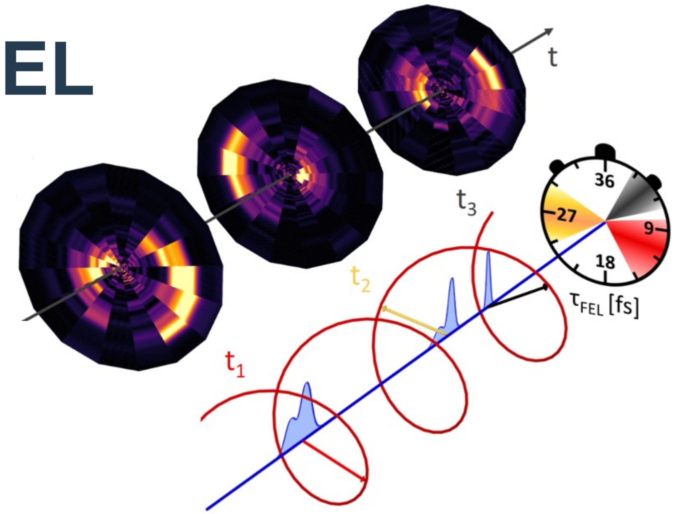
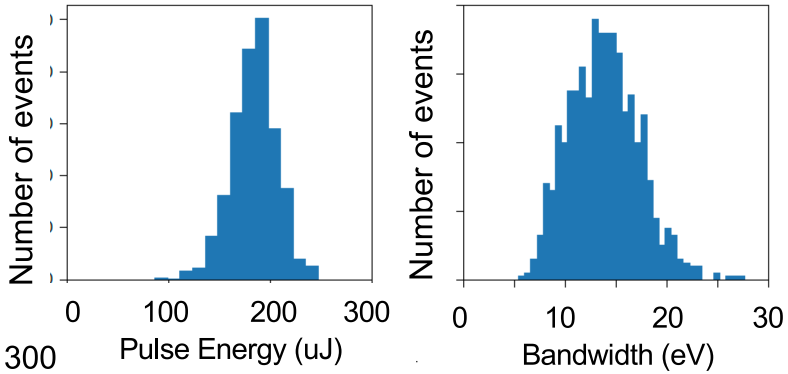
Current generation capabilities at the European XFEL

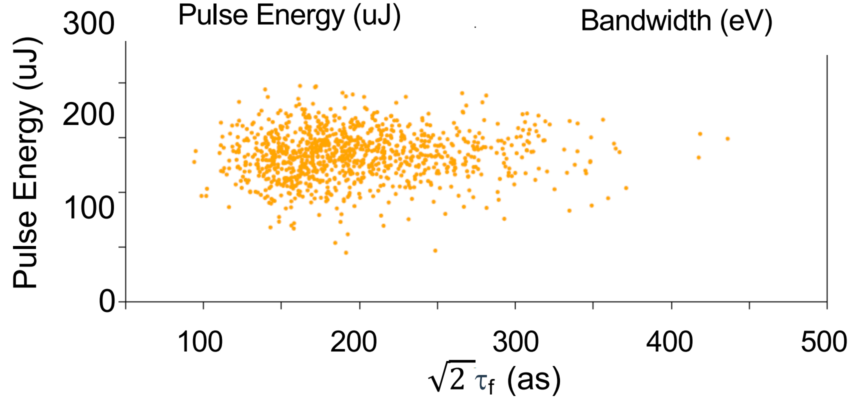
Soft X-rays
- up to mJ level
- ~ keV photon energy
- few 100 as
- 2-color pulses up to few 100 uJ each

Hard X-rays
- up to few 100 uJ
- ~ 9keV photon energy
- few 100 as
- 2-color pulses - preliminary demonstration









Terawatt-attosecond hard X-ray free-electron laser at high repetition rate

Jiawei Yan, Weilun Qin, Ye Chen, Winfried Decking, Philipp Dijkstal, Marc Guetg, Ichiro Inoue, Naresh Kujala, Shan Liu, Tianyun Long, Najmeh Mirian & Gianluca Geloni

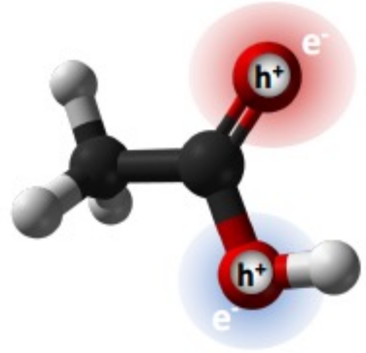
Nature Photonics **18**, 1293–1298 (2024) | Cite this article

SQS

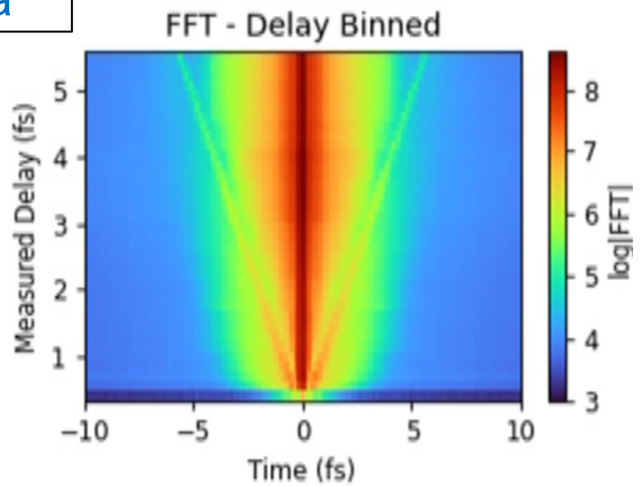
Electron Dynamics in Molecules

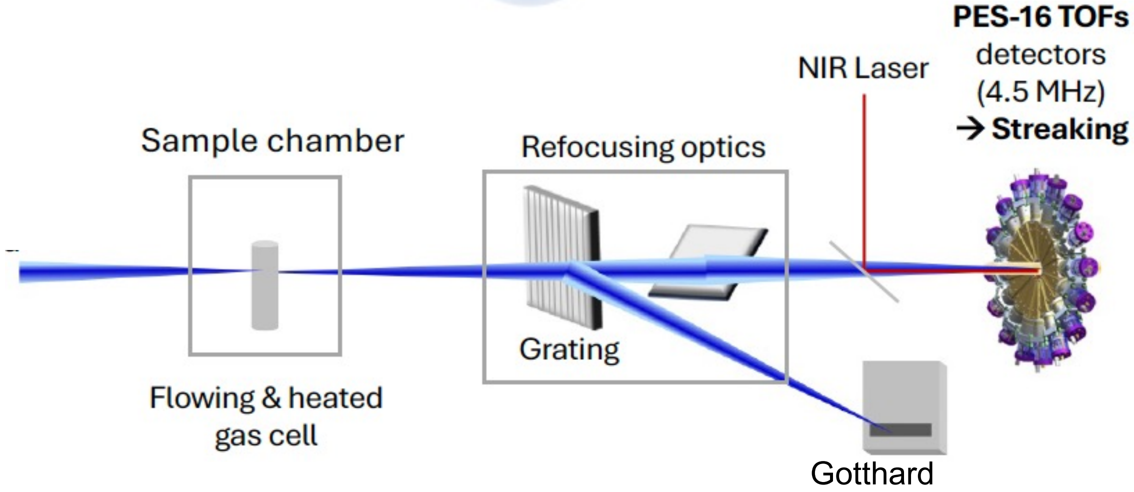
Transient Absorption on Acetic Acid

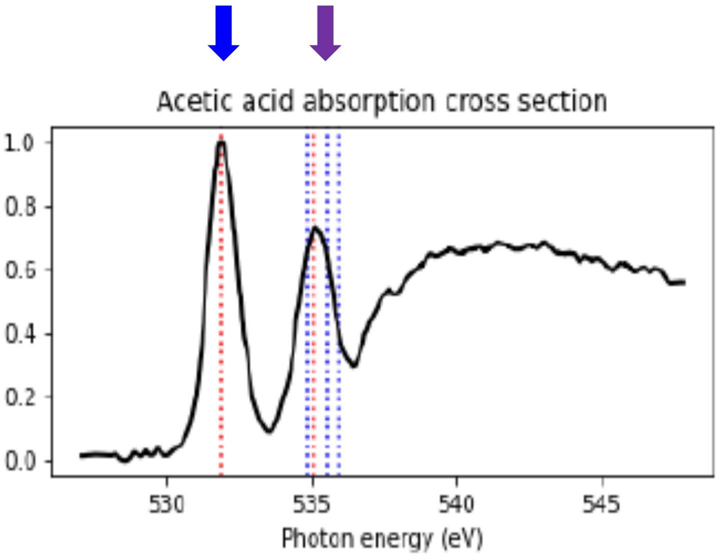
Preliminary data

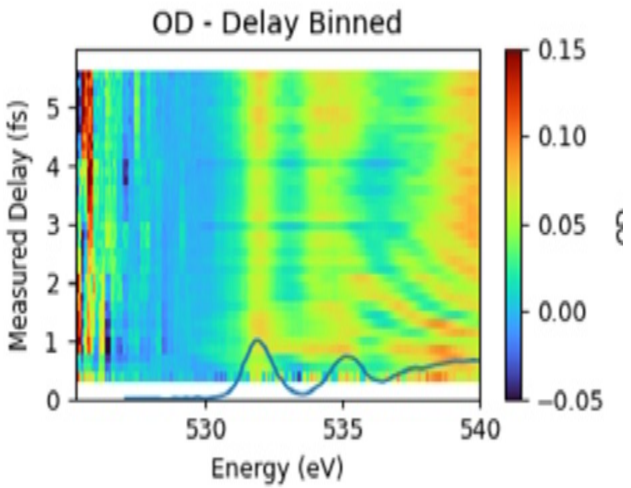


Site-resolved electron dynamics on two chemically distinct oxygen atoms









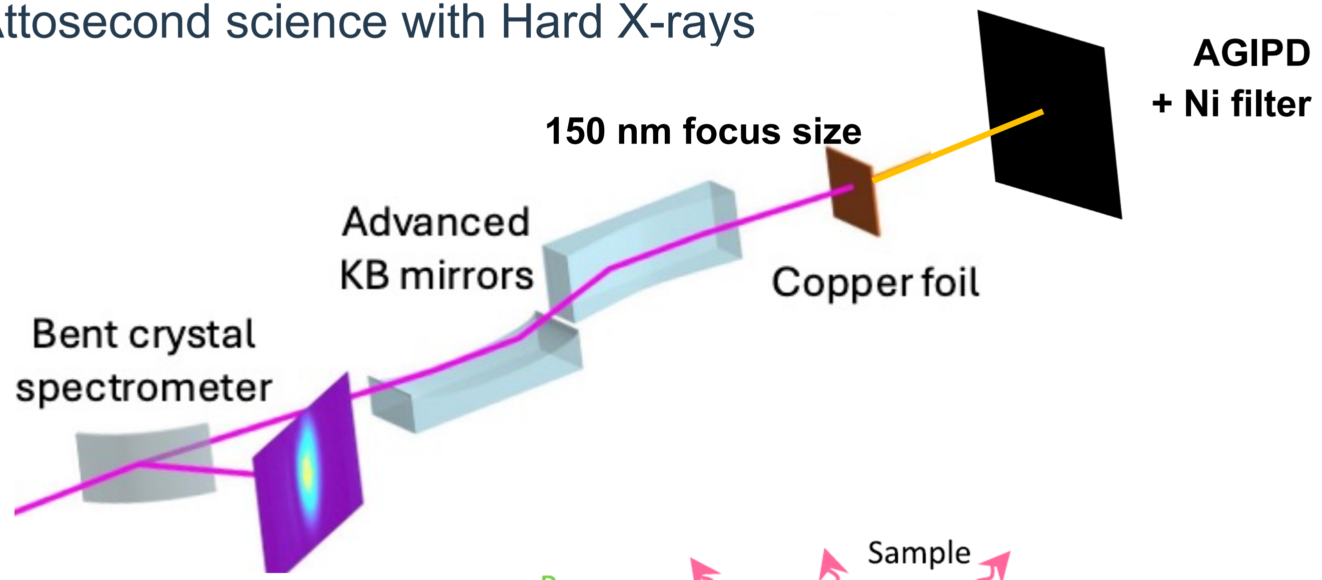
Two-Color (X-ray / X-ray) Spectroscopy at SQS

A.S. Morillo-Candas, C. Ott, T. Pfeifer (MPIK Heidelberg)

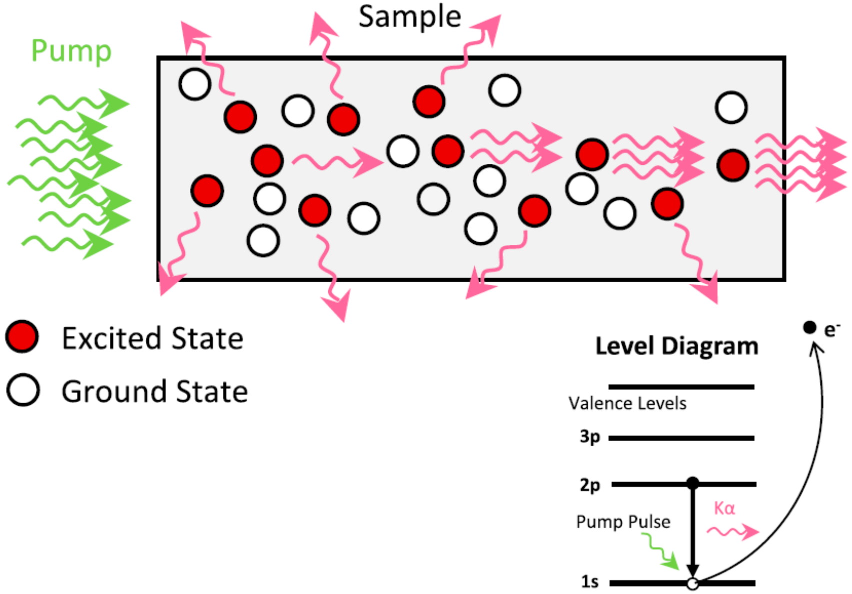
Amplified Spontaneous Emission in Cu

MID

Attosecond science with Hard X-rays

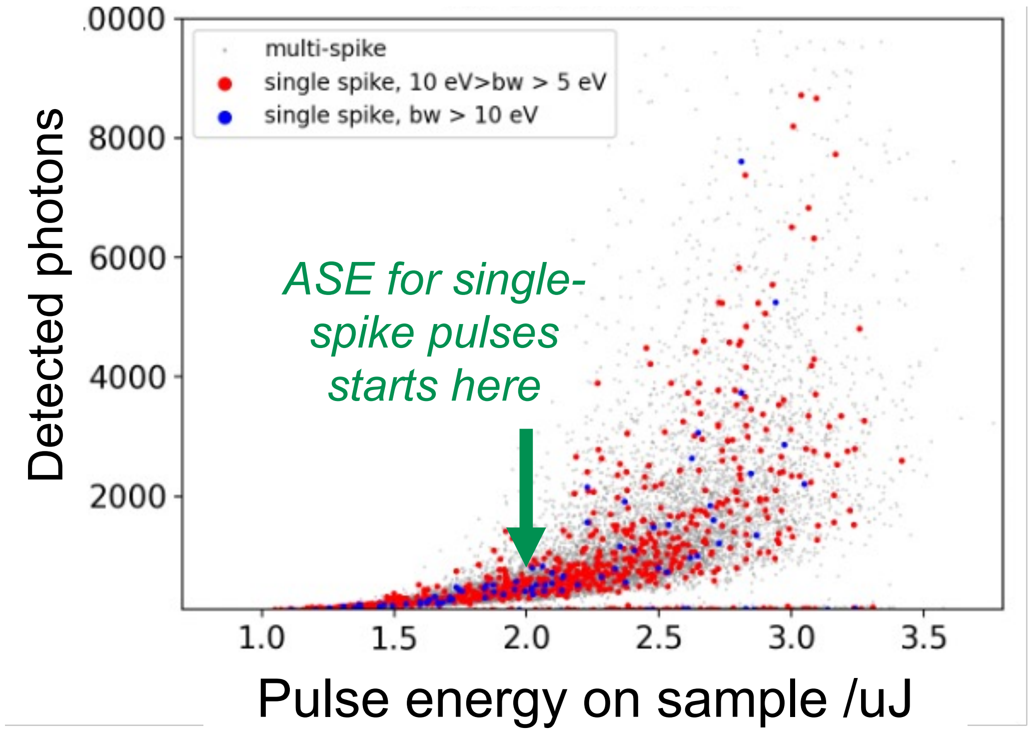


$E_{photons}$ ~ 9 keV



ASE: Amplified Spontaneous Emission

(onset of non-linear behaviour at ~ 2 x 10^{19} W/cm^2)



Ichiro Inoue *et al.* (in preparation)

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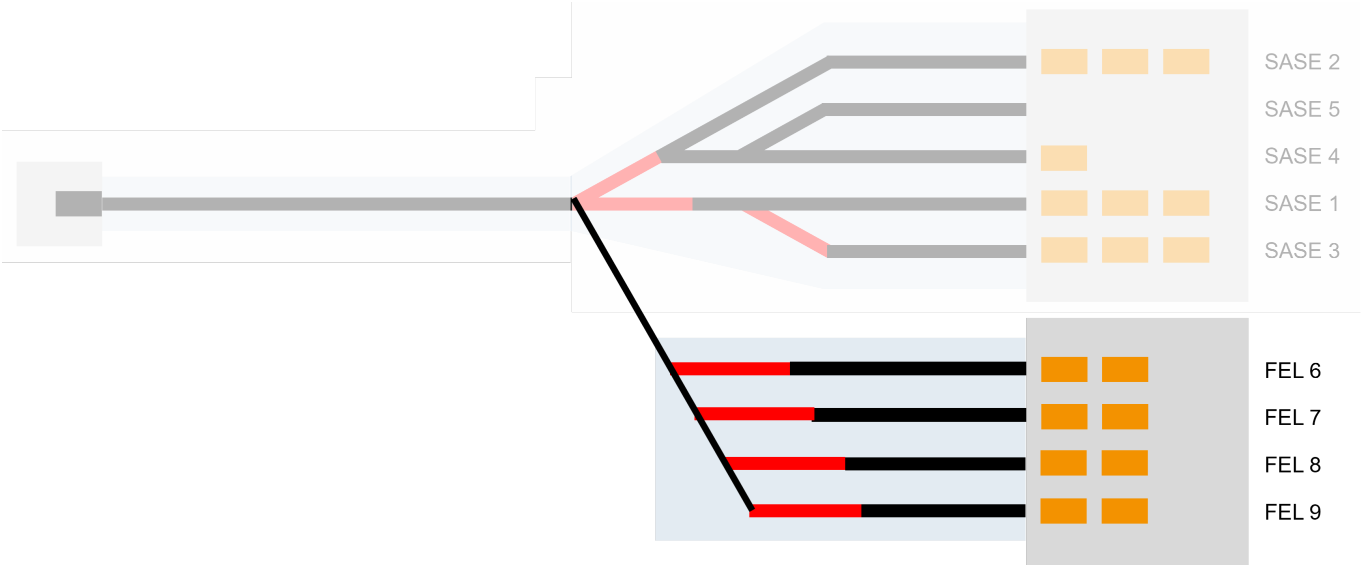
Outlook I: Making an impact

- X-ray FELs are new research infrastructures providing research opportunities complementary to well-established SR sources.

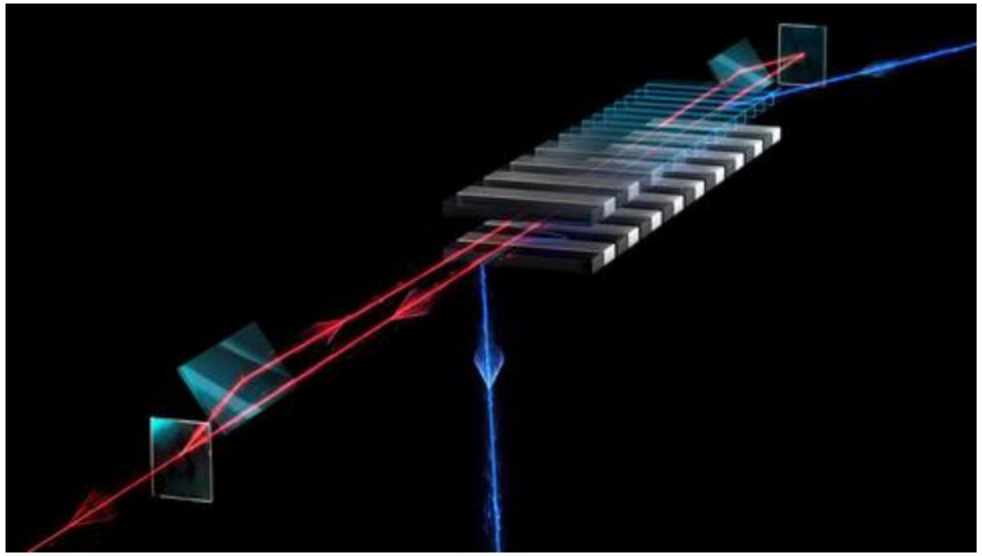
- Very few facilities; the community is still small. Experiments gradually transitioning from "heroic" to "application oriented".



- Future facilities designed for beam distribution to multiple beamlines & instruments w/standardized platforms

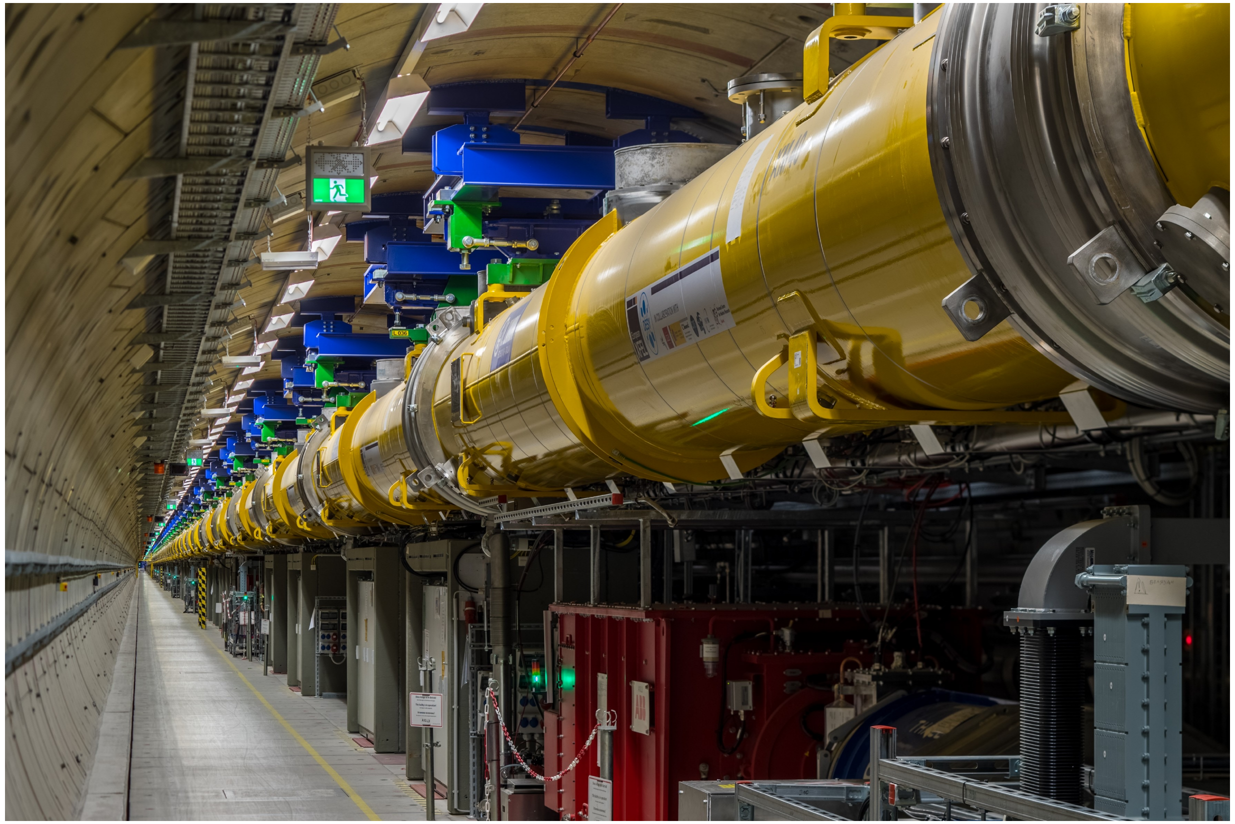
- **With more research opportunities, including for non-expert and smaller groups, XFEL user communities will reach the critical mass for XFEL science to make real impact on society.**

Outlook II: X-ray science of the future



- With the lasing of our X-ray cavity, the EuXFEL and DESY have achieved one of the most ambitious goals in accelerator-based light source research.
- **Cavity based FEL may represent for X-ray science what the invention of the optical laser represented for optics: the transition from bright but incoherent light bulb to fully coherent laser radiation**
- Stable, fully coherent, spectrally pure hard X-ray pulses will **unlock regimes in quantum X-ray optics and enable transformative experiments**
  - meV-resolved inelastic and nuclear resonance spectroscopy
  - ultrafast pump–probe resonant inelastic X-ray scattering in the hard X-ray regime
  - nonlinear wave-mixing
  - ………

Thank you for your attention !



Additional slides

Literature I – FEL theory, FEL schemes & first papers

Firsts & proposals:

J.M.J. Madey, J. Appl. Phys. 42, 1906(1971)

?. Deacon et al., Phys. Rev. Lett. (1977)

J. Andruszkow et al., Phys. Rev. Lett. 85, 3825(2000)

W. Ackermann et al., Nature Phot. 1, 336(2007)

P. Emma et al., Nature Phot. 4, 641(2010)

T. Ishikawa et al., Nature Phot. 6, 540(2012)

Theory:

A.M. Kondratenko, E.L. Saldin, Part. Accel. 10, 207 (1980)

R. Bonifacio, C. Pellegrini, L.M. Narducci, Opt. Communications 50, 373 (1984)

Seeding & beam manipulation:

J. Feldhaus et al., Opt. Communications 140, 341(1997)

P. Emma et al., Phys. Rev. Lett. 92, 074801 (2004)

A.A. Zholents et al., N. Journal Phys. 10, 025005(2008)

G. Geloni et al., J Mod Opt 58, 1391 (2011)

J. Amann et al., Nature Phot. 6, 693 (2012)

E. Allaria et al., Nature Phot. 6, 699 (2012)

E. Allaria et al., Nature Phot. 7, 913 (2013)

D. Ratner et al., Phys. Rev. Lett. 114, 054801 (2015)

A.Lutman et al., Nature Phot. 10, 745 (2016)

S. Liu et al. Nature Phot. 17, 984 (2023)

P. Rauer et al., Phys. Rev. Accel. Beams 26, 020701 (2023)

Literature II – FEL facilities & instrumentation

Facilities:

W.E. White et al., J. Synchrotron Rad. 22, 472 (2015)
E. Allaria et al., J. Synchrotron Rad. 22, 485 (2015)
M. Yabashi et al., J. Synchrotron Rad. 22, 477(2015)
In Soo Ko et al., Appl. Sci. 7, 479 (2017)
Th. Tschentscher et al., Appl. Sci. 7, 592 (2017)
W. Decking et al., Nature Phot. 14, 391 (2020)

Diagnostic:

K. Tiedtke et al., J Appl. Phys. 103, 094511 (2008)
Y. Feng et al., Appl. Phys. Lett. 101, 034103 (2012)
M. Beye et al., Appl. Phys. Lett. 100, 121108 (2012)
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FEL parameters

- Full 3-dimensional FEL theory is extremely demanding
- Simplified 1-dimensional approach
- Pierce (FEL) parameter ρ

$$\rho = \left(\frac{I A_{JJ}^2 K^2 \lambda_{rad}^2}{I_A 32\pi^2 \gamma^2 \varepsilon_n \beta_f} \right)^{1/3}$$

ρ~2-5×10^{-4}(0.1 nm)

- **Number of cooperating electrons N_c**

$$N_c = \left(N_e \lambda_{rad} / L\right) / 2\pi\rho$$

N_c~1/500×N_e (0.1 nm)

- **Power gain length L_G**

$$L_G \approx \lambda_{und} / 4\pi\rho$$

- **Saturation length L_{sat}**

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

- **Radiated energy E_{sat}**

$$E_{sat} = \rho N_e E_{e,kin,total}$$

- **Radiation bandwidth $\Delta\lambda/\lambda$**

$$\Delta\lambda / \lambda \approx 2\rho$$

FEL process is critically sensitive to electron parameters

- Transverse emittance (diffraction limit)

$$\varepsilon < \lambda_{rad} / 4\pi$$

→ $\varepsilon \sim 8$ pm ($\lambda = 0.1$ nm) → $\varepsilon_n \sim 0.22 \times 10^{-6}$ mrad (15 GeV)

- Energy spread

$$\sigma_e / E < \rho$$

→ $\sim 10^{-4}$

- Gain length

$$L_G < L_{Rayleigh} = 2\pi\sigma_{rad}^2 / \lambda_{rad}$$

In general, small emittance, small energy spread, and high peak current are needed simultaneously.

FELs vs. storage rings

Storage rings

- Electron bunches are circulated
- Stable operation conditions
- Many science instruments, often dedicated to specific methods or science applications
- Large number of exp.s and users per year
- Average spectral brightness is key property
- Specialization on low/medium/high energy facilities with resp. spectral coverage
- ~50 yrs development

FELs

- Normally electron bunch is used only once
- Single path means instable operation conditions
- Few science instruments, often designed for multi-purpose applications
- Typ. only many 10s of experiments per year
- Peak spectral brightness is key property
- Specialization on low/medium/high energy facilities with resp. spectral coverage
- High repetition and multi-beamline facilities will broaden access and average flux properties
- ~10 yrs development

Comparison of SR and FEL x-ray properties

X--ray pulse properties	SR x-rays	X-ray FELs
Pulse energy	pJ - nJ	µJ - mJ
Photons per pulse (~10 keV)	10^5 – 10^8	10^{10}- 10^{13}
Pulse duration / time-resolution	30 - 100 ps	2 - 100 fs
Coherence degree (~10 keV)	< 10^{-3}	0.1 - 1
Rel. bandwidth (Undulator)	10^{-2}	10^{-3}
Spectral characteristics	continuous	spiked
Divergence (hor. × vert.)	1000 × 10 µrad^2	< 2 × 2 µrad^2
Repetition rate	~100 MHz	~MHz | 10 - 100 Hz
Peak brilliance	~10^{24}	~10^{33}
Average brilliance	~10^{20}	~10^{24} | ~10^{22}

Comparison of SR and FEL experiments

Synchrotron experiments	FEL experiments
Typically continuous illumination until desired S/N-ratio is reached (ms to hrs)	Typically single pulse illumination and collection of few – 100s pulses to reach desired S/N
Continuous illumination facilitated by high stability and linear intensity dependence ☺	Single-shot illumination due to strong fluctuations of pulse properties and possibility of non-linear dependence !
Single pulses typically not meaningful	Single pulses typically give meaningful results ☺
Coherence degree small and requires to limit phase space/flux to reach good degree	High coherence degree enables use of full pulse ☺
50 ps- to µs- time resolution; ps to hrs probing	fs- to ps- time resolution; fs to ms probing
Samples typically probed non-destructively ☺	Samples often degrade and need to be refreshed (OL-pumping; irreversible; damage) Can use X-ray pulse to pump sample !
OL most often cw; few sync. OL systems	Complex OL for pump-probe experiments !
Many (O(10-30)) parallel experiments ☺	Few (O(1-5)) parallel experiments

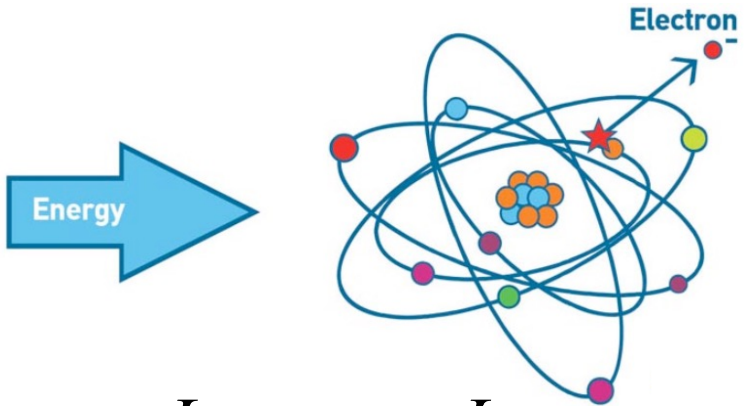
Short recap – FEL applications focus on …

- Ultrashort pulses (fs)
- High pulse energies (mJ)
- High transverse coherence (~100%)
- High peak & average brightness

Field	Application	FEL property required
Condensed-matter		
Atoms, molecules, optical phenomena		
Materials		
Chemistry		
Life science		

Damage by intense x-ray pulses

- While most SR experiments are performed in a regime in which the x-ray pulse is minimally interacting with the sample, FEL experiments often depart from this regime.
- Need to estimate x-ray – matter interaction
- Experiment specific sample response
  - **Ultrafast (fs): change of probed system**
  - **Fast (ns-µs): diffusion, expansion, ablation**
- Minimize absorption !
  - **Use low Z materials (optics, absorbers)**
  - **Optimize sample geometry**
  - **Reduce pulse intensity**
  - **Reduce pulse duration**

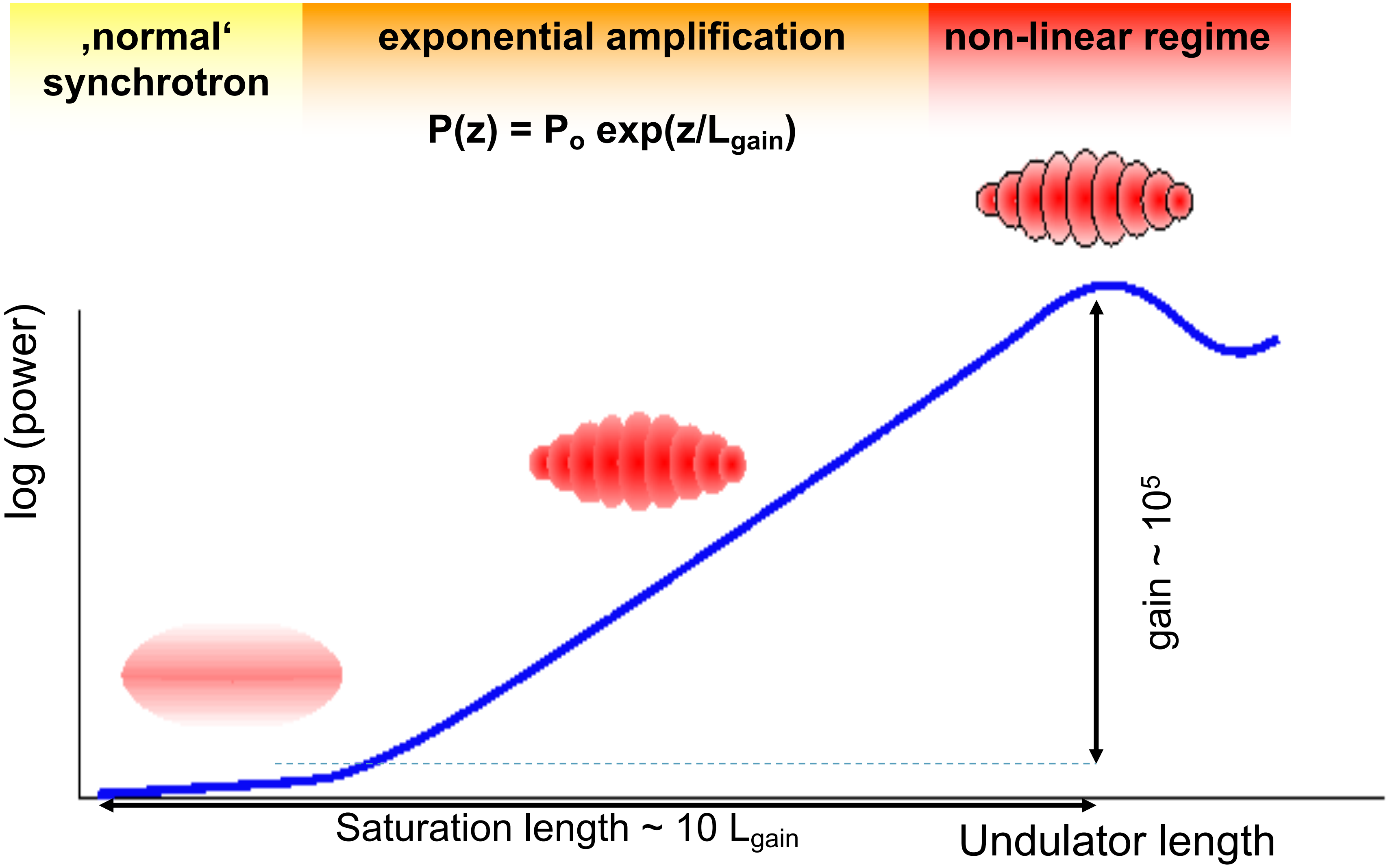


$$I_{scatter} << I_{absorb}$$

At ~12 keV for bio-samples (C, H, N, O) $I_{scatter}$ ~0.1 I_{absorb}

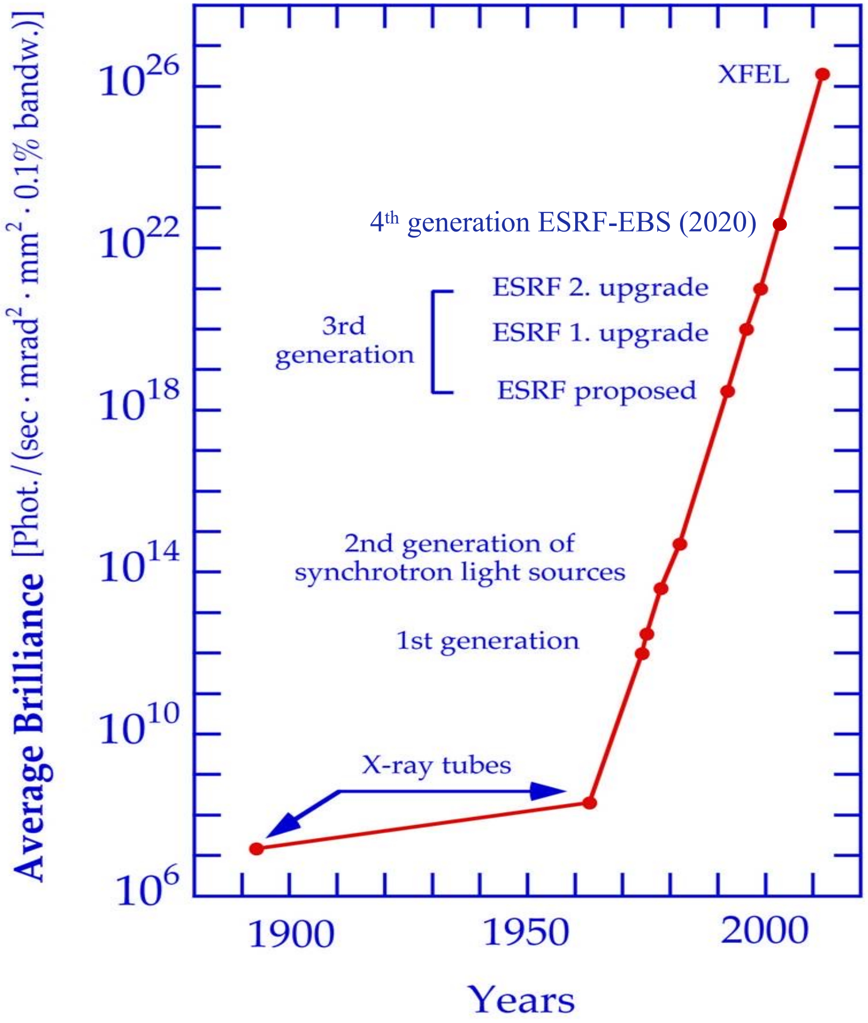
- Absorption generates photo-electrons → damage
- Cascading generates add. electrons → more damage
  - **1st photo-electron**
  - **2nd Auger-electron**
  - **Many electrons by inelastic electron scattering**

FEL gain

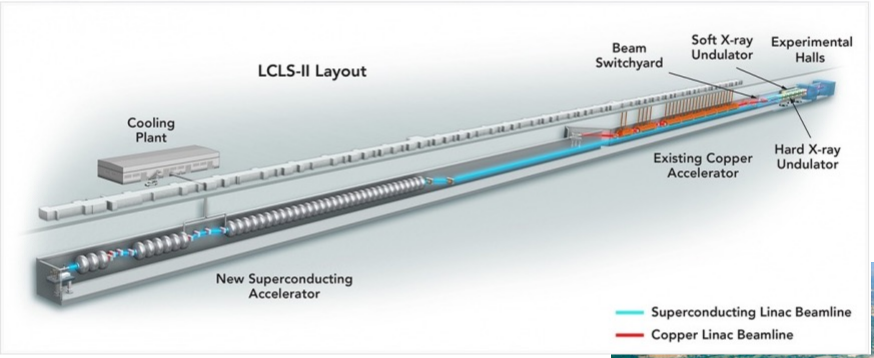

‚normal'
synchrotron
exponential amplification
$P(z) = P_o \exp(z/L_{gain})$
non-linear regime
log (power)
gain ~ 10^5
Saturation length ~ 10 L_{gain}
Undulator length

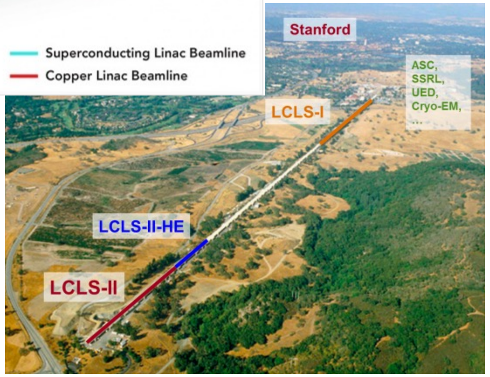
Accelerator based X-ray facilities

European XFEL

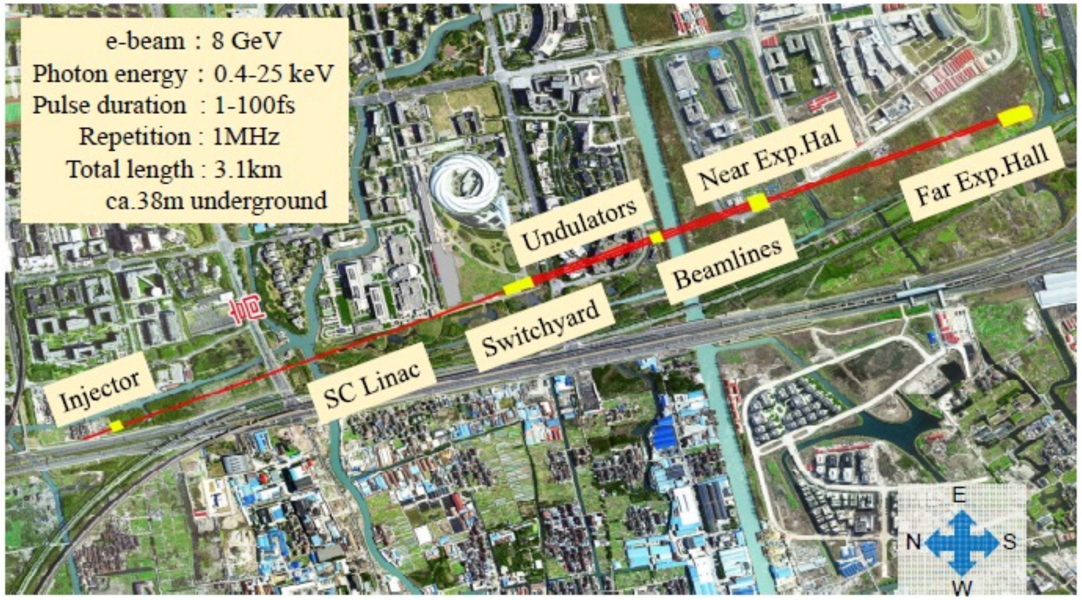


Towards CW-type FELs





- CW == high repetition rate continuous wave accelerators
  - **Superconducting RF to deal with power losses**
  - **High rep. rate low emittance injectors**
- First project is LCLS-II – operating now
  - **Using know-how and technology developed for European XFEL**
  - **4 GeV → soft x-rays**
  - **8 GeV → coming**
- Second project is Shanghai Coherent Light Source (SHINE)
  - **8 GeV → soft and hard x-rays**
- European XFEL design enables upgrade to CW-operation

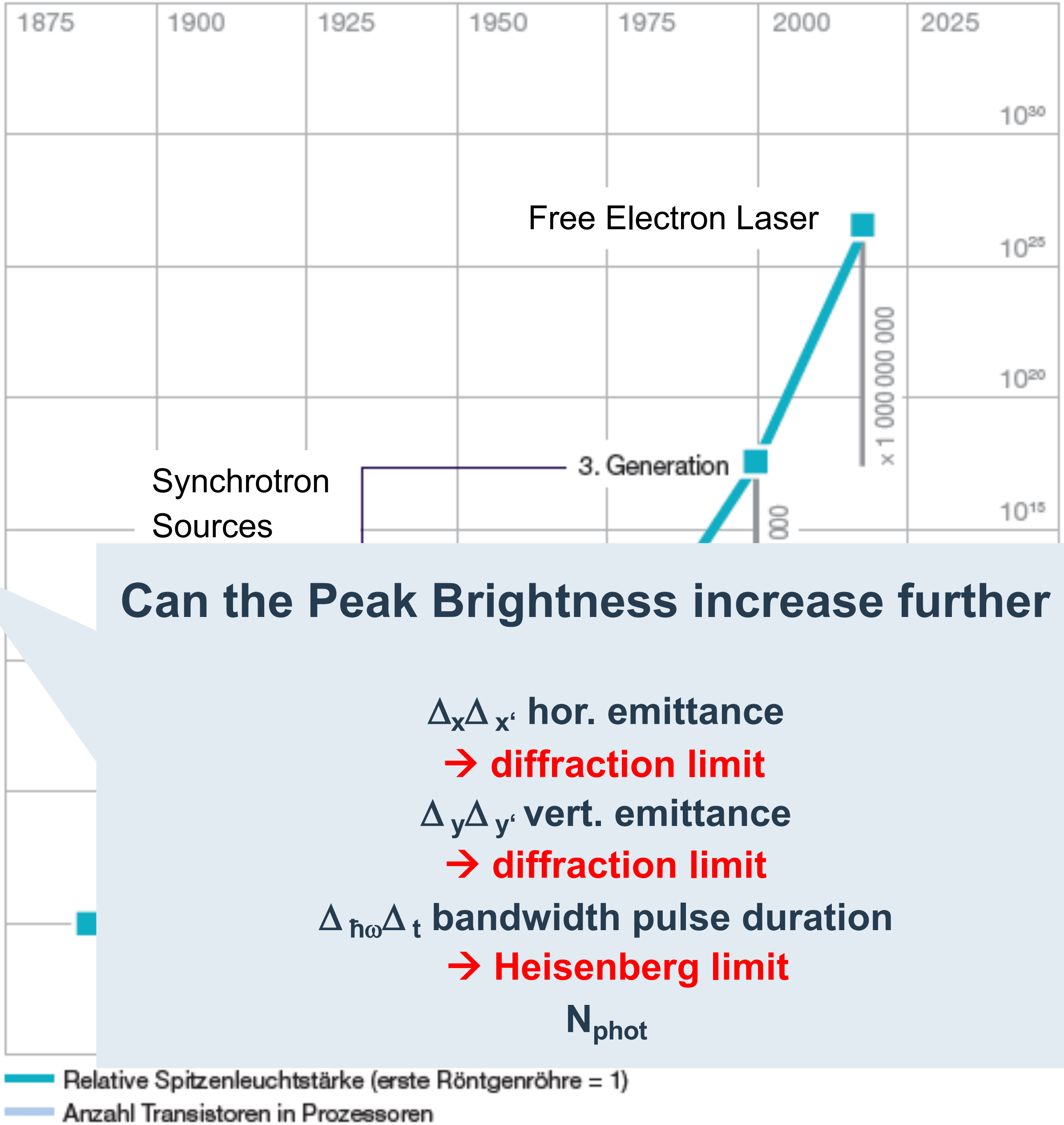


Development of peak brightness

- Peak brightness is the quantity best describing performance of pulsed coherent (laser) x-ray sources

$$\text{Peak brightness} = \frac{\textit{Number of photons}}{\Delta_x \Delta_{x'} \Delta_y \Delta_{y'} \times \textit{bandwidth} \times \Delta_t}$$

- SR sources use average brightness (brightness scaled to 1 second)
- Tremendous improvement opens route to new methods & applications



Can the Peak Brightness increase further ?

$\Delta_x \Delta_{x'}$ hor. emittance
→ diffraction limit
$\Delta_y \Delta_{y'}$ vert. emittance
→ diffraction limit
$\Delta_{\hbar\omega} \Delta_t$ bandwidth pulse duration
→ Heisenberg limit
N_{phot}

From 'first's' to applications

- X-ray FELs are operational since ~ 15 yrs.
- Many new observations for the interaction of intense (energy & ultrashort) x-ray pulses with matter have been made. Large number of highly visible papers published.
- A next step will be to develop applications which can be used by a broader science community. Potential candidates are:
  - **Structure and dynamics of proteins and similar bio-molecules**
  - **Chemical reaction dynamics : Intermediates & pathways**
  - **Materials science: visualization of irreversible, stochastic, rare, processes**
- FEL experiments are complex → still small community, how can we make experiments simpler
- One can expect still lot of new results and new methods to come out of the (still young) FEL research

Most important science drivers

- Capability to measure ultrafast dynamics will allow to determine the response of photo-active catalysts to light excitation → develop new compounds/materials for solar energy conversion

- Capability to determine atomic structures of bio and biochemical objects will allow to better understand their function → develop new drugs and disease treatments

- Capability to observe new and yet undiscovered states of matter and their structural properties will allow to better understand fundamental physical properties of matter and to detect new materials properties → develop new materials and processes

- Possibility to observe non-linear x-ray processes will allow to develop new x-ray spectroscopy methods → enable new methods to study excited matter

Summary

- X-ray FELs are new research infrastructures providing research opportunities complementary to well-established SR sources.
  - **Femtosecond time resolution**
  - **High pulse energies enabling single shot experiments and non-linear x-ray scattering**
  - **High coherence facilitating imaging and correlation spectroscopy experiments**
- Since 2017 5 hard x-ray facilities are operational. This will broaden the experiment and user base and will provide better access and research opportunities.
- Many applications so far concern basic science, many are exploratory. With a better under-standing of what is possible using FELs and an increase in available beam-time an expansion of scientific applications is expected.
- The field is still very young and dynamic → new developments are very frequent: Stay tuned !