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X-ray FEL sources

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October 15, 2012

La^{3}Net, Laser School

GANIL, Caen (France)

X-ray FEL sources

Acknowledgements:
SwissFEL team, PSI

Outline

- Motivation
- Ultrashort X-ray pulses from FEL light sources
- FEL technology
- Science program at X-FEL facilities

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Time-resolved studies: Motivation

Challenge in science: "directly" detect atomic motions during a structural transition.

Information on both dynamics and structure on the relevant length and time scales to fully understand the natural phenomena of interest is needed.

Range of length and time scales is very broad.

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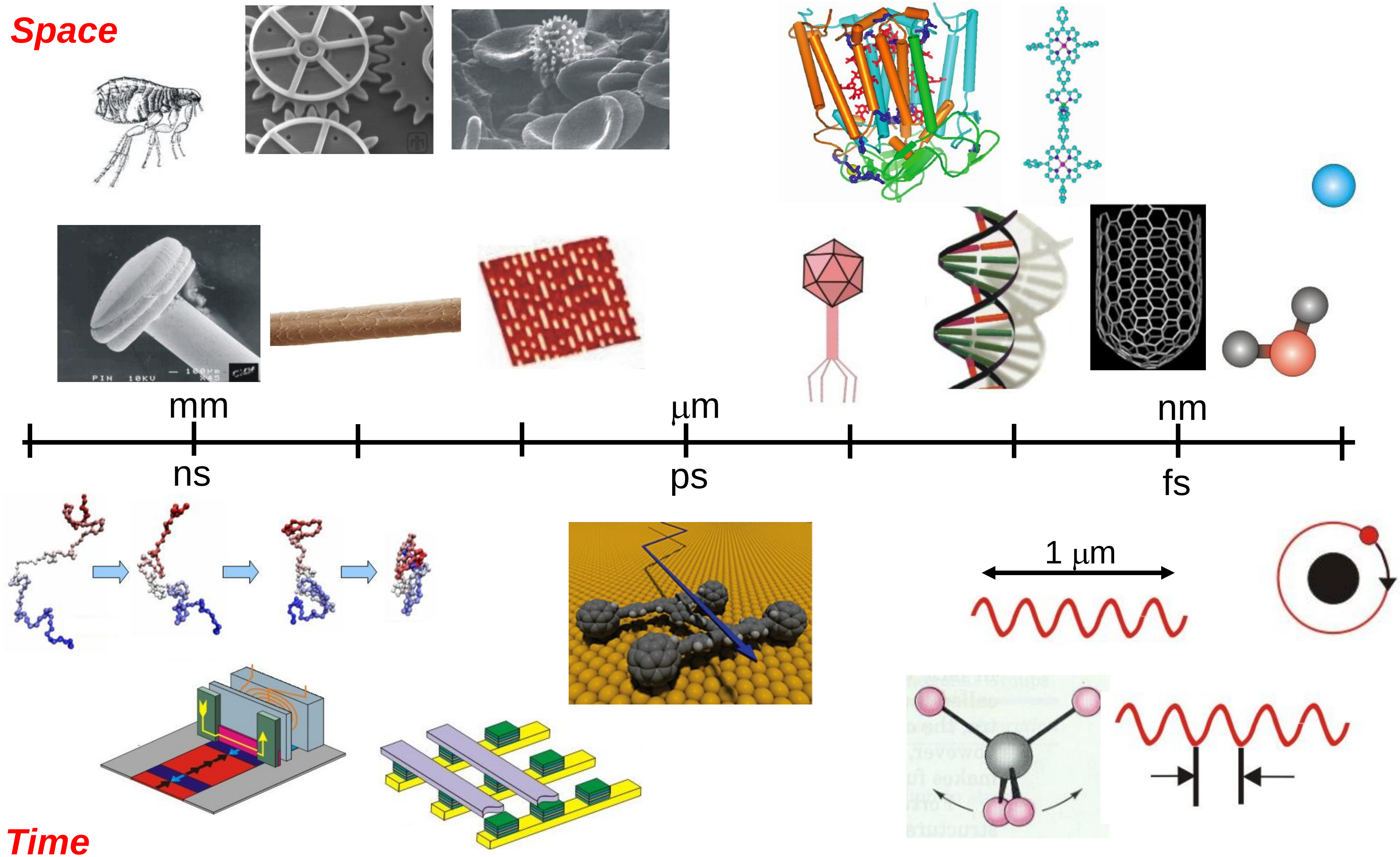
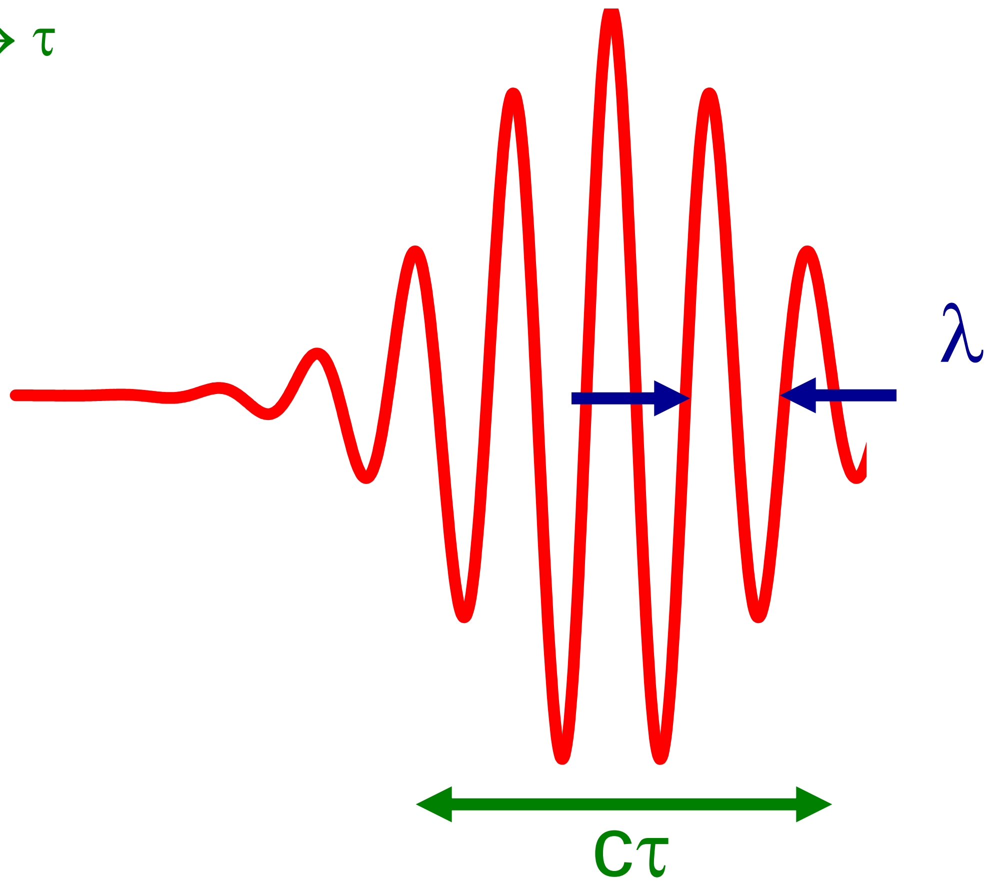


Light as probe

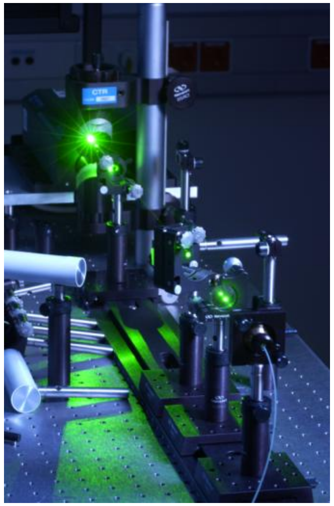
Resolution:

Space→ λ

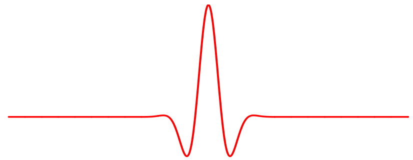
Time→ τ



Light sources

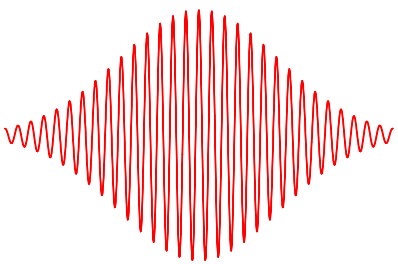


Optical Laser

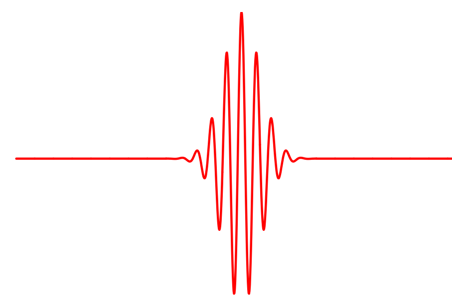


„Fast“ : τ = 2 fs … (0.4 fs)
„ Low res. “ : λ = 200 nm…(14 nm)

Synchrotron light

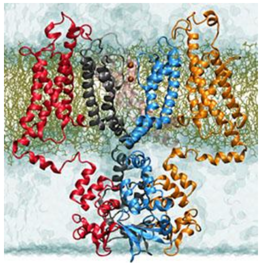


„ High res.“ : λ = 0.1 nm
„Slow“ : τ = 100.000 fs



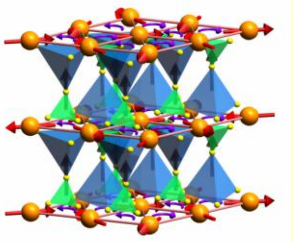
XFEL: High res. and Fast λ = 0.1 nm, τ = 10 fs

1. Biochemical structure and dynamics

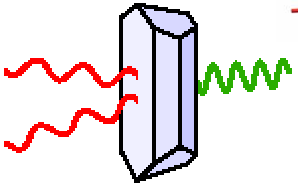


2. Surface catalysis and artificial photosynthesis

3. Ultra-fast switching in electronic materials



4. X-ray non-linear optics



Time-resolved studies: Motivation

How fast can a phase transition involving a change in symmetry occur?

What is the *driving force* behind phase transitions in interesting (strongly correlated electron) materials?

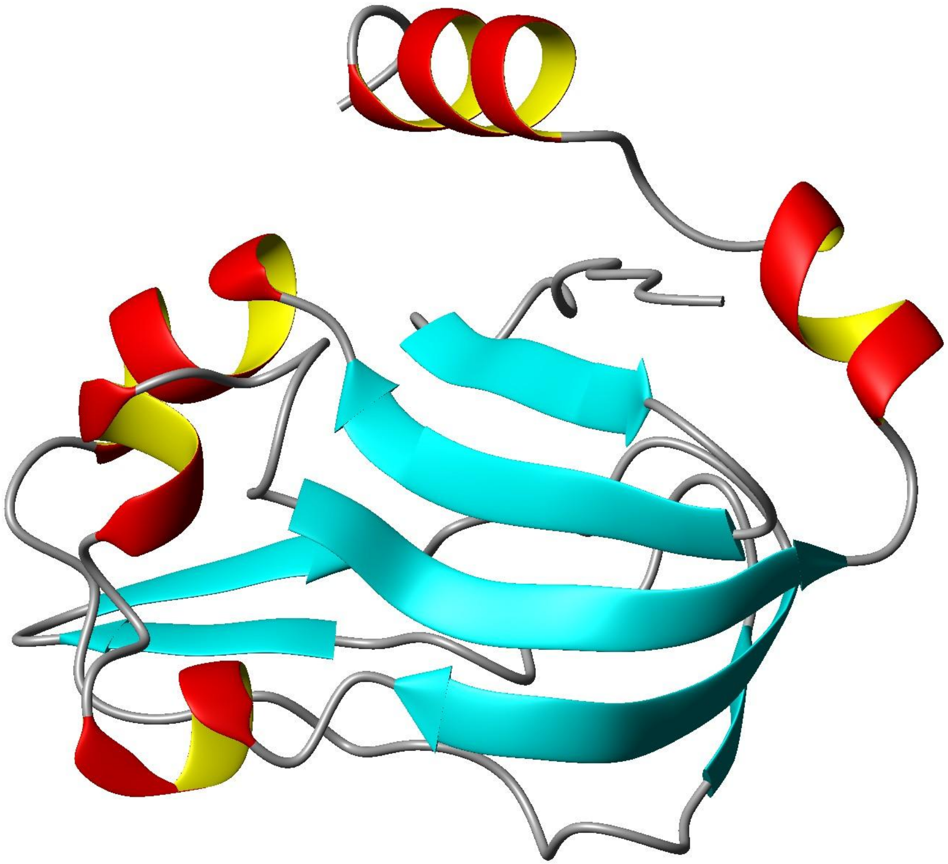
How can we influence the structure of solids via *non-thermodynamic pathways*?

How is *equilibrium established* after a perturbation?

Which are the *pathways in a chemical* reaction?

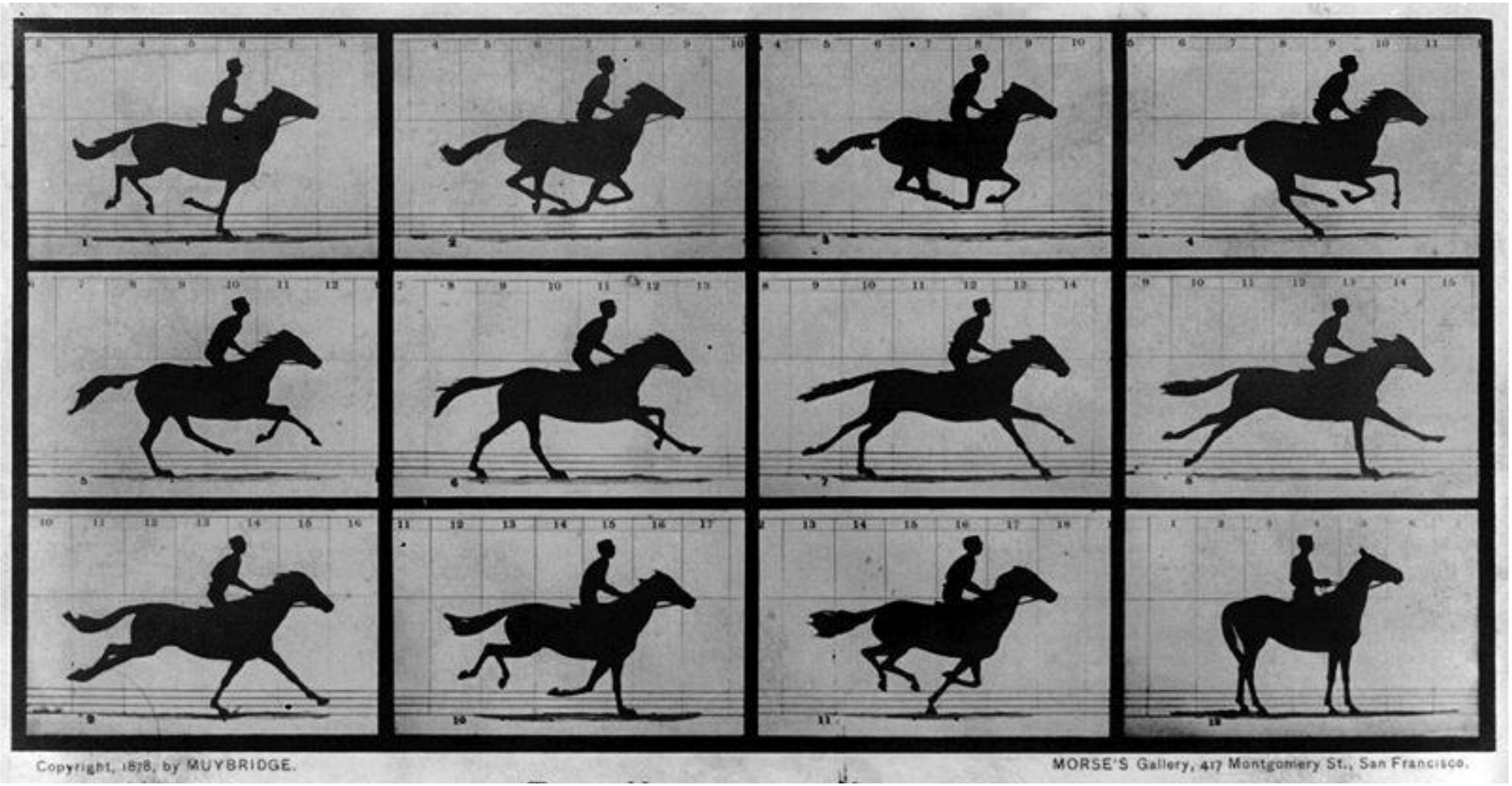
Single molecule diffraction

- low scattering intensity
- random orientation



2(???) − 10 Å

Sallie Gardner galloping



In 1878 Legend Stanford commissioned Eadwear Muybridge to use newly invented photographic technology to establish whether a galloping horse ever has all four feet off the ground simultaneously, which, it was found, they do.

MOTIVATION

Short wavelength (0.1nm): atomic resolution

Short pulses (<20 fs – 2 fs): time-resolved measurements, („pre-damage through radiation“)

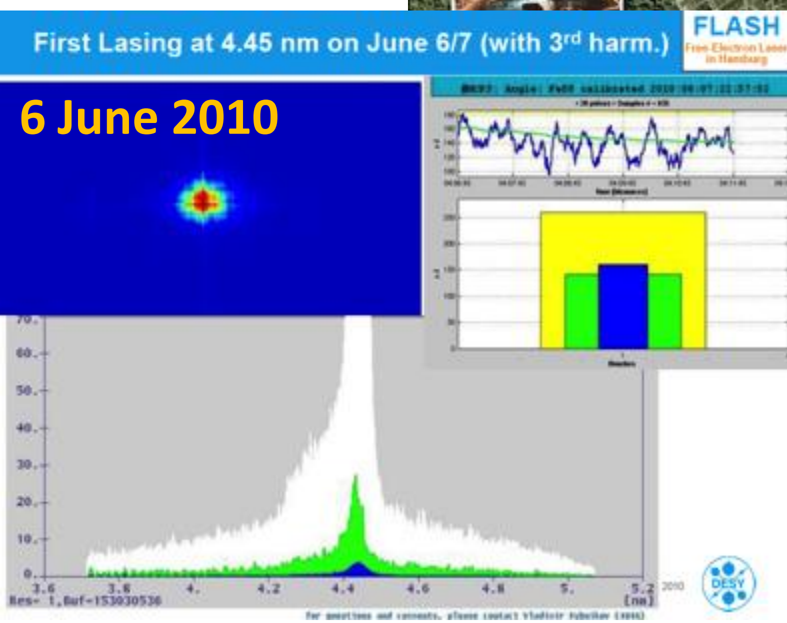
Coherence: lensless imaging

High brilliance: short measurements (single-pulse „shot by shot“)

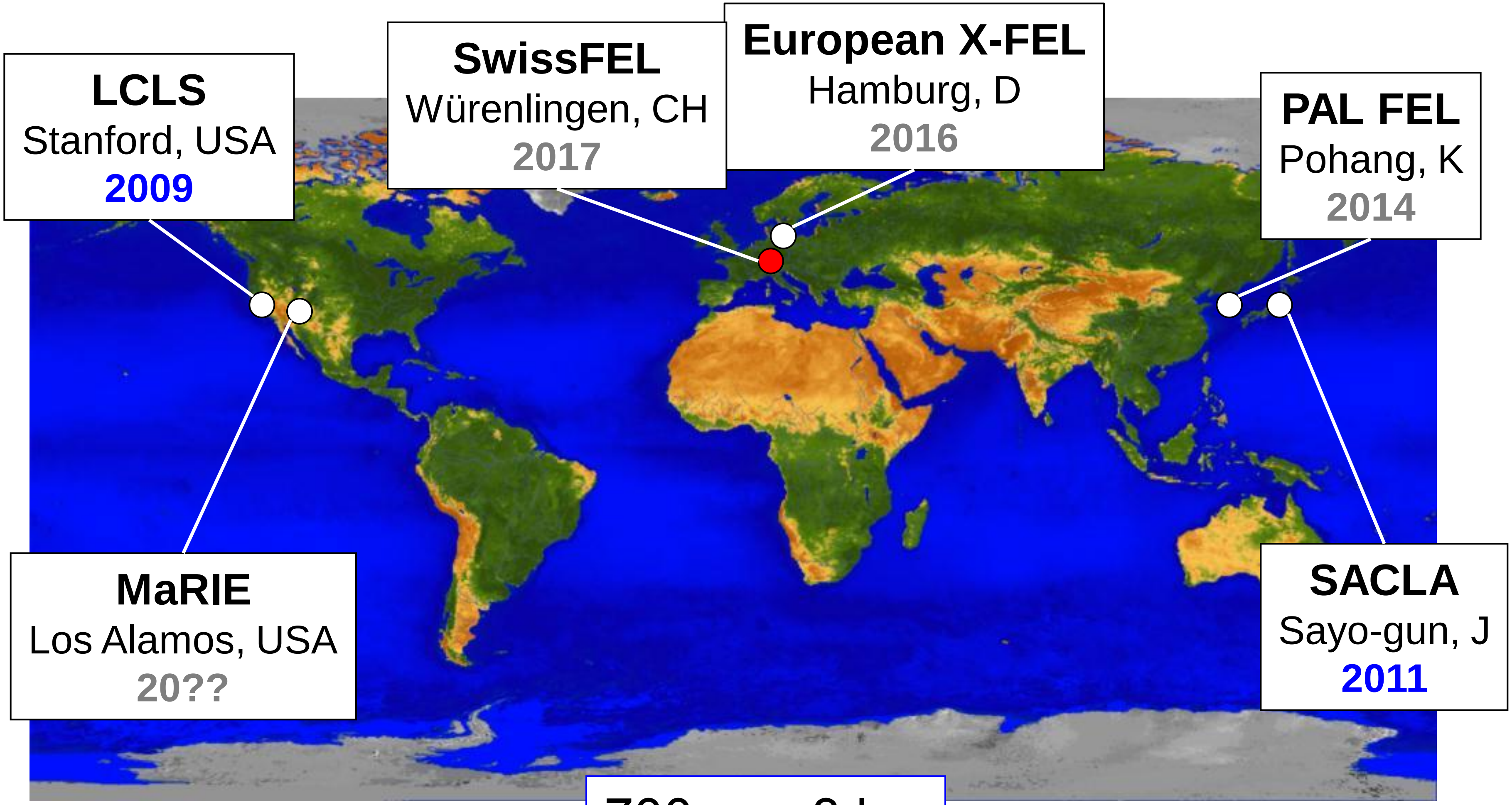
Outline

- Motivation
- Ultrashort X-ray pulses from FEL light sources
- FEL technology
- Science program at X-FEL facilities

The young history of XFELs



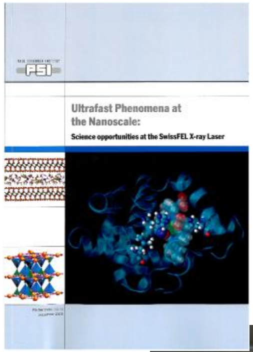
Hard X-ray FELs around the world

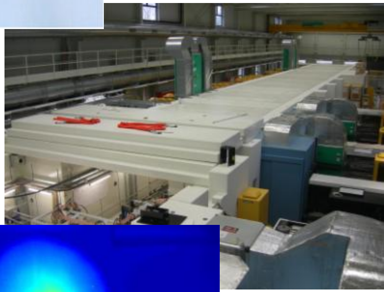


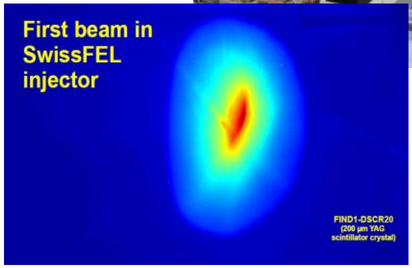
700 m – 3 km
5.8 – 20 GeV
~ 1 Å

Construction site

SwissFEL Milestones





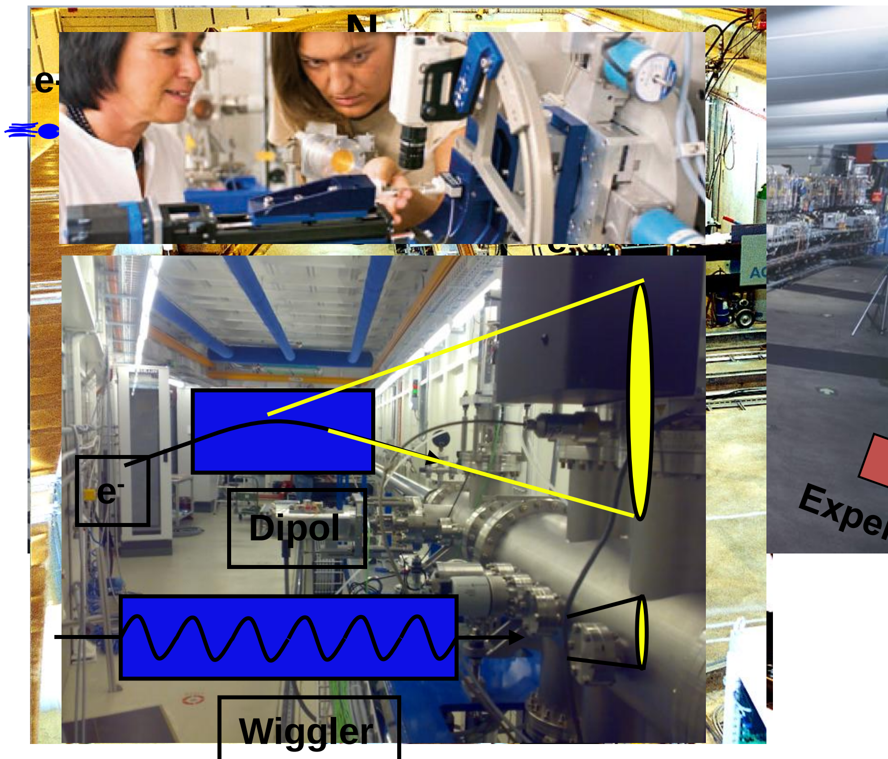


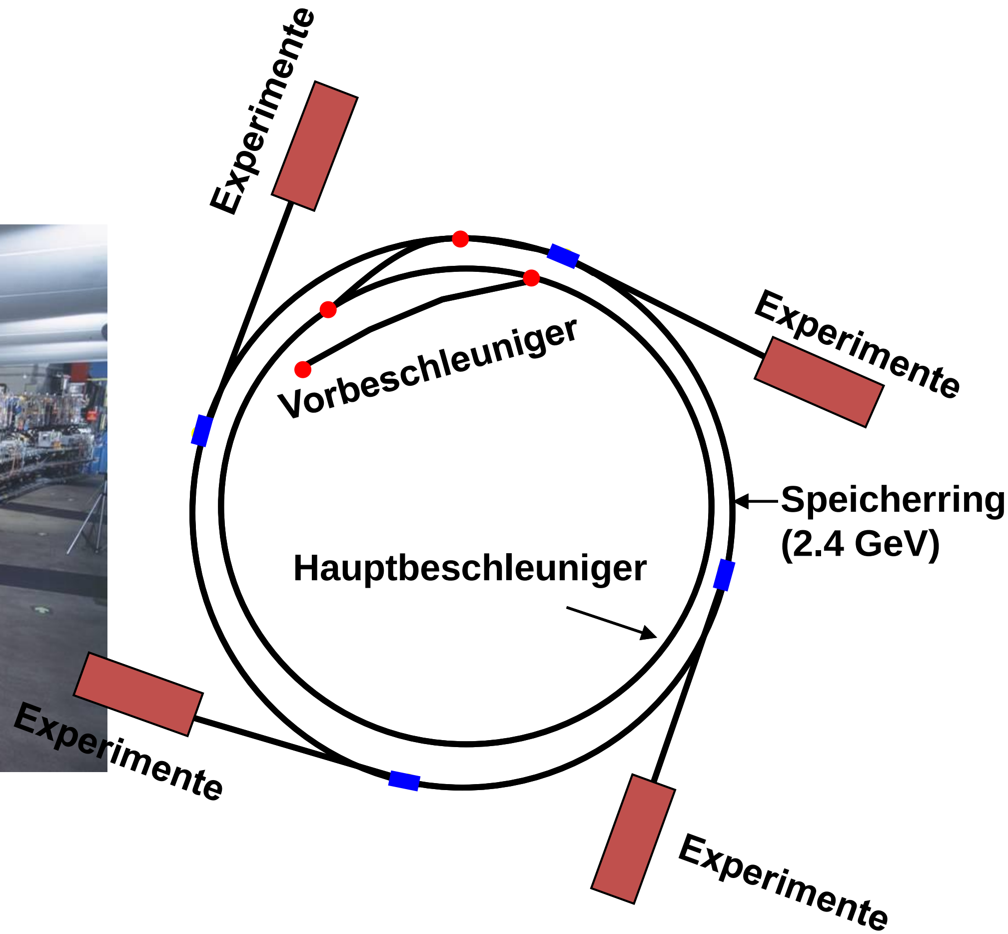
Scientific Case: September 2009
Inauguration 250 MeV inj. August 24th 2010

Parliament decision: 2012
Start of civil construction: 2013
Start of Commissioning July 2016
Aramis operation: July 2017
Athos operation: 2019

http://fel.web.psi.ch

von der Quelle zu den Experimenten

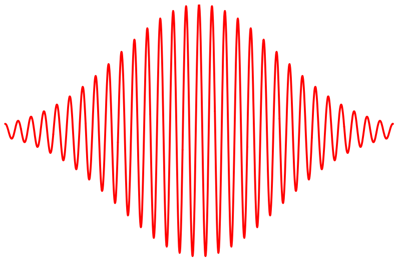




Die Elektronenpakete werden auf die notwendige Energie von ... werden mit nahezu ... Hauptbeschleuniger

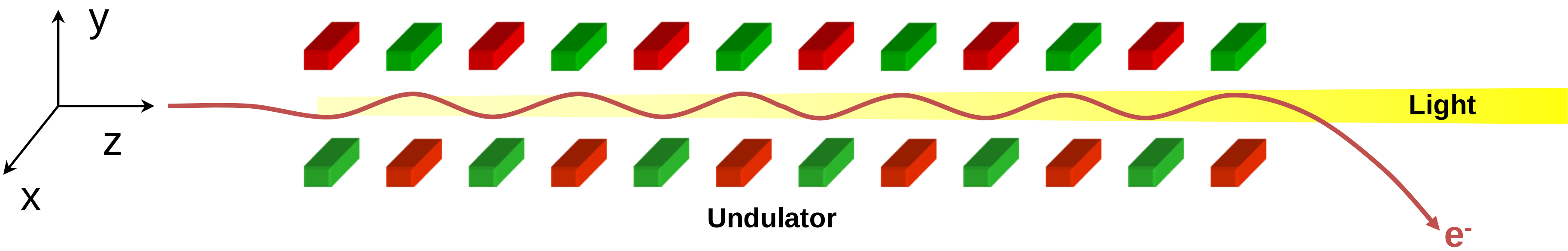
99,999 ...% Lichtgeschwindigkeit

Radiation from Undulator

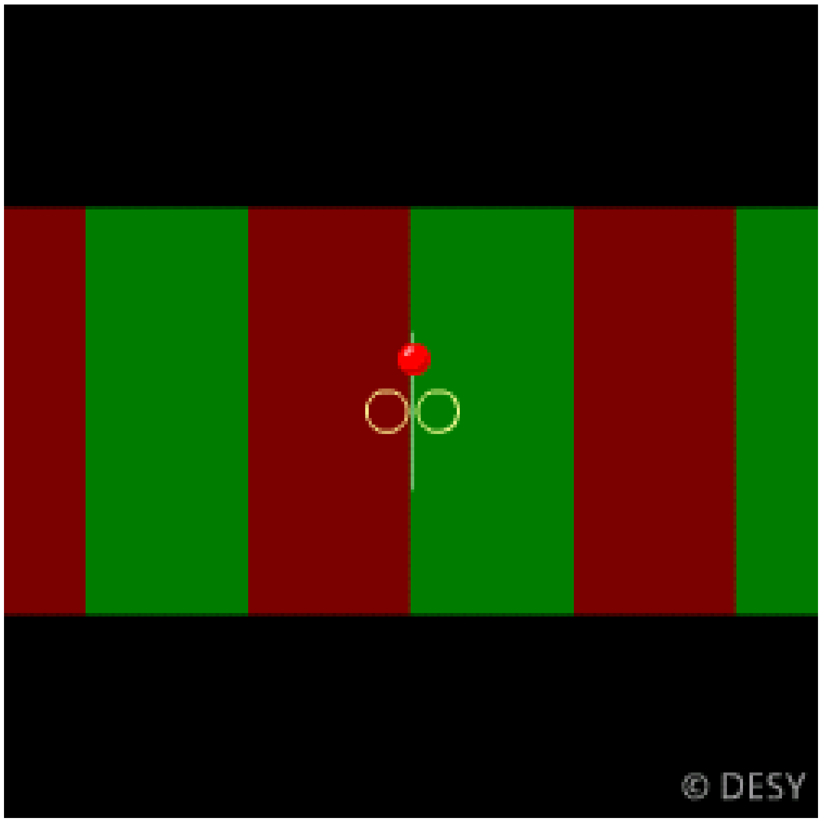


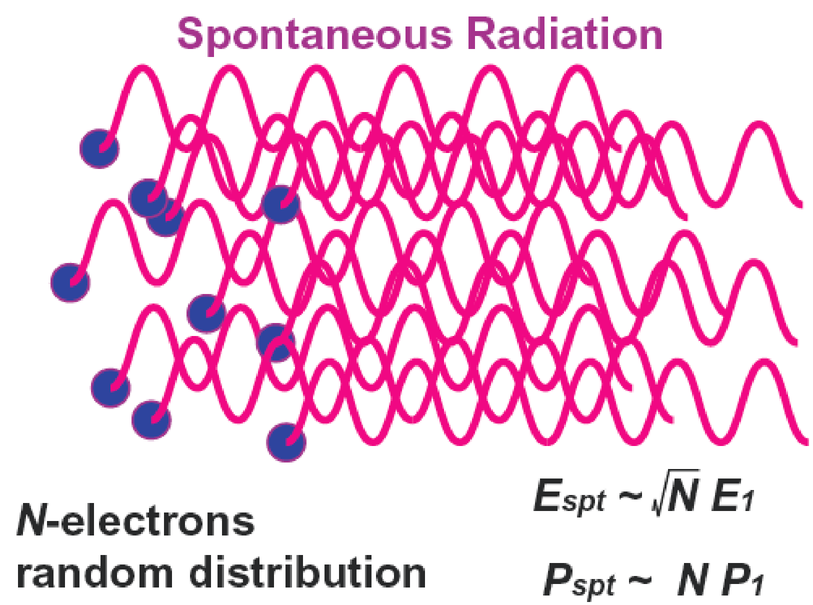
Synchrotron light

„ High res.“ : λ = 0.1 nm
„Slow“ : τ = 100.000 fs



Motion of electrons in Undulator





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Experimente

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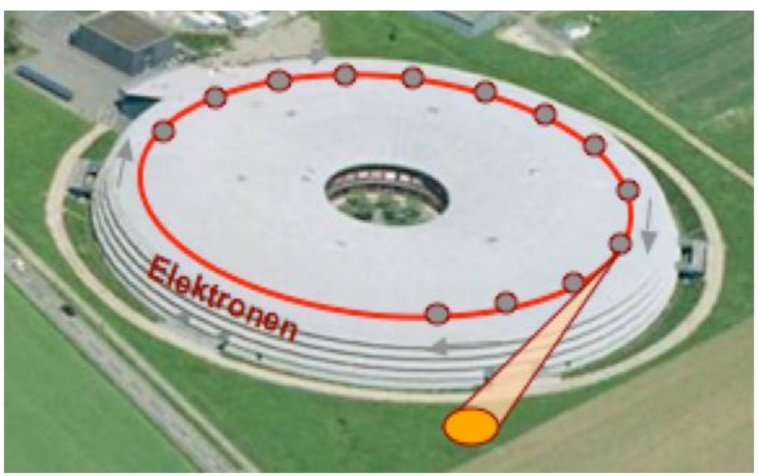
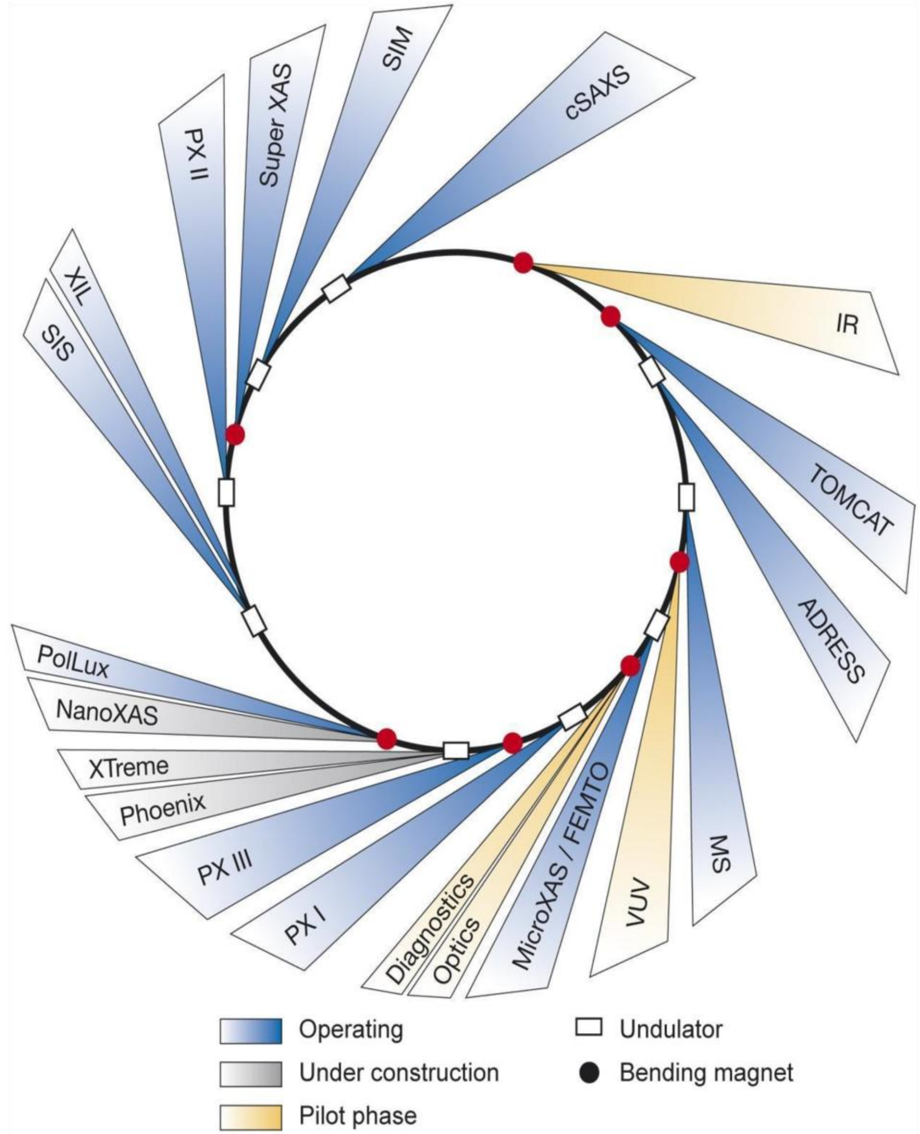
Experimente

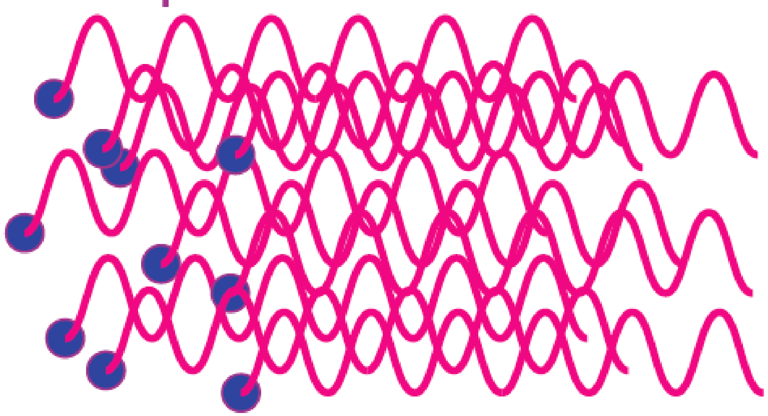
- 16 Experimente
- ca. 280 Tage pro Jahr
- 7 Tage pro Woche
- 24 Stunden pro Tag





Electrons from the same bunch radiate as one!

Spontaneous Radiation

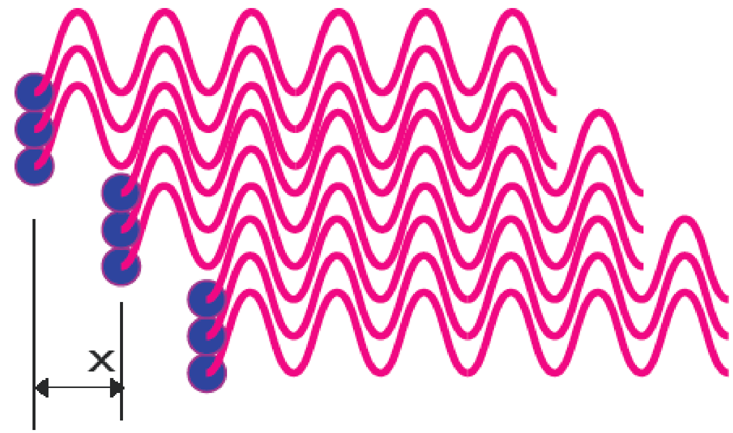


***N*-electrons random distribution**

$E_{spt} \sim \sqrt{N}\, E_1$

$P_{spt} \sim N\, P_1$

Coherent Radiation



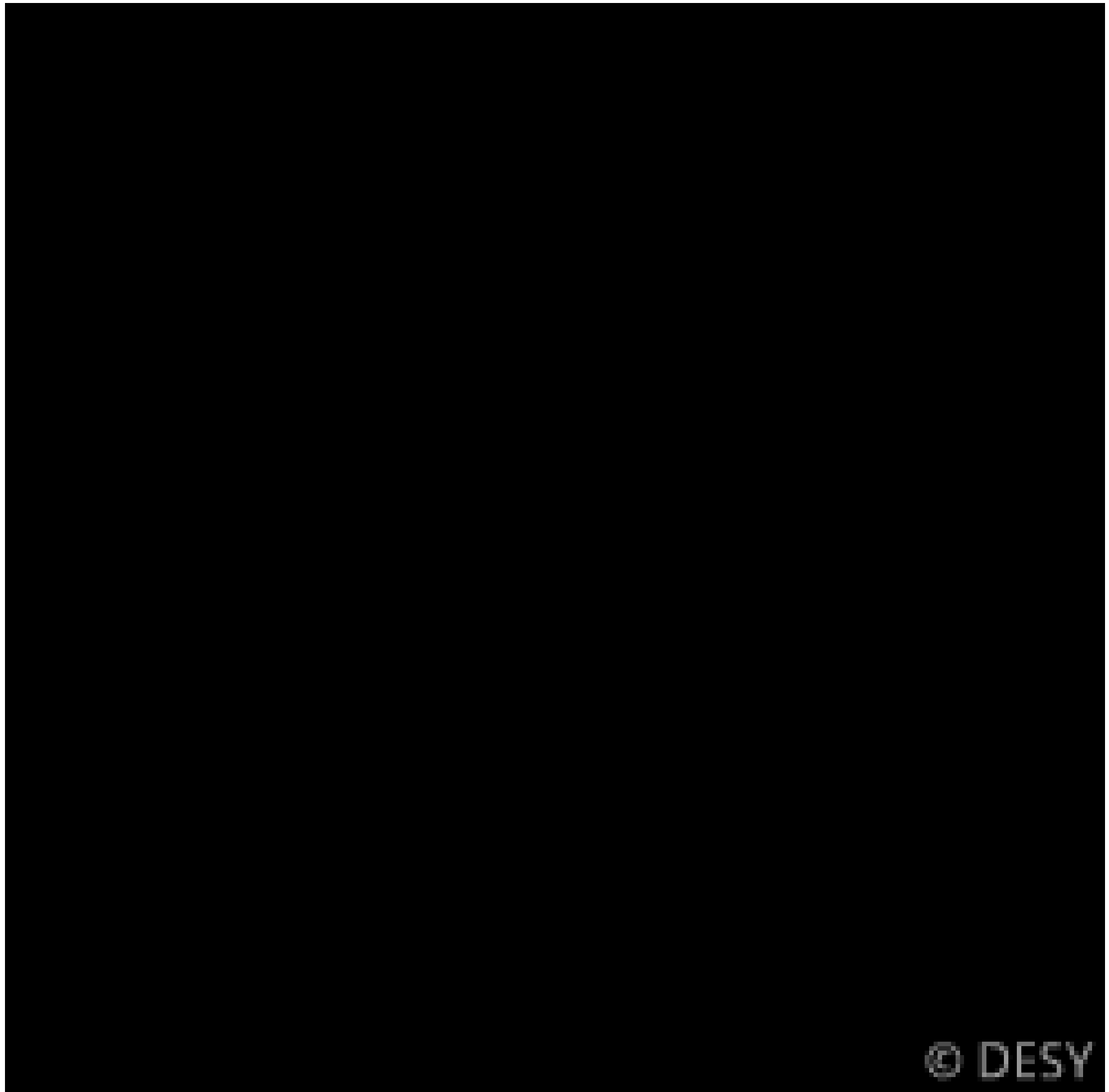
***N*-electrons micro-bunched**

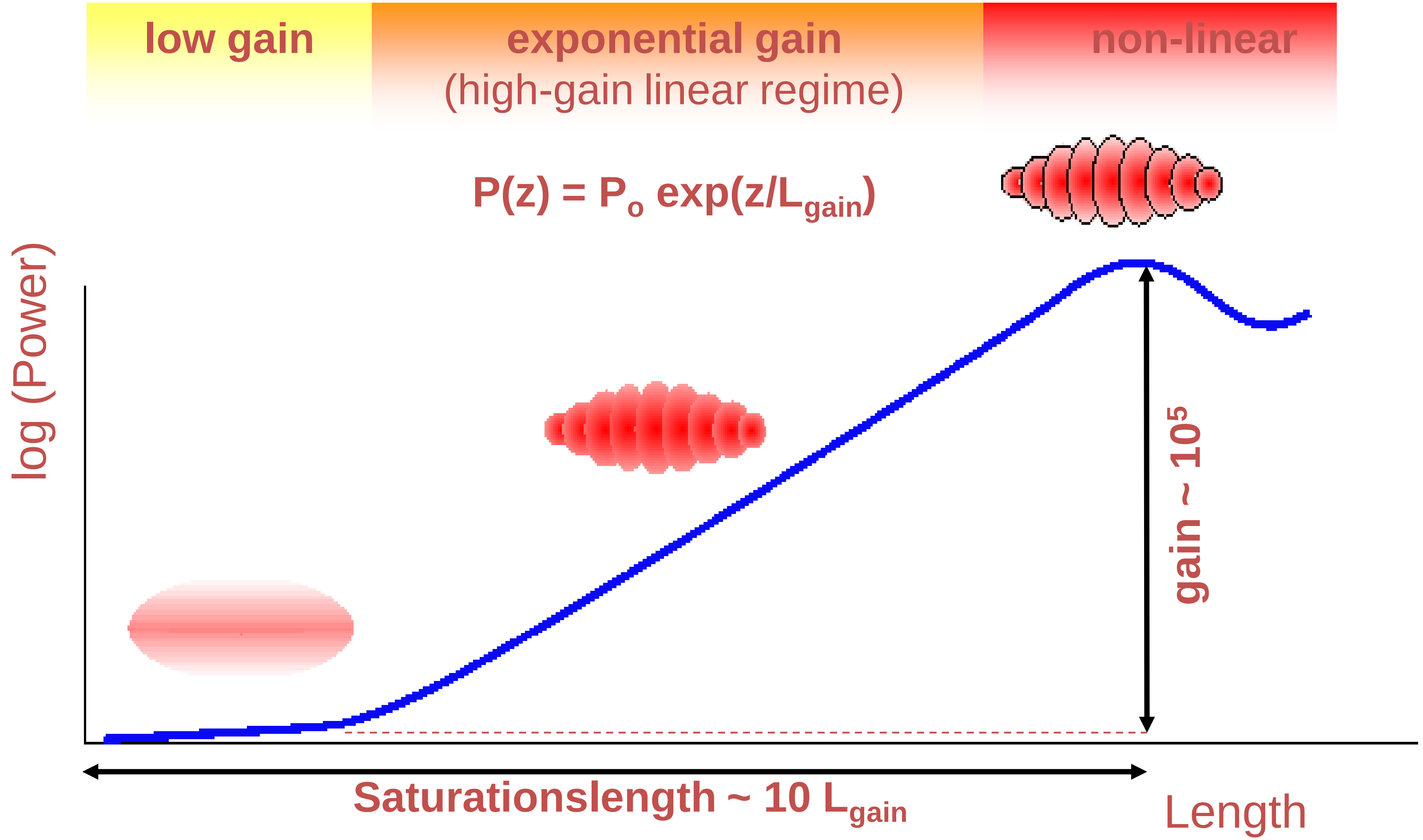
$E_{coherent} \sim N\, E_1$

$P_{coherent} \sim N^2 P_1$

The radiation is stronger by a factor N ***(10^8 – 10^9)***

Micro-bunching





Process: „self-amplified spontaneous emission“ (SASE).

What do you win?

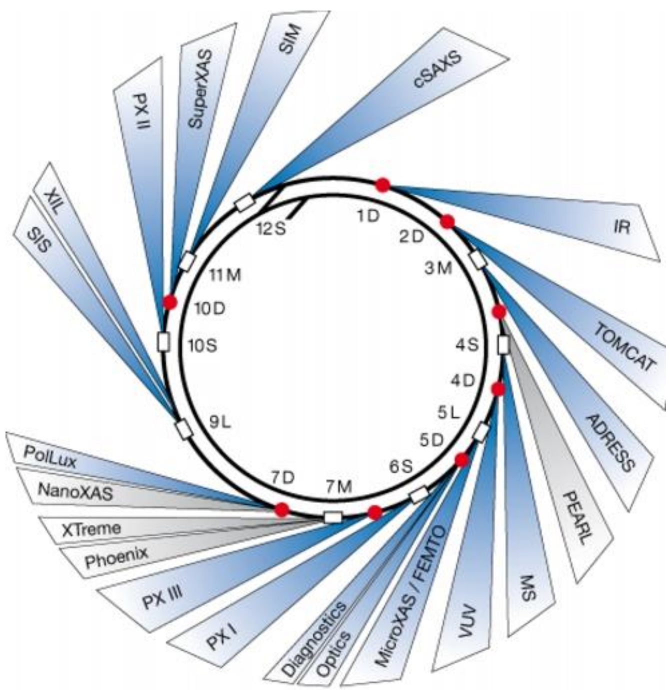
- High peak brightness (10^{22} ->10^{32} ph.mm^{-2}.mrad^{-2}.s^{-1}/0.1% BW)
- Higher electron bunch density (200pC)
- Short bunch pulse (0.1 ns -> 2-20 fs)
- High effective saturation power (2 GW)

The price:

- Long undulators: (4 -> 60 -120 m)
- Storage ring -> Linear accelerator
- Low rep. rate (500 MHz -> 100 Hz)

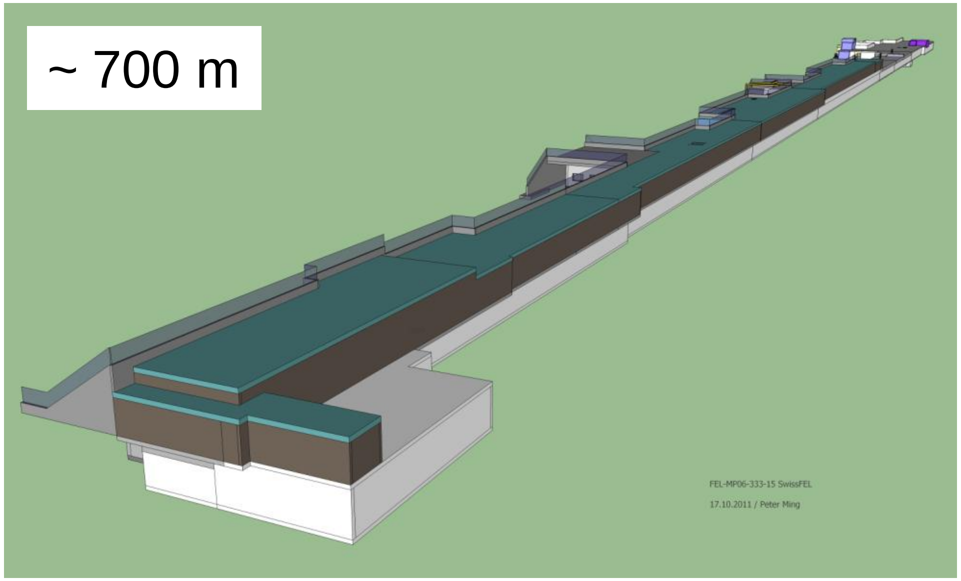
Synchrotron ↔ XFEL

Syncrotron (SLS)



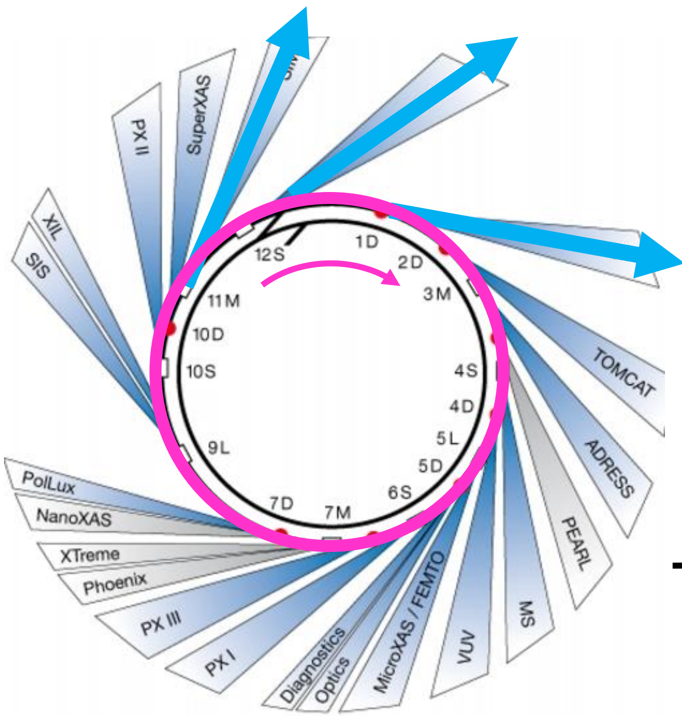
~ 150 m

(Swiss)**FEL**

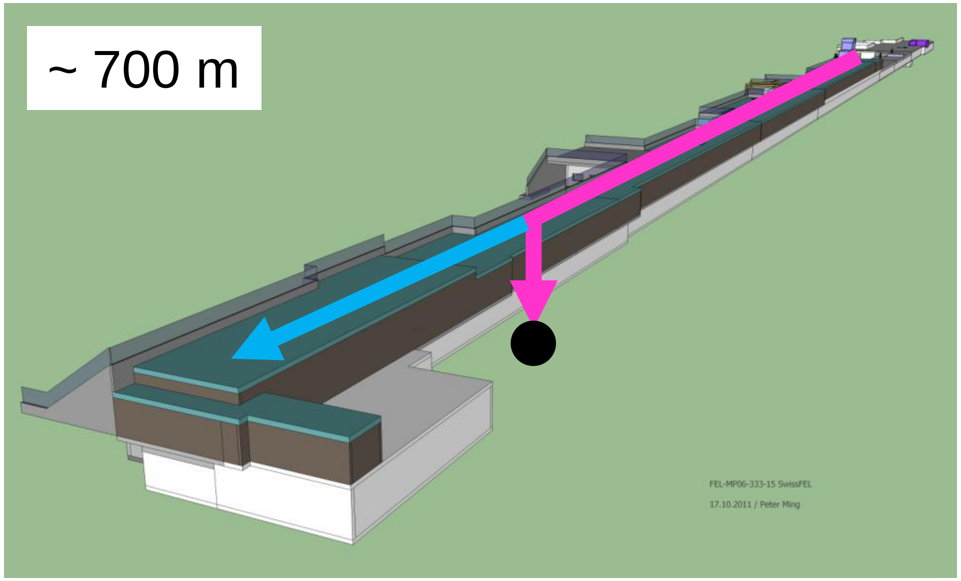


Synchrotron ↔ XFEL

Syncrotron (SLS) (Swiss)**FEL**



~ 150 m



x 10^{10} peak brilliance

„Bausteine“ eines FELs

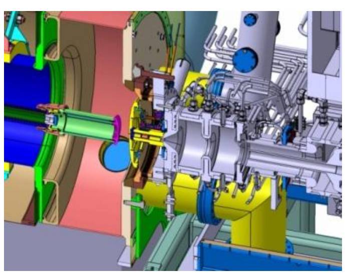
Erzeugung vom Elektronen

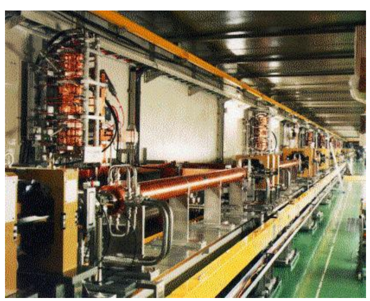
Beschleunigung

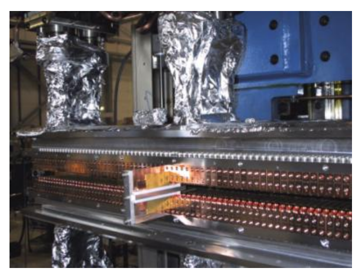
Erzeugung des Röntgenlichtes

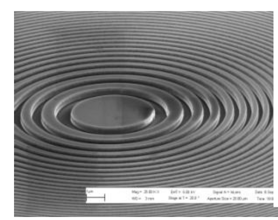
Transport und Fokussierung

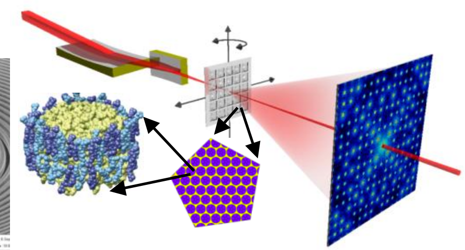
Elektronen-quelle → Linear Beschleuniger → Undulator / Undulator / Undulator → Experimente / Experimente / Experimente











Synchrotron vs. X-FEL

Airbus

Saab Gripen

Outline

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- Ultrashort X-ray pulses from FEL light sources
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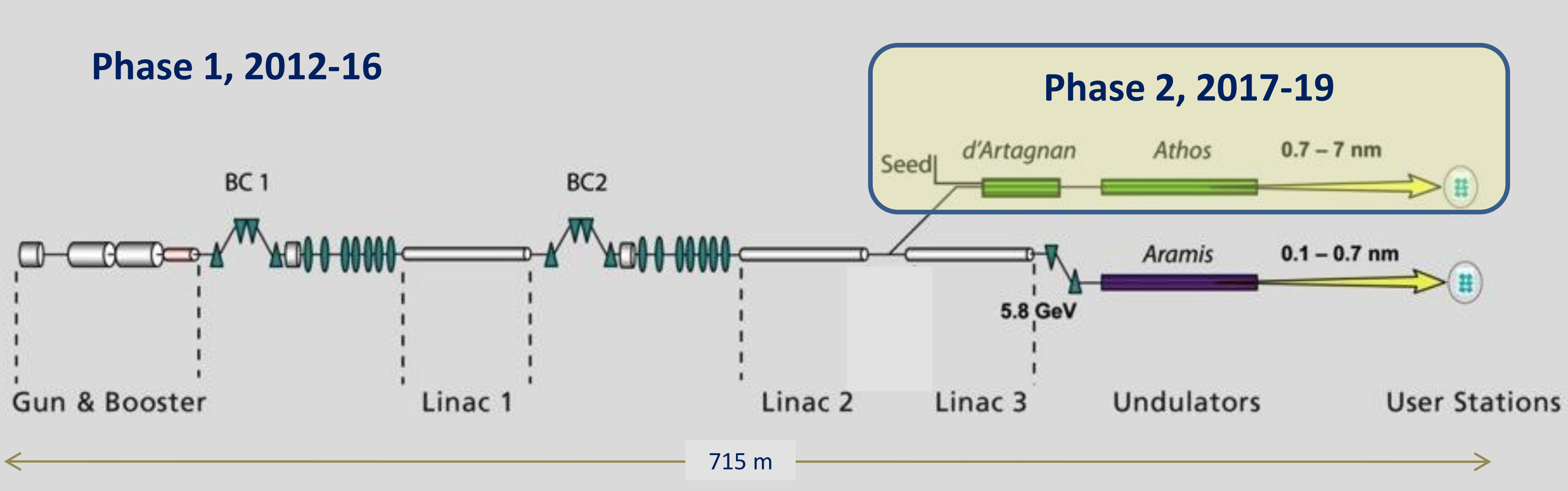
SwissFEL

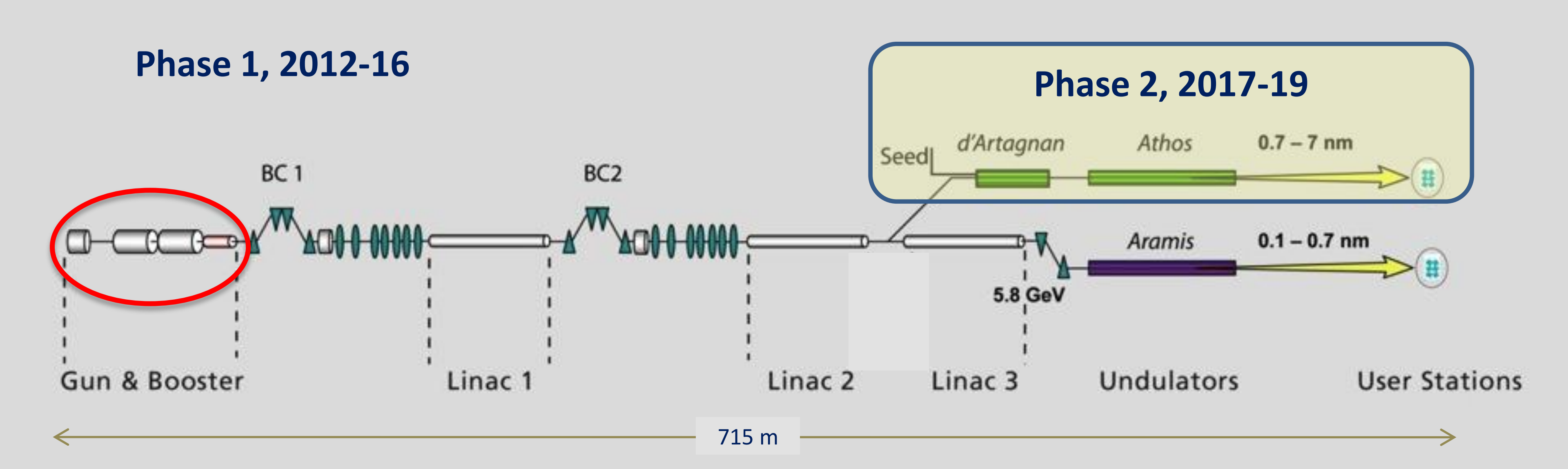


Aramis: 1-7 Å hard X-ray SASE FEL,
In-vacuum , planar undulators with variable gap.
User operation from mid 2017

Athos : (2nd phase) 7-70 Å soft X-ray FEL for SASE & Seeded operation .
APPLE II undulators with variable gap and full polarization control.
User operation end 2019?

SwissFEL parameters	
Wavelength from	1 Å - 70 Å
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

SwissFEL



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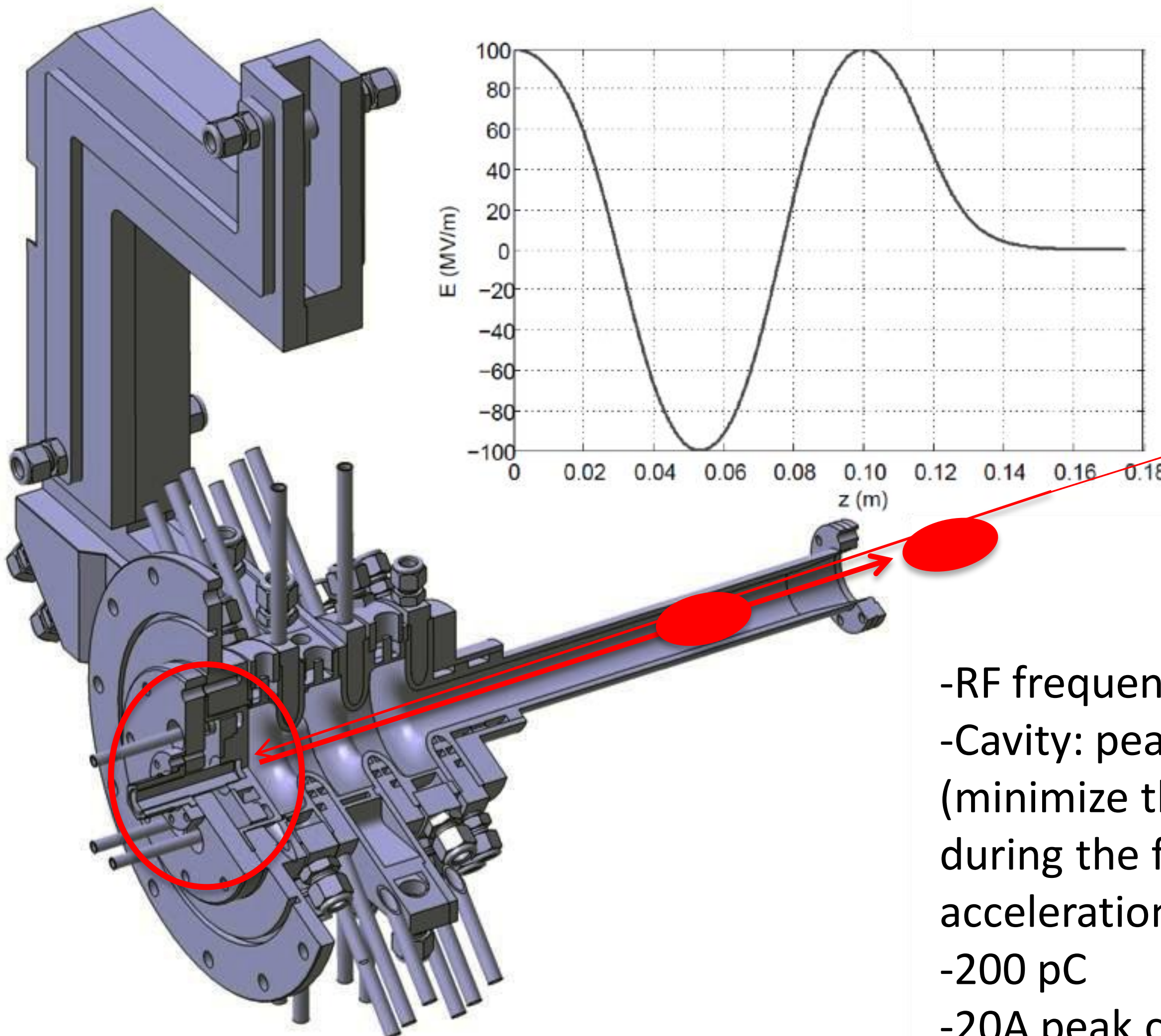
Electron gun (Photo Cathode)



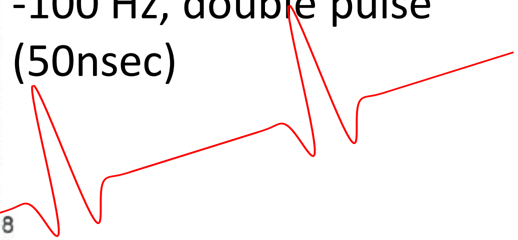
Laser

-Ti:Sa Laser

-3th 282 nm(BBO crystal)

-100µJ,

-100 Hz, double pulse (50nsec)



-RF frequency of 2998.8 MHz.

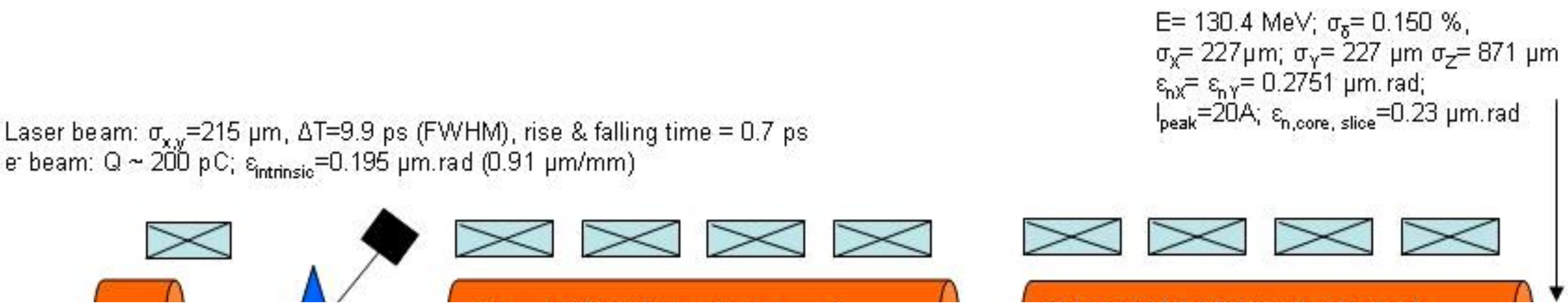
-Cavity: peak accel. 100 MV/m (minimize the effects of space charge during the first centimetres of acceleration)

-200 pC

-20A peak curent

-> low emittance.

Gun and Booster 1

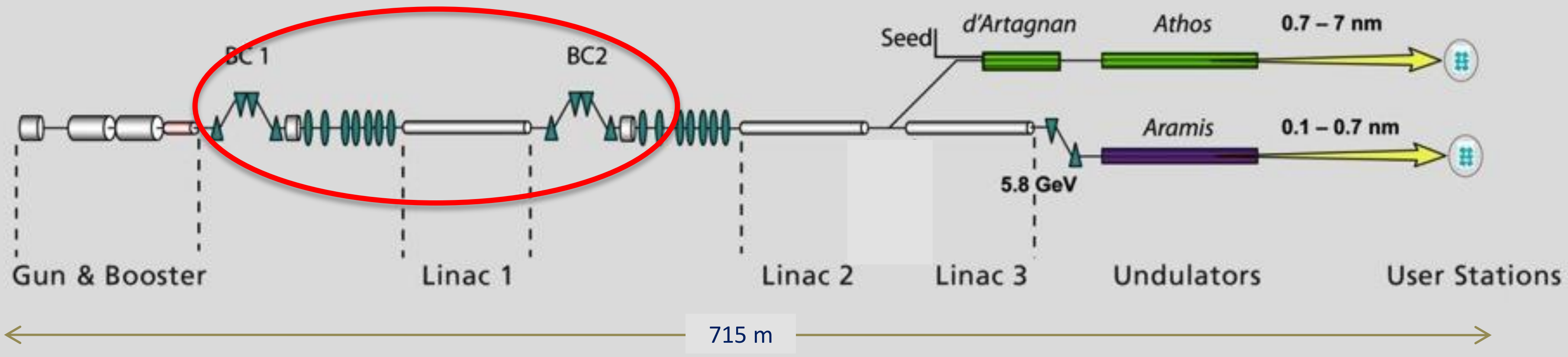


Gun and Booster 1 main parameters

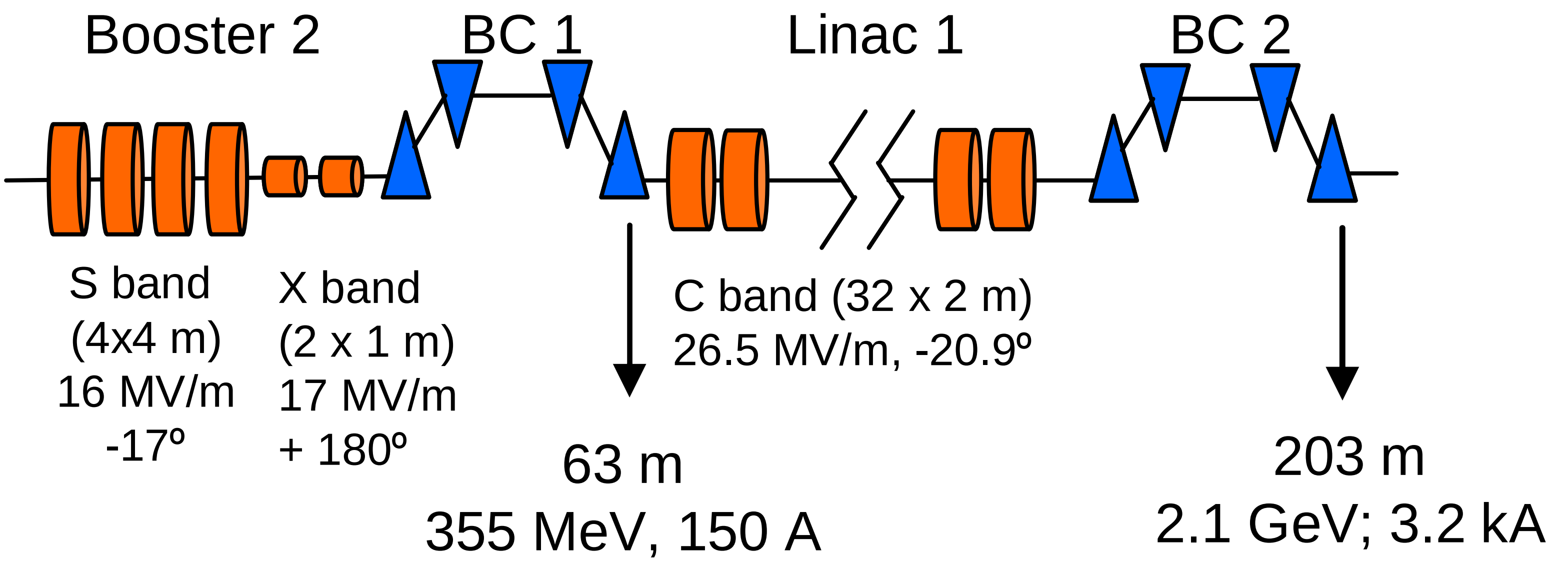
Bunch charge	**200 pC**	**10 pC**
Gun gradient	100 MV/m	100 MV/m
Beam peak current	20 A	3 A
Laser transverse size (rms)	215 µm	101 µm
Laser longitudinal length (Full Width)	9.9 ps	3.7 ps
Intrinsic (Thermal) emittance	0.195 µm	0.092 µm
Projected normalized emittance at 130 MeV	0.276 µm (0.275 µm)	0.089 µm
Slice normalized emittance at 130 MeV	0.250 µm (0.230 µm)	0.070 µm
Energy	129.36 MeV (130.4 MeV)	130.5 MeV
Relative energy spread	0.155%(0.162%)	0.02%
Bunch length at 13 m (FWHM)	9.87 ps (10.8 ps)	3.68 ps

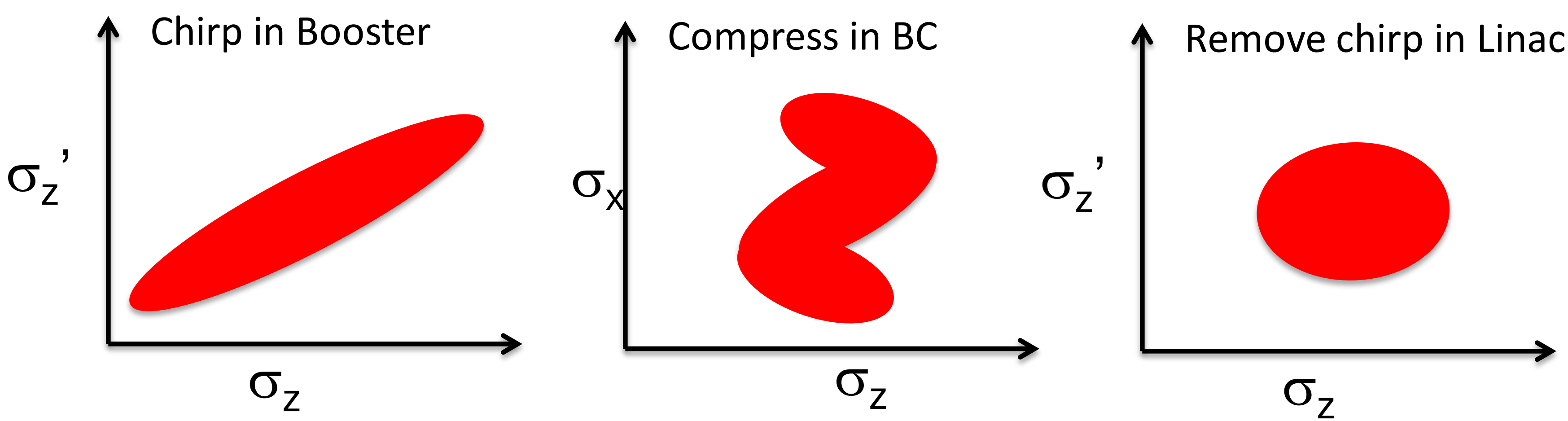
psec to fsec

Phase 1, 2012-16



Bunch compression





Bunch compression

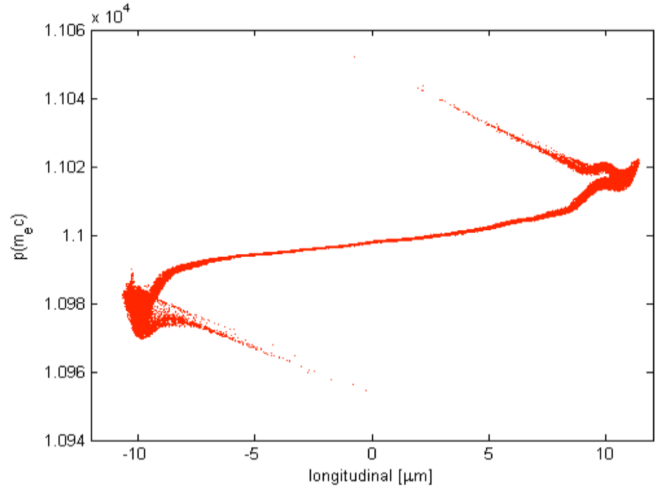
200 pC

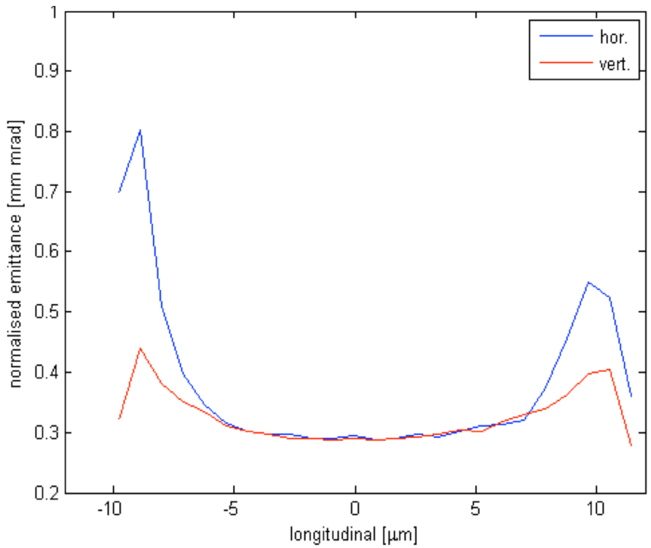
σ_z = 838 µm, rms
(or 2.8 ps, rms)

BC1
σ_z = 124 µm
(413 fs)

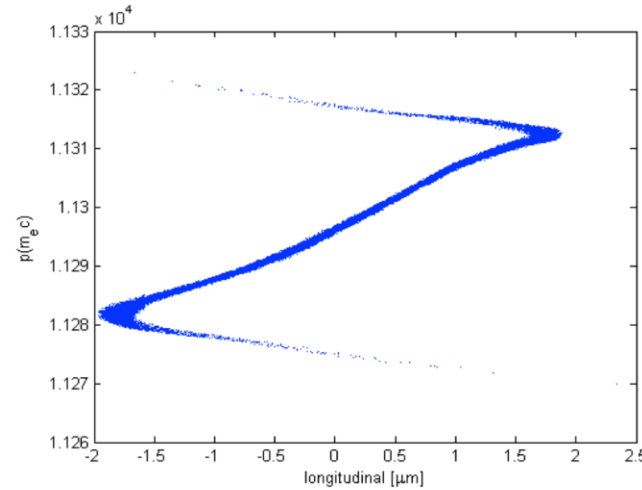
BC2
σ_z = 6 µm
(20 fs rms)

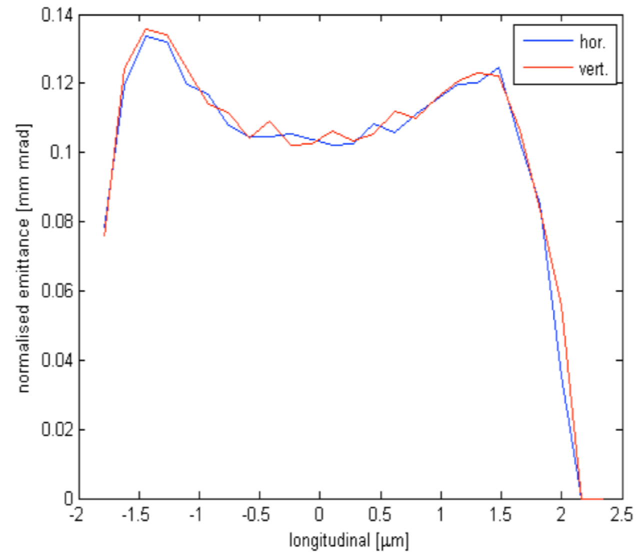
200 pC





10 pC





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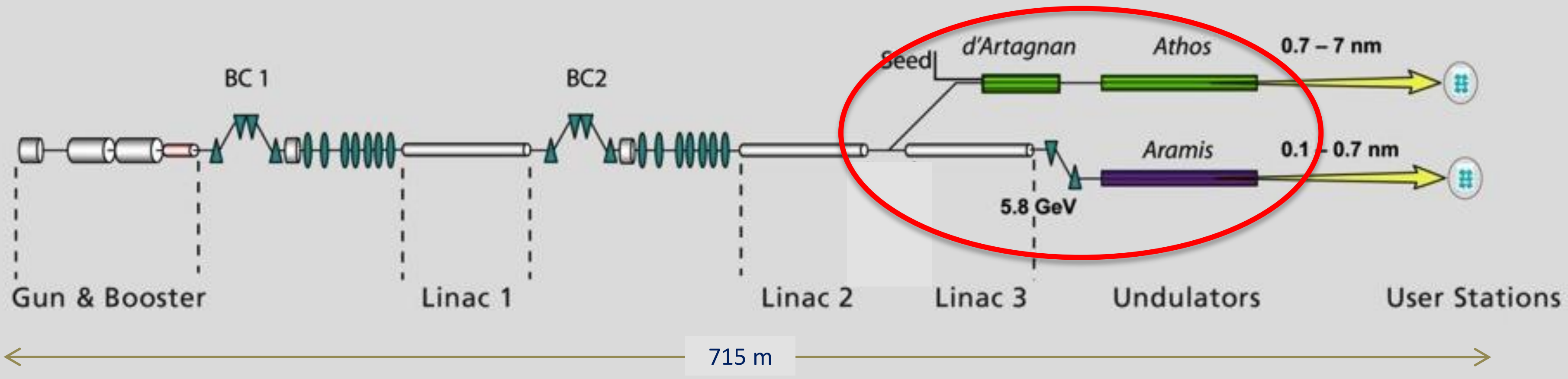
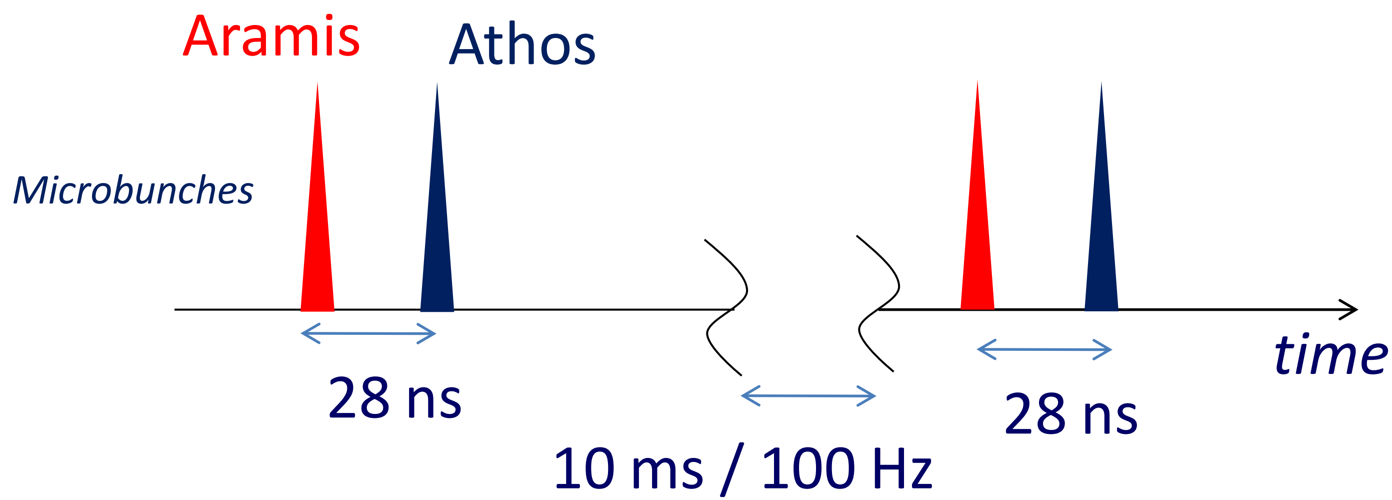
Operation mode	**200 pC Normal**	**10 pC Normal**	**200 pC (BW)**	**10 pc (as)**
	BC 1			
Beam energy	355 MeV			
Bunch length, rms σ_z	124.2 µm		124.2 µm	
Compression factor	6.75		6.75	
	BC 2			
Beam energy	2040 MeV			
Bunch length, rms σ_z	6.2 µm (20 fs rms)	1 µm (3 fs rms)	6.2 µm (20 fs rms)	0. 2 µm (600 as rms)
Compression factor	20.1		24.6	

Phase 1, 2012-16



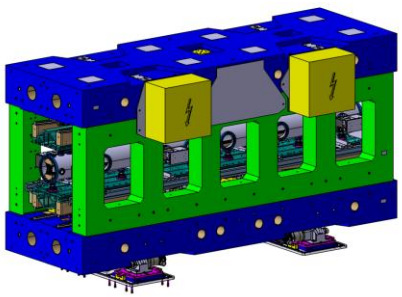
Time structure



- Fast extraction at 3.4 GeV allows to serve 2 undulator lines simultaneously at full repetition rate

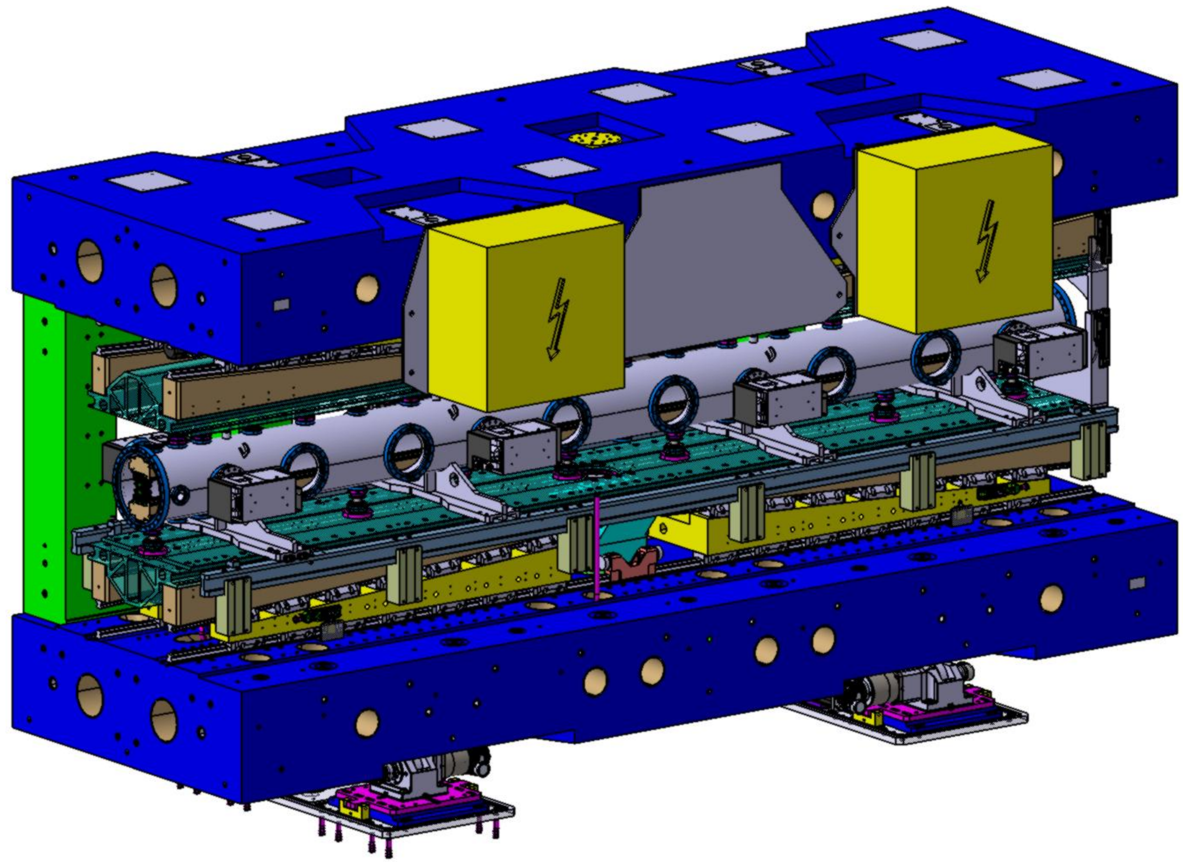
This time structure is well adapted to typical readout times of large array photon detectors for scattering experiments

SwissFEL Undulators: Aramis Hard X Ray Beamline

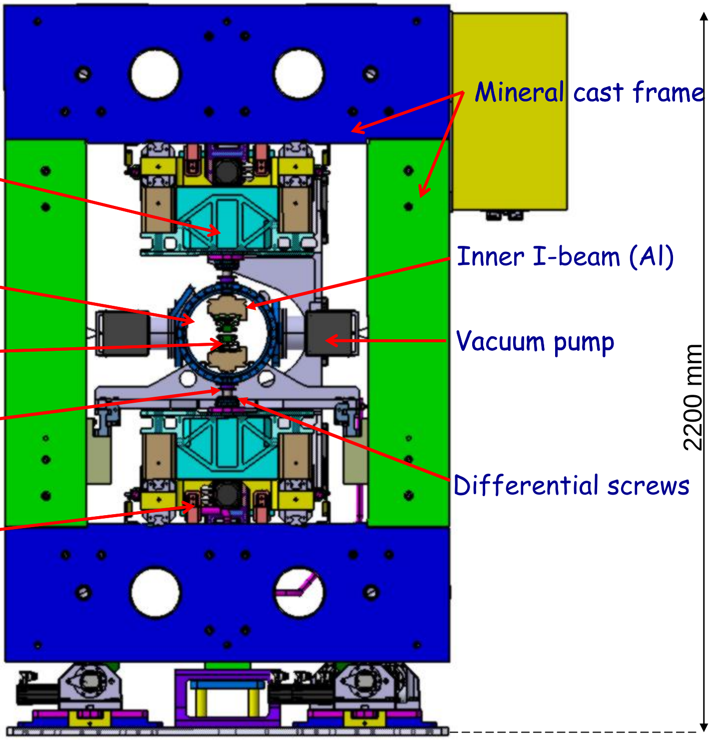


Symmetric Support Structure: Stability & Cost effective
Mineral Cast: Mechanical Rigidity
Gap Adjustment with Wedge system: Precision (0.3 µm)

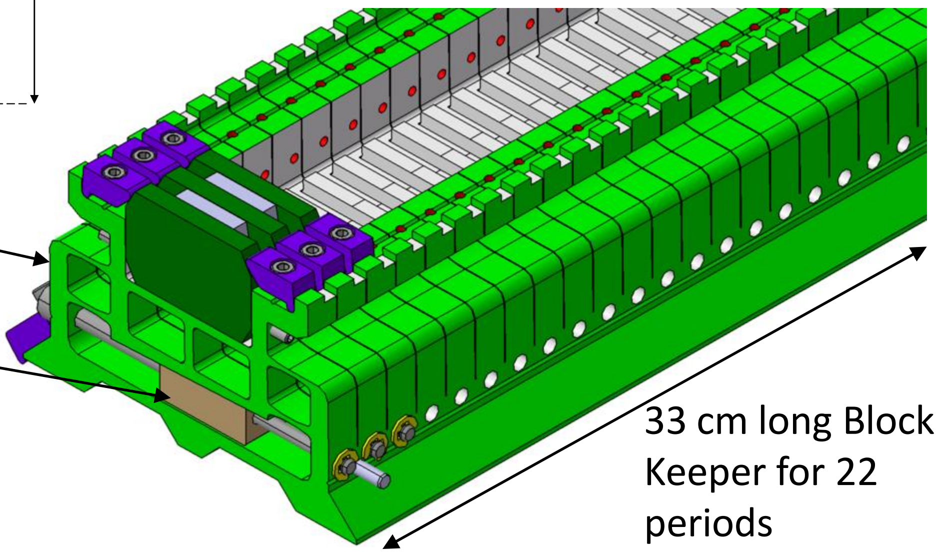
Undulator Type	Hybrid – In Vacuum
Undulator Magnetic Length	3990 mm
Number of Undulators	12
Undulator Period	15 mm
Nominal K value	1.2
Nominal gap	4.7 mm
Magnetic material	NdFeB-Dy
Pole Material	CoFeVa



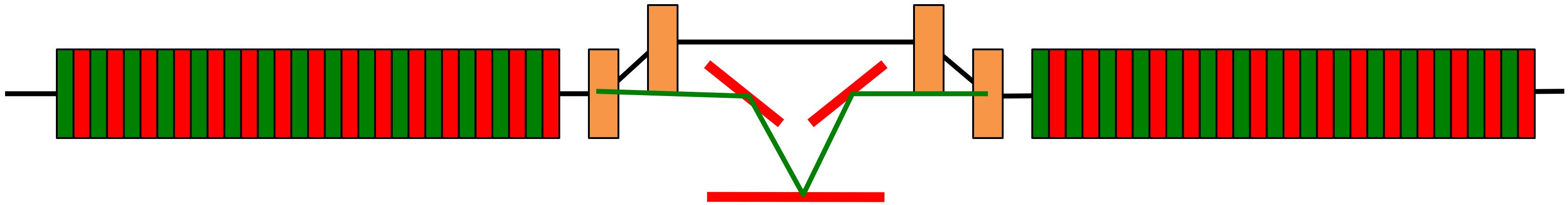
SwissFEL Aramis Undulators (Hard X Ray): Precisions



Residual Field Integral / segment:	40 µT.m
Phase Shake / segment:	2.5 º/λ_r
Good Field region (W×h):	2 mm × 0.06 mm
ΔK/K over 1 segment:	10^{-4}
Straightness Inner I-beam:	10 µm over 4 m



Self-Seeding (tested and available @ LCLS)

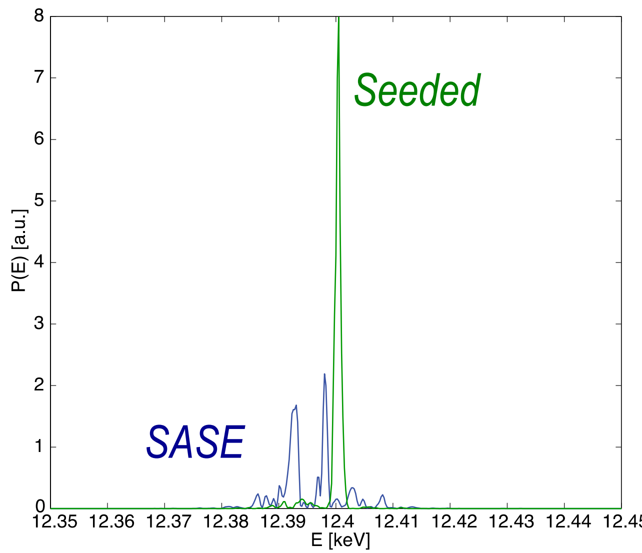


•Seed derived from SASE FEL and monochromatic device.
•No intrinsic problem with wavelength and robustness of SASE FEL.

•Both for hard and soft X-ray wavelength very compact designs for the intersection exists.
•Also, the FEL can easily fall back on SASE operation due to sufficient length of combined stages.

Required length about 1.5 the saturation length of SASE FEL

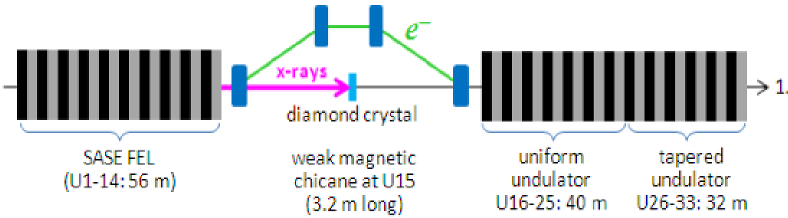
Bunching removed but not energy modulation and spread
→Profile distortion in second stage

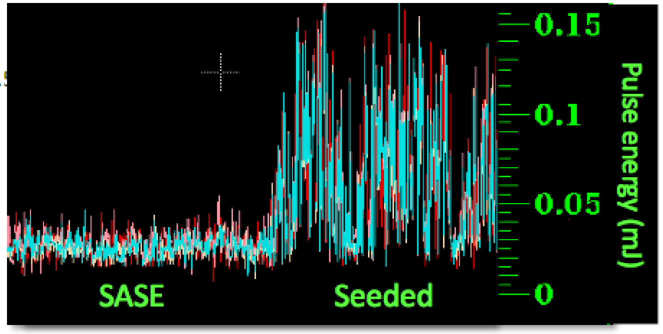


Limitation on wavelength given by availability of monochromators

First Demonstration of Hard X-ray Self Seeding at LCLS

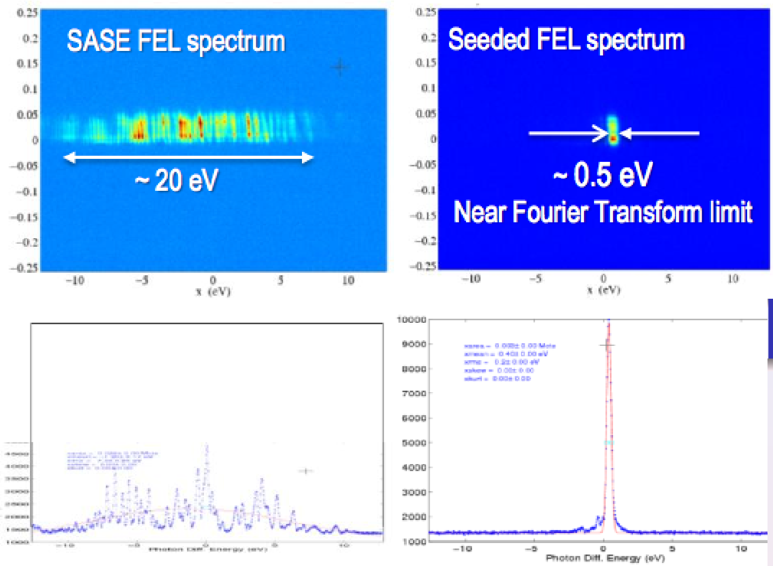
Courtesy Paul Emma / LBL





Single shot pulse energy from the gas detectors with 40pC charge

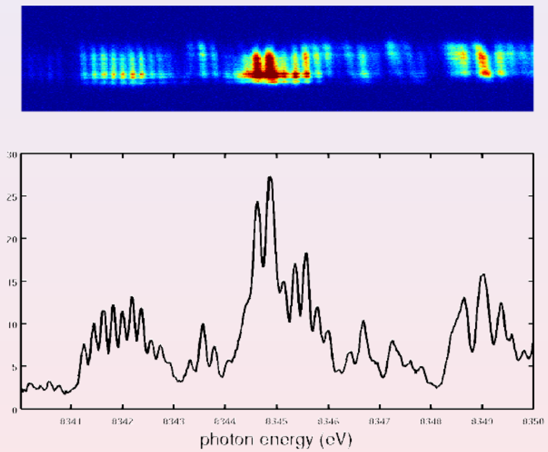
- Concept developed by Geloni, Kocharyan and Saldin, DESY 10-053 (2010).
- The mean seeded FEL power is 8 GW with a



SASE and Seeded spectra recorded on single shots. The left panels are SASE with 150 pC, 3kA peak current, un-seeded. The FWHM of the SASE spectrum is 0.2 % Bandwidth. The right panels are the seeded beam with the same electron beam parameters. The FWHM of the seeded beam is 0.5 eV ($5x10^{-5}$ bandwidth)

SLAC-Argonne-

Single shot spectrometer: Si(333) resolution



Resolution 0.13 eV, should be single spike !

Possible uses: pulse duration measurement, single shot absorption, correcting for machine energy jitter

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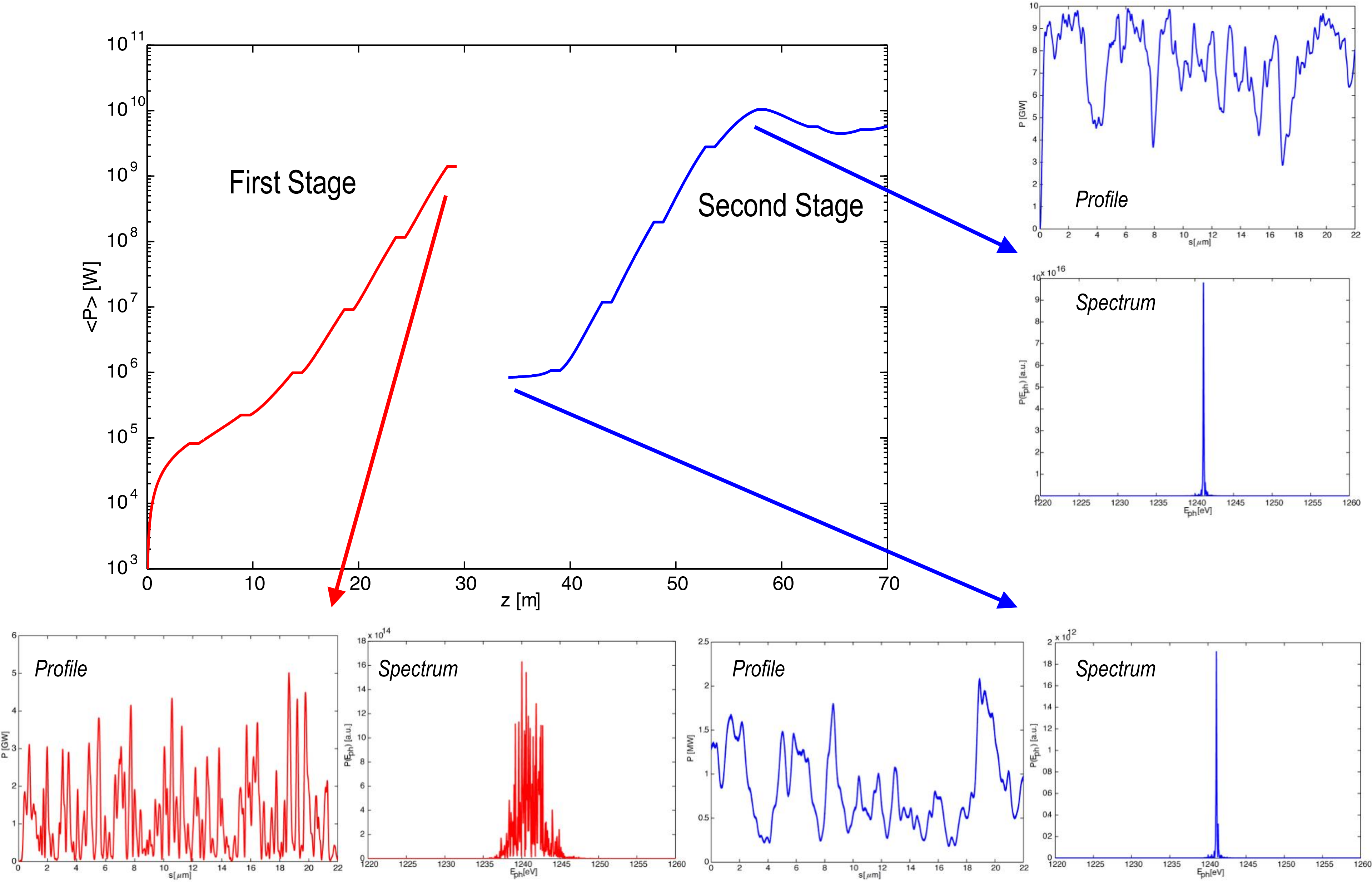
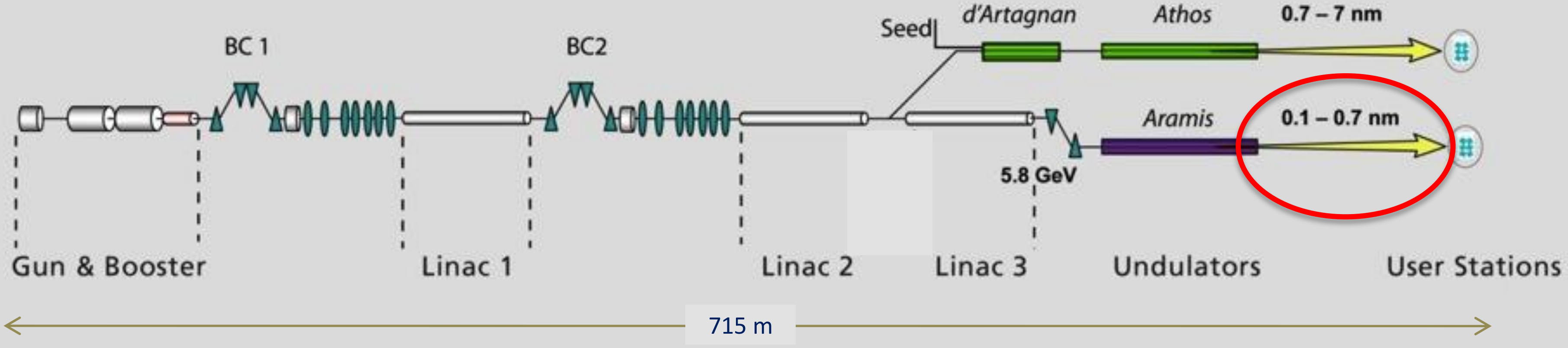
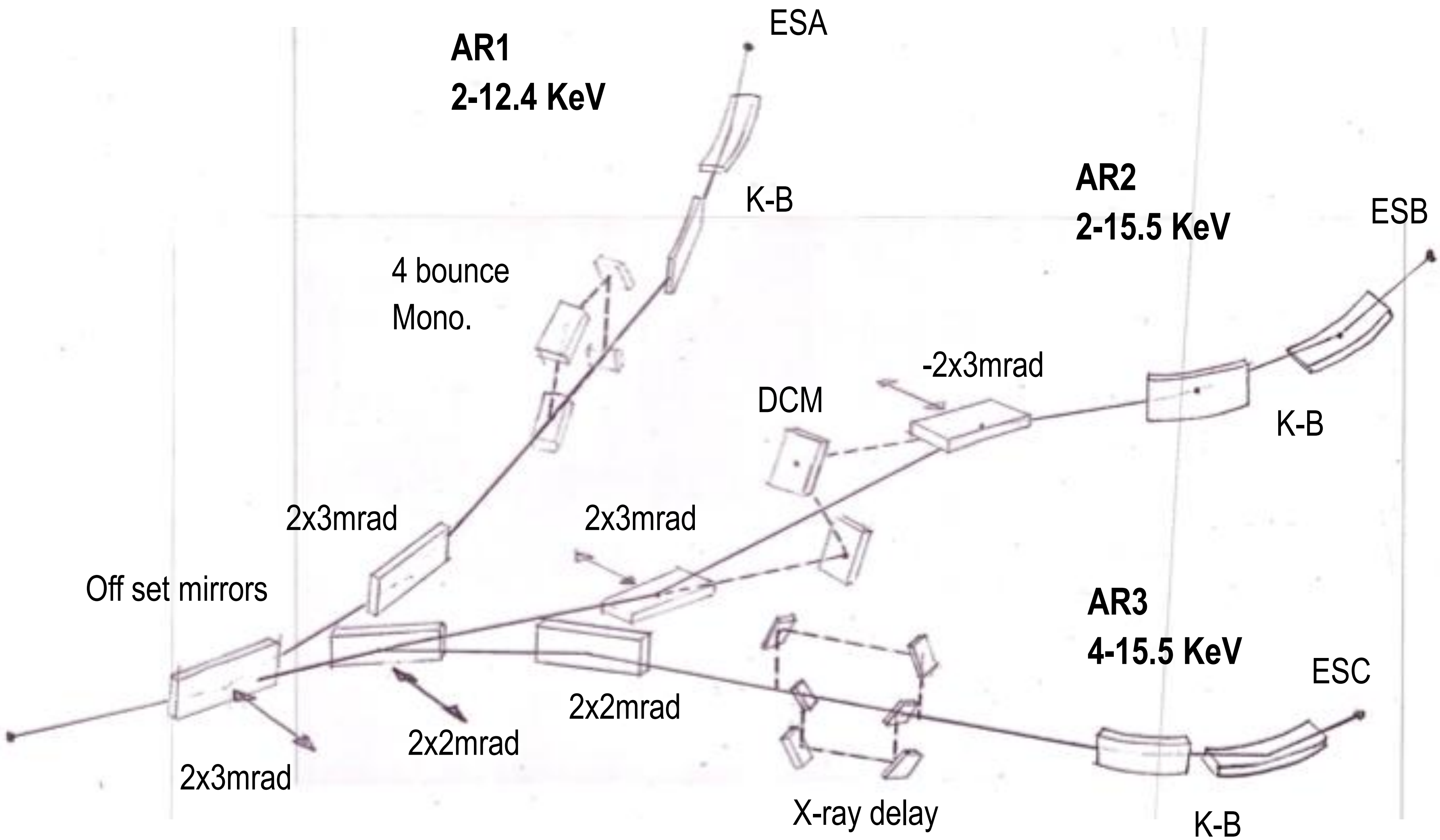
Performance at 1 nm



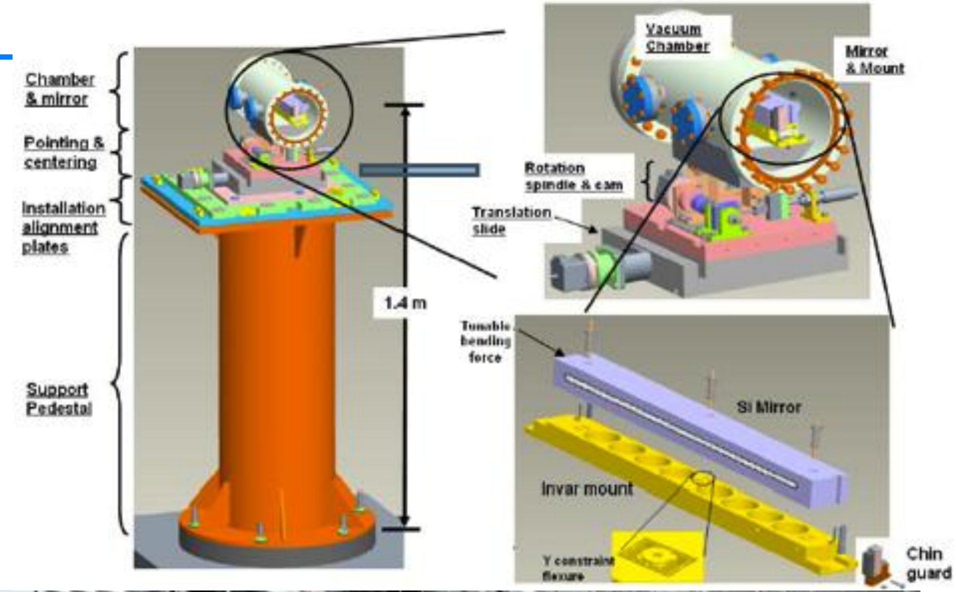
Phase 1, 2012-16



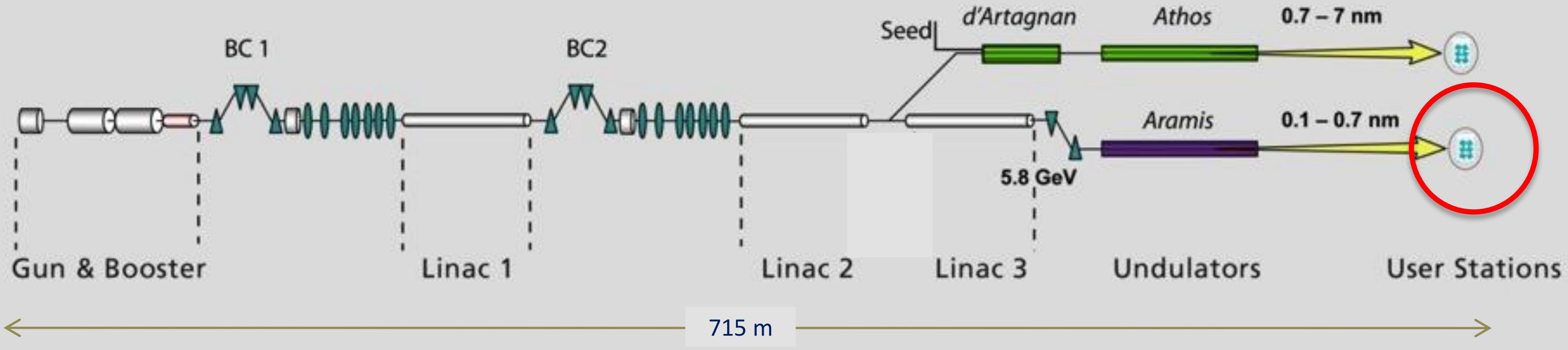
Aramis Optical Layout



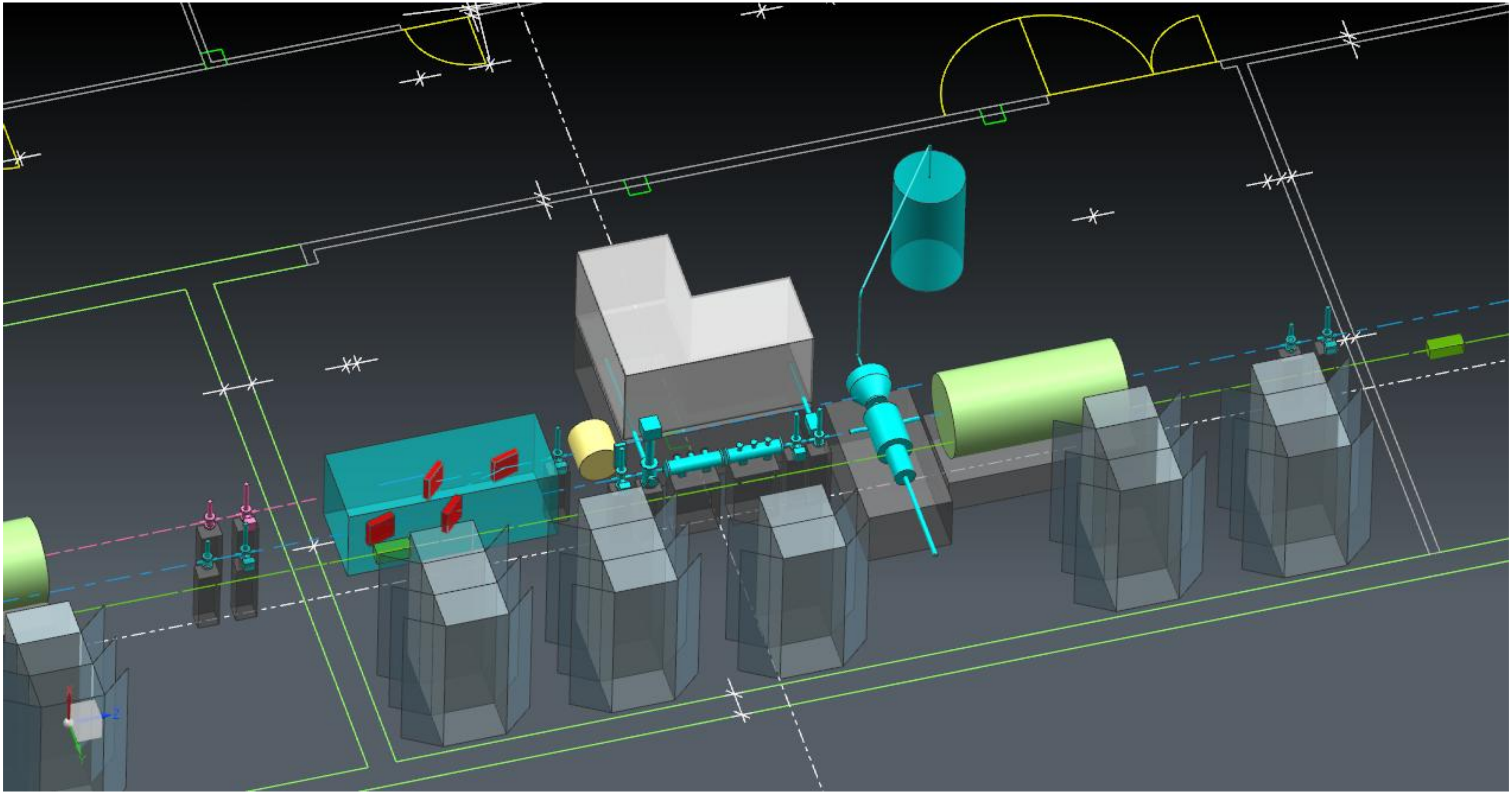
Offset mirrors (LCLS)



Phase 1, 2012-16

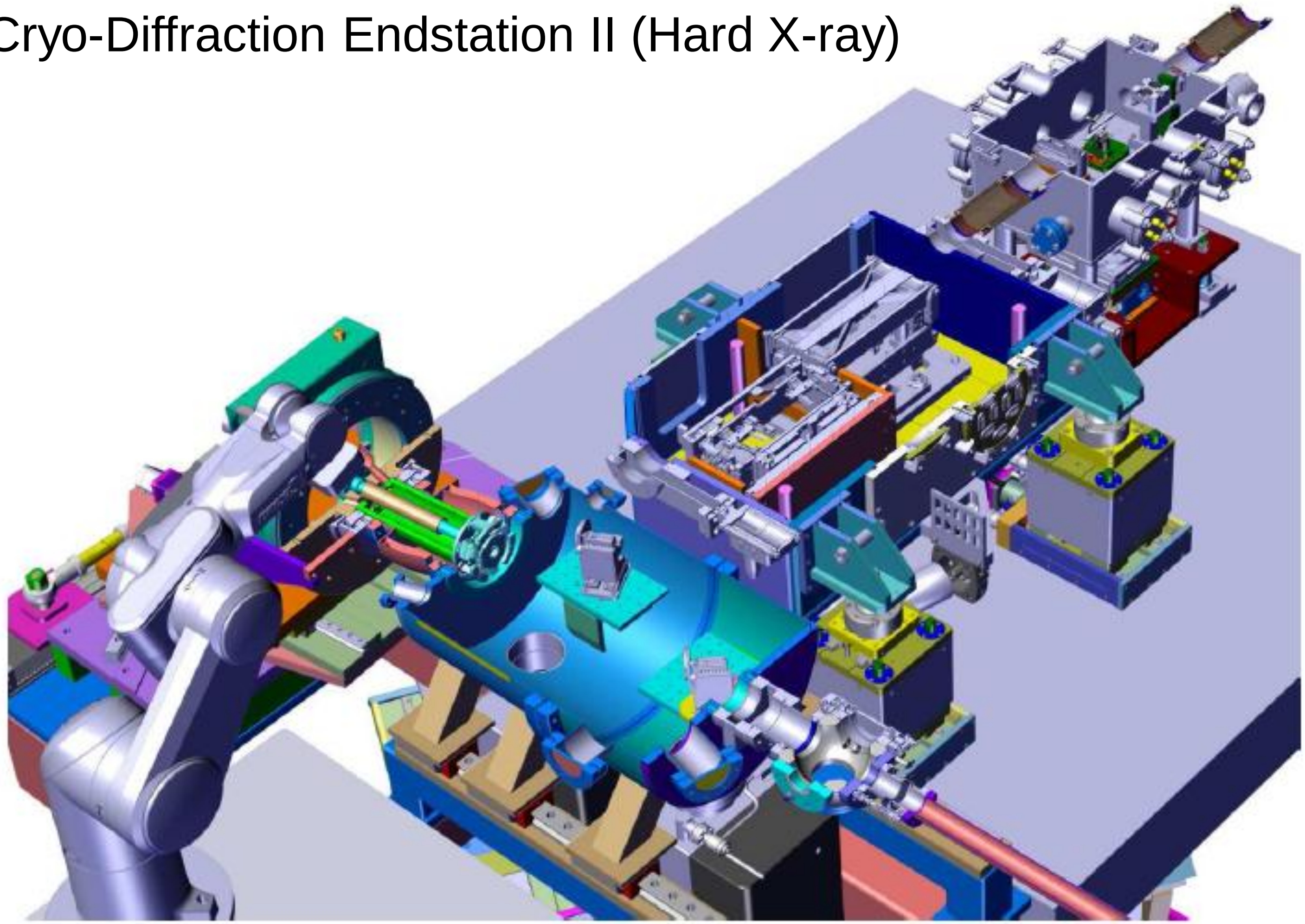


A typical end-station



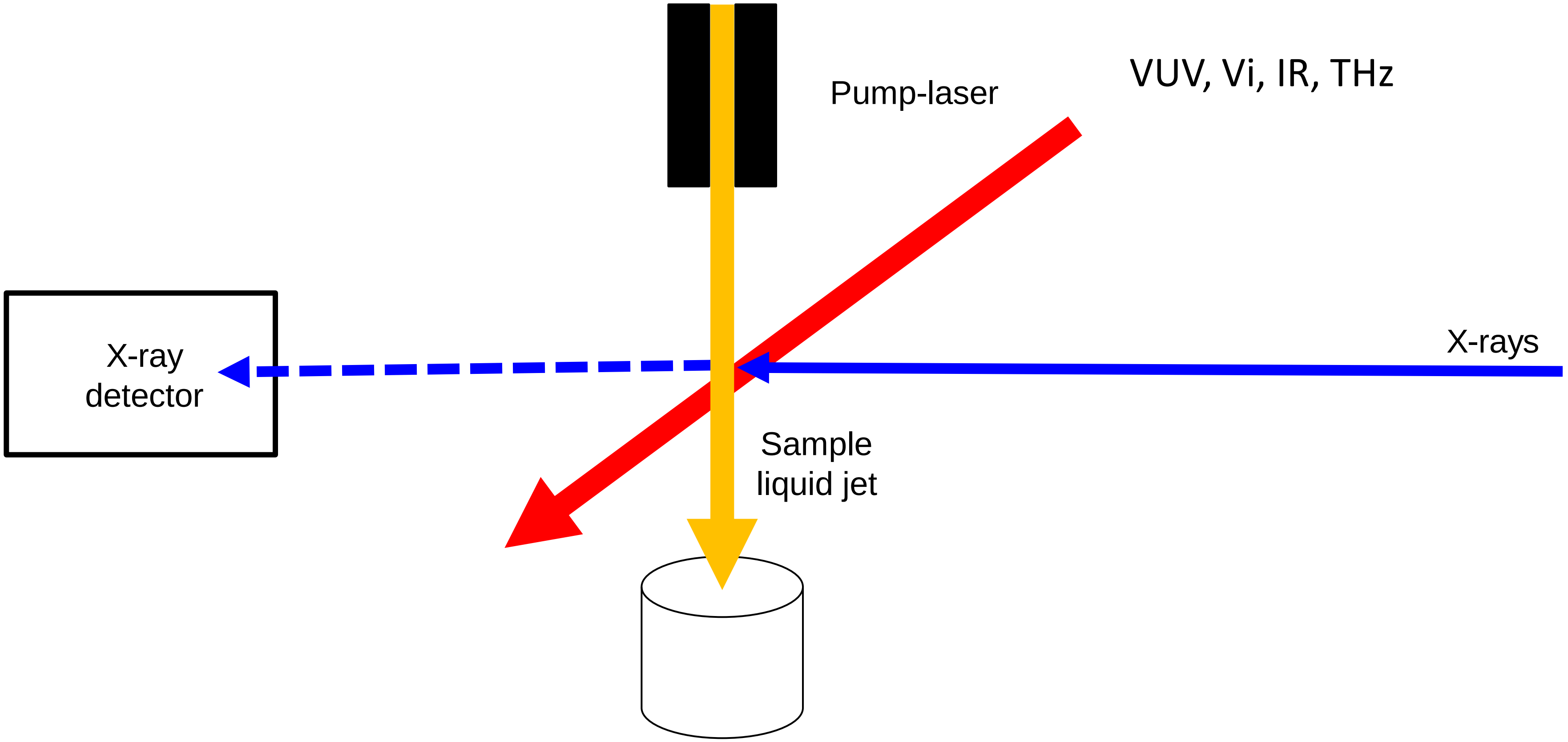
ES-B: pump-probe crystallography

e.g., FEMTO Cryo-Diffraction Endstation II (Hard X-ray)



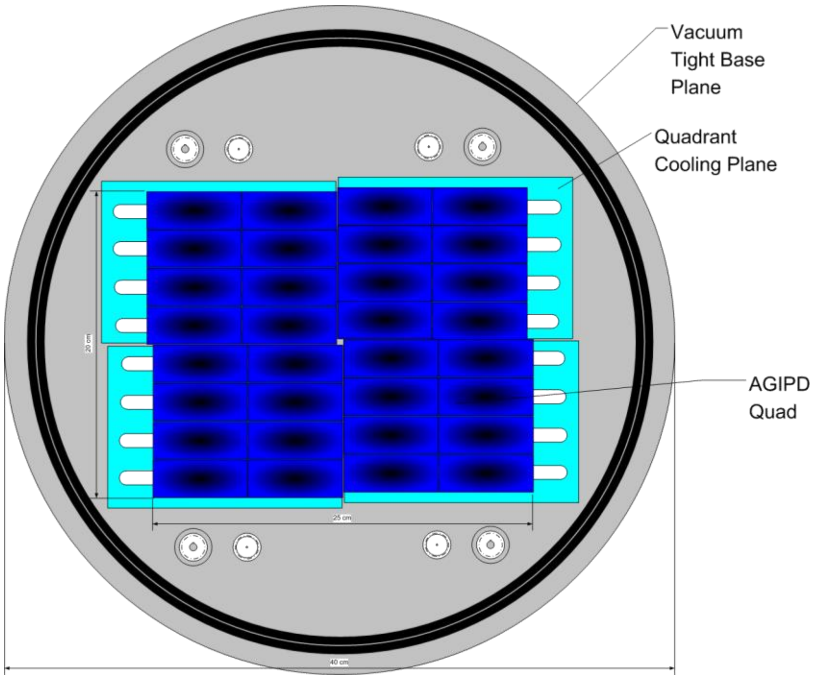
courtesy: G: Ingold

Pump-probe



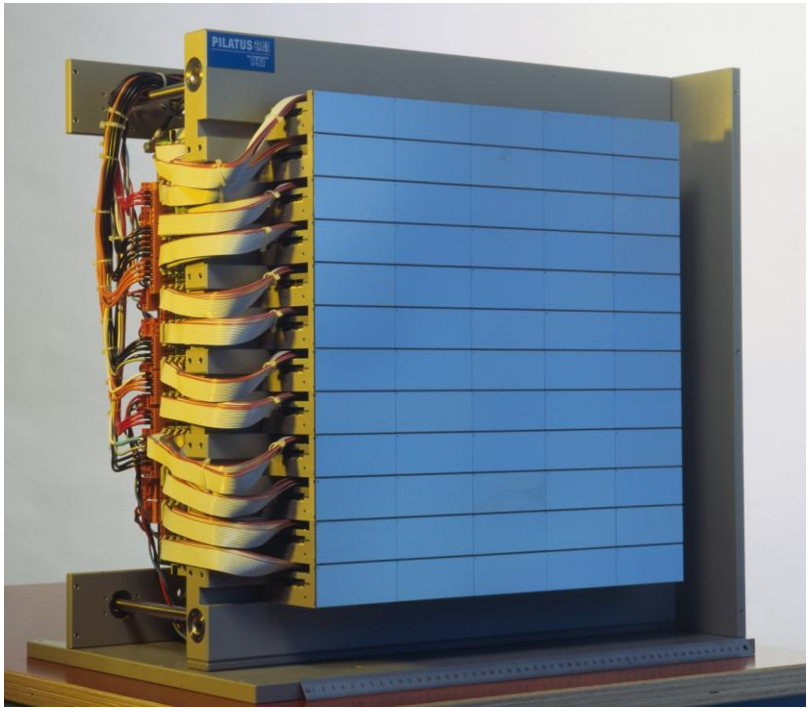
Pump-laser
VUV, Vi, IR, THz
X-rays
X-ray
detector
Sample
liquid jet

Detector Development



PIXEL Detector for

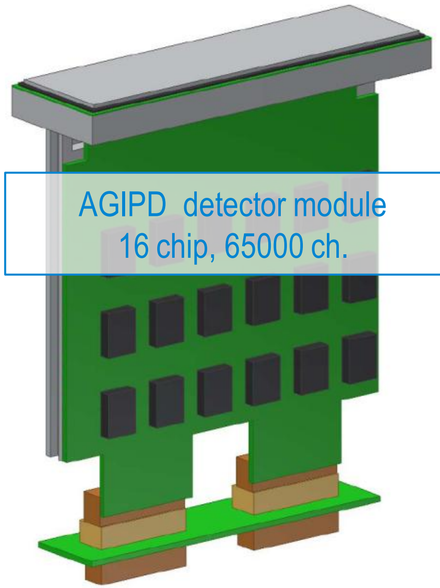
European XFEL AGIPD
SwissFEL



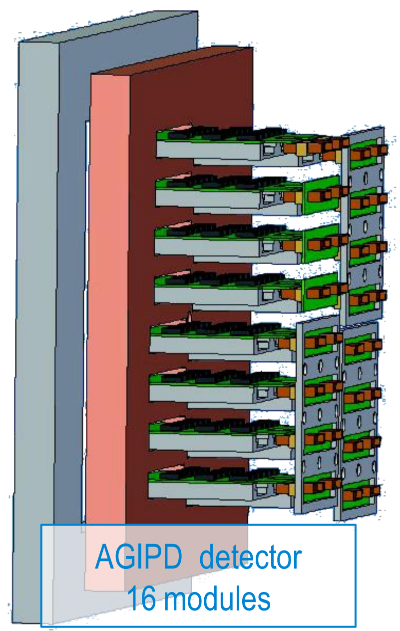
PIXEL Detectors at the SLS

PILATUS, GOTTHARD,EIGER

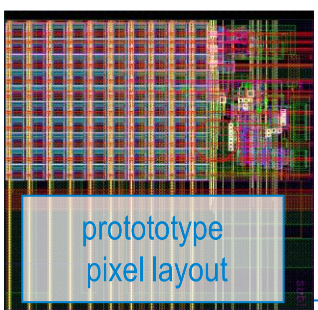
THE AGIPD Pixel Detector



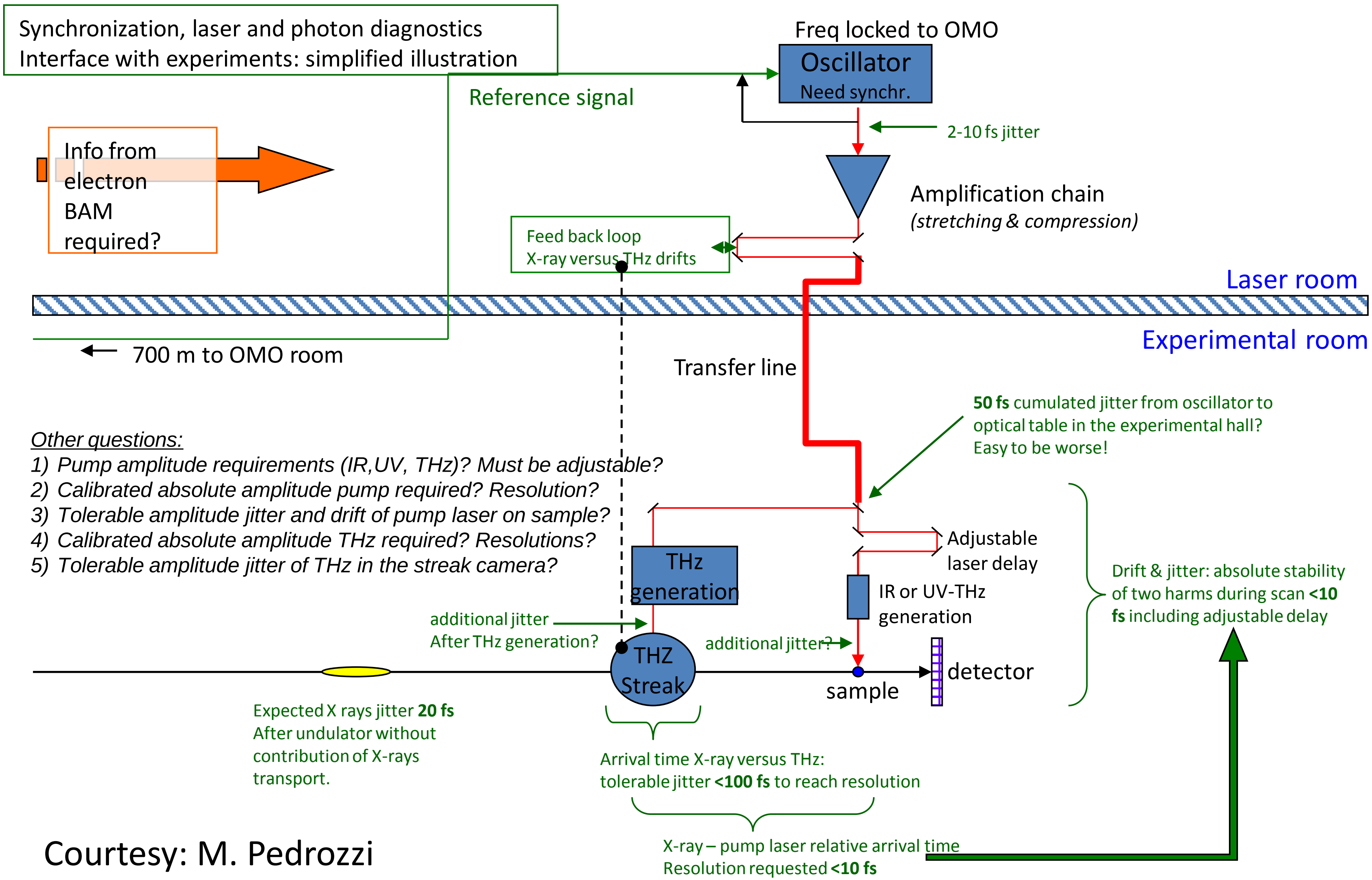
AGIPD:
Adaptive Gain Integrating Pixel Detector



- 200x200μm^2 pixel size
- 1 million pixels (1024x1024)
- ~350 on-pixel storage cells



Pump Laser – Probe X-ray synchronization over 700m



Other questions:

1) *Pump amplitude requirements (IR,UV, THz)? Must be adjustable?*
2) *Calibrated absolute amplitude pump required? Resolution?*
3) *Tolerable amplitude jitter and drift of pump laser on sample?*
4) *Calibrated absolute amplitude THz required? Resolutions?*
5) *Tolerable amplitude jitter of THz in the streak camera?*

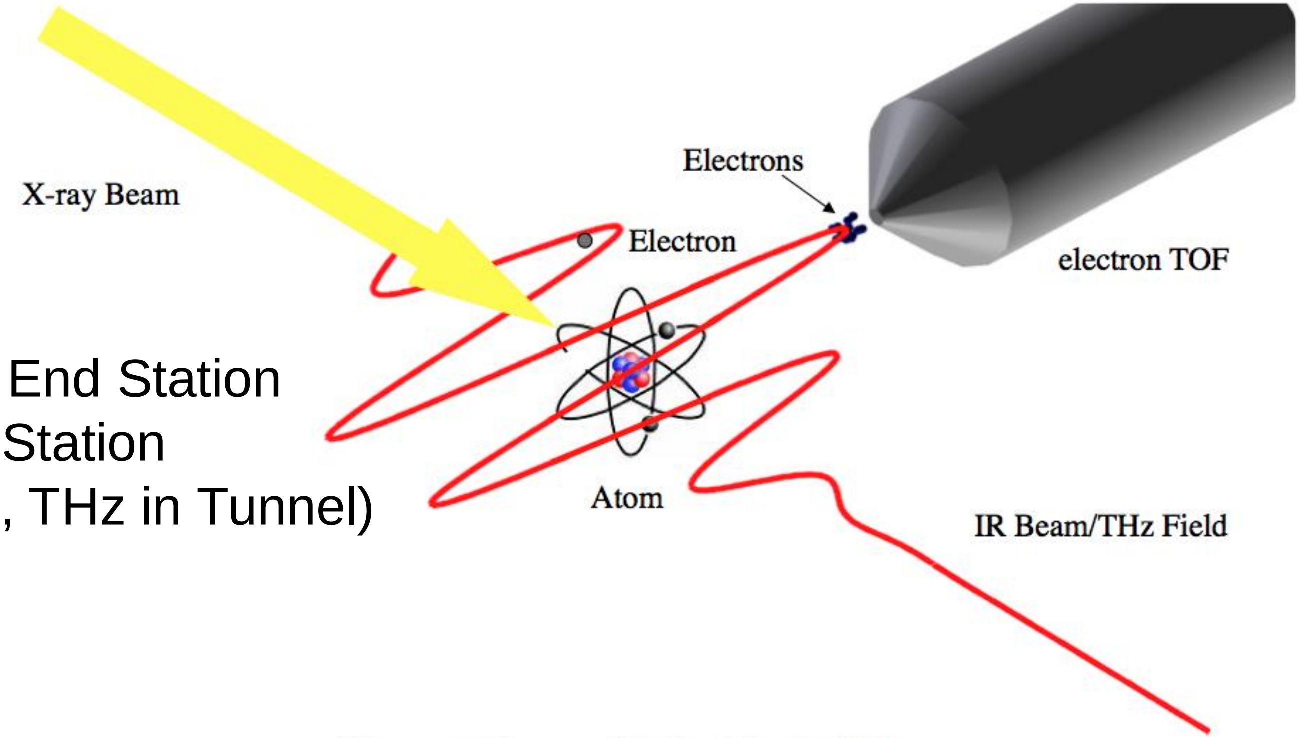
Courtesy: M. Pedrozzi

Pulse Arrival Time and Pulse length

- Use a THz streak camera concept to measure the arrival time and length of the photon pulse.

Tolerable jitter **<100 fs**

Resolution **<10 fs**



-Pulse Arrival Time @ End Station
-Pulse Length @ End Station
(DCR, Laser transport, THz in Tunnel)

$KE_{electron} = E_{photon} - \text{Binding Energy} \pm W$

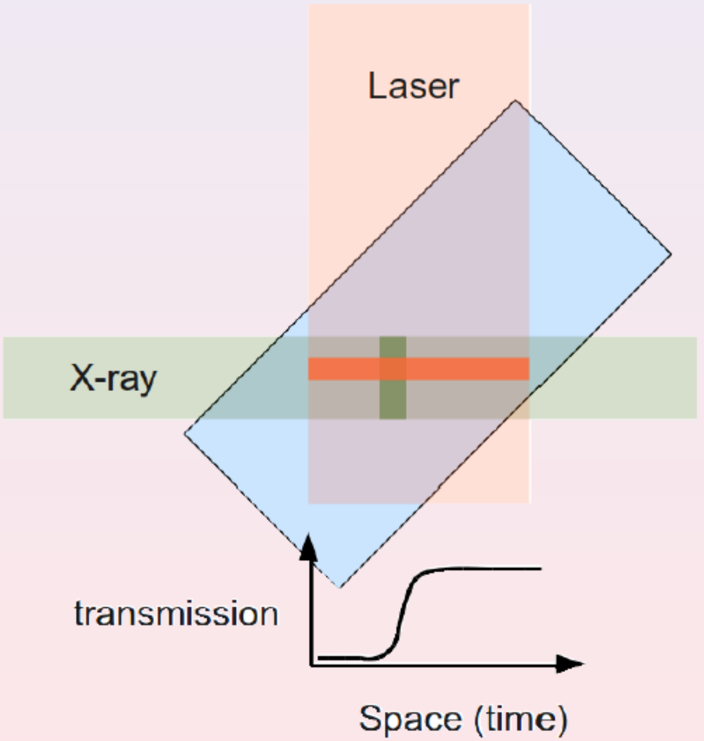
Schedule:
-Under construction @ PSI
-Test with soft X-ray, Flash (summer 2012)
-Test with hard in X-ray, SACLA, M. Yabashi (in 2013)
-SwissFEL final version (in 2014)

P. Juranic, R. Ischebeck, V. Schlott

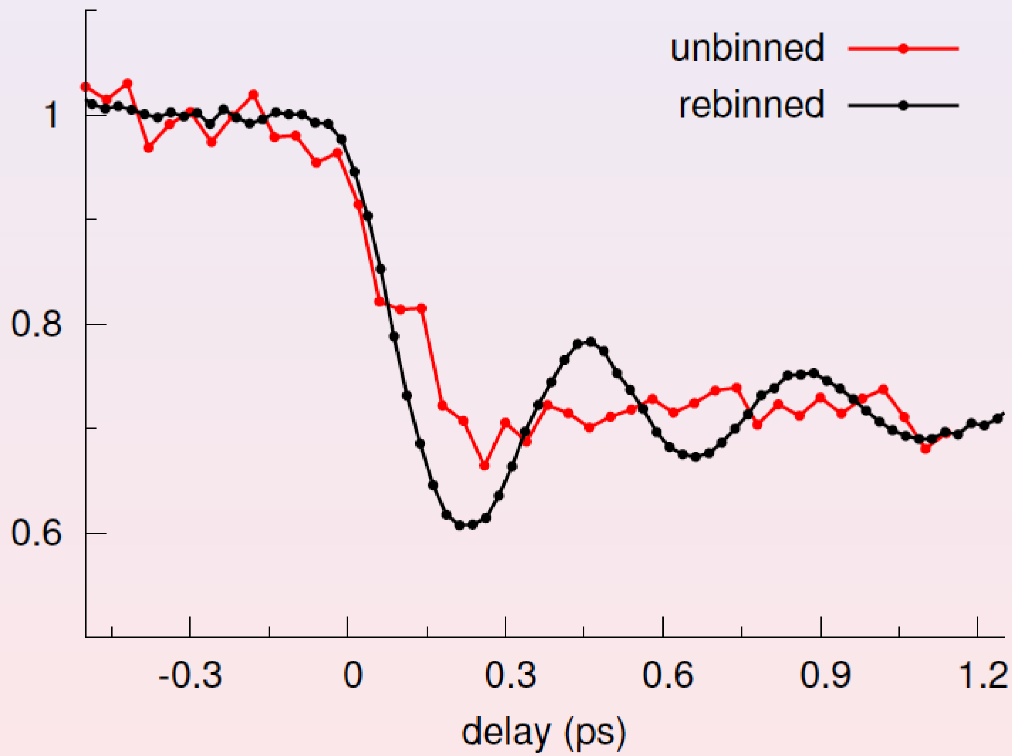
Improving time resolution
measuring pump and probe delay

XCOR

- Core electrons don't influence optical properties
- X-rays promotes core electrons into conduction band
- Change of optical properties captured by encoding time in space (or in wavelength)



Dec 2011 Bismuth data



- Raw data scanning time delay (12 minutes scan)
- Rebinned using one of the timing tools (same data!!)

Outline

- Motivation
- Ultrashort X-ray pulses from FEL light sources
- FEL technology
- Science program at X-FEL facilities

Experiment types

Pump-Probe
(Laser) - (X-ray)

Time resolution, laser-x-ray synchronisation

XAS, XES, RXD, RIXS,…..

- Nano-particules, single molecules
- Catalytic process
- Correlated system

Diffraction/Imaging

"very photon hungry"
structure directly (from diffraction)

XD, CXS,…

- serial 3D nano-crystallography
- 2D "membrane" crystallography

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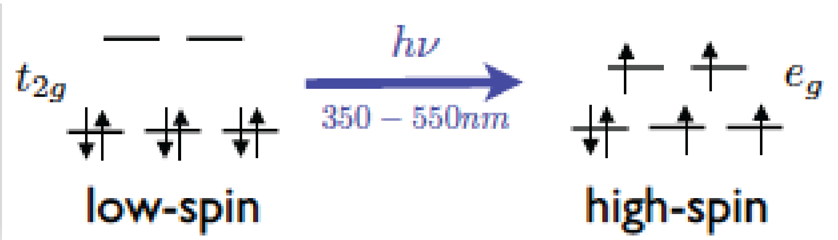
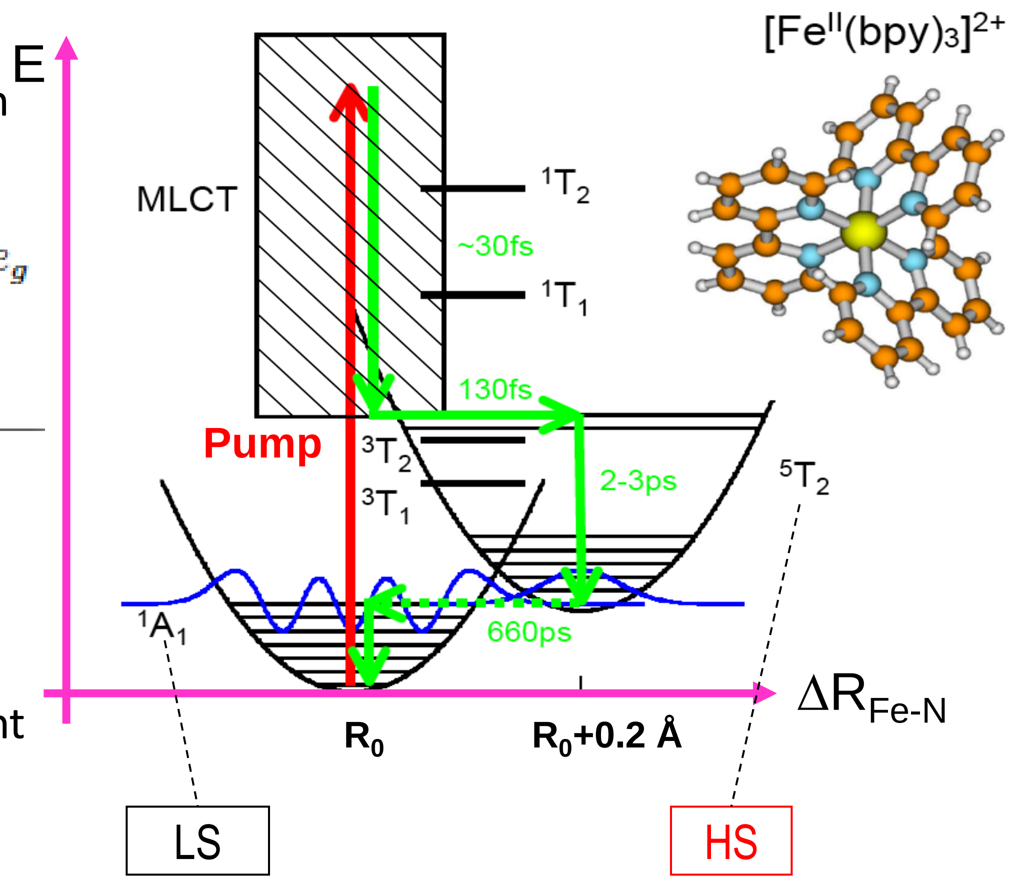
Pump-probe XAS

[FeII(bpy)3]2+ requires optical excitation and shows fs to ns relaxation dynamics



Spin-crossover phenomenon: a transition from a low-spin ground state to a high spin excited state

- can be induced by temperature or light
- Fe(II) compounds represent a general class of spin-crossover systems



Applications:
- ultrafast magnetism
- bistable devices
- model biological systems (heme proteins)

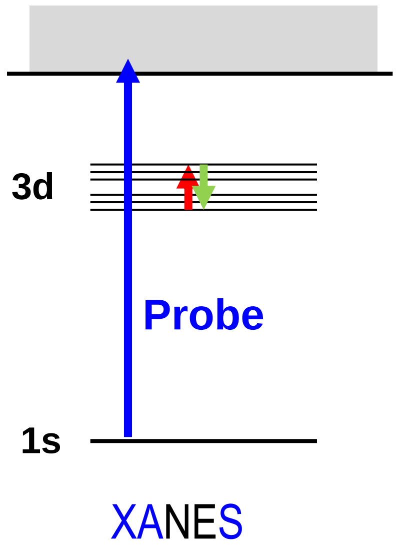
W. Gawelda *et al.*, JACS **129**, 8199−8206 (**2007**)

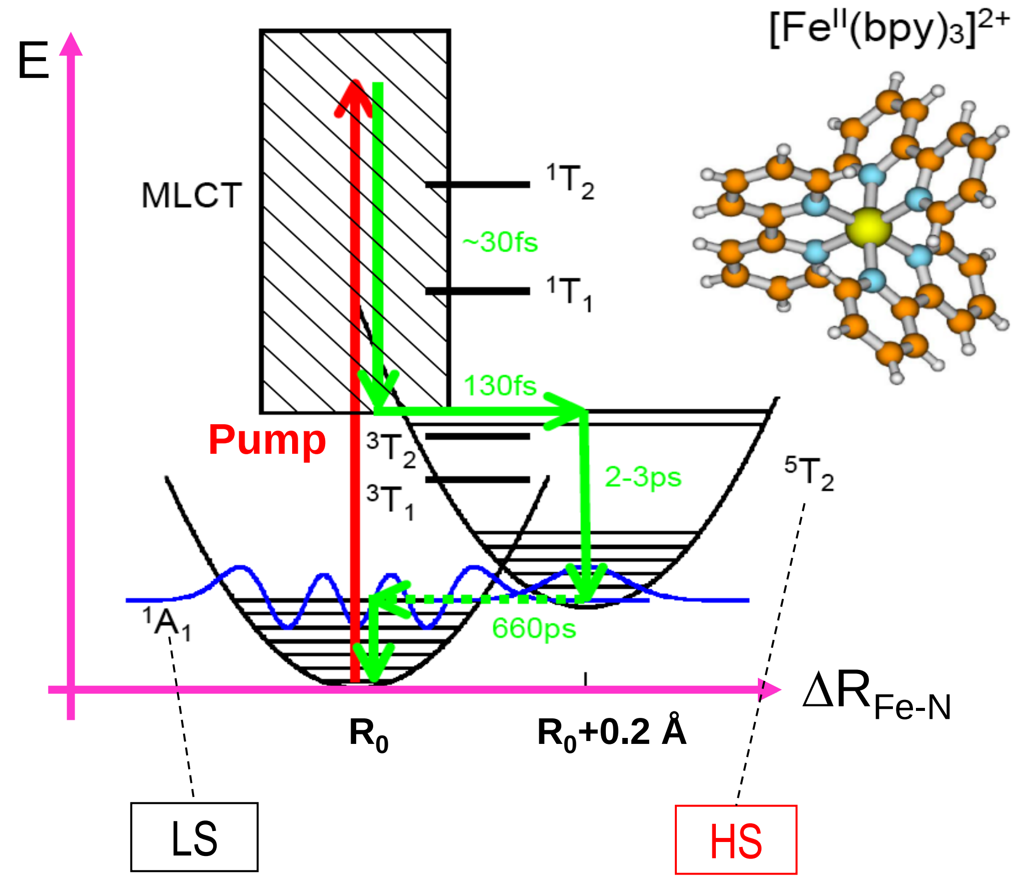
W. Gawelda *et al.*, Phys. Rev. Lett. **98**, 057401 (**2007**)

W. Gawelda *et al.*, J. Phys. Chem. **130**, 124520 (**2009**)

C. Bressler *et al.*, Science **323**, 489−492 (**2009**)

Pump-probe XAS





W. Gawelda *et al*., JACS **129**, 8199−8206 (**2007**)

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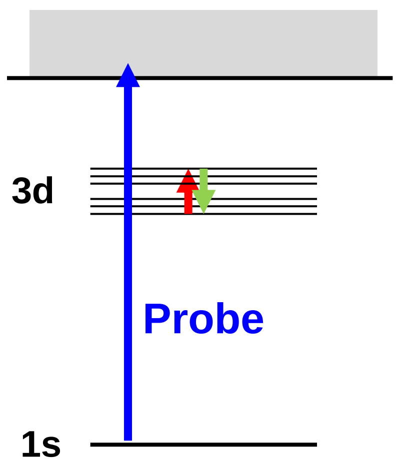
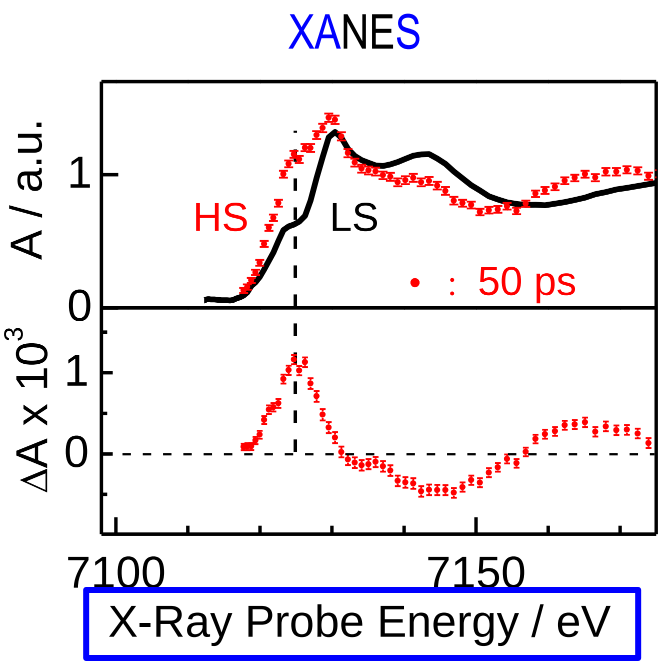
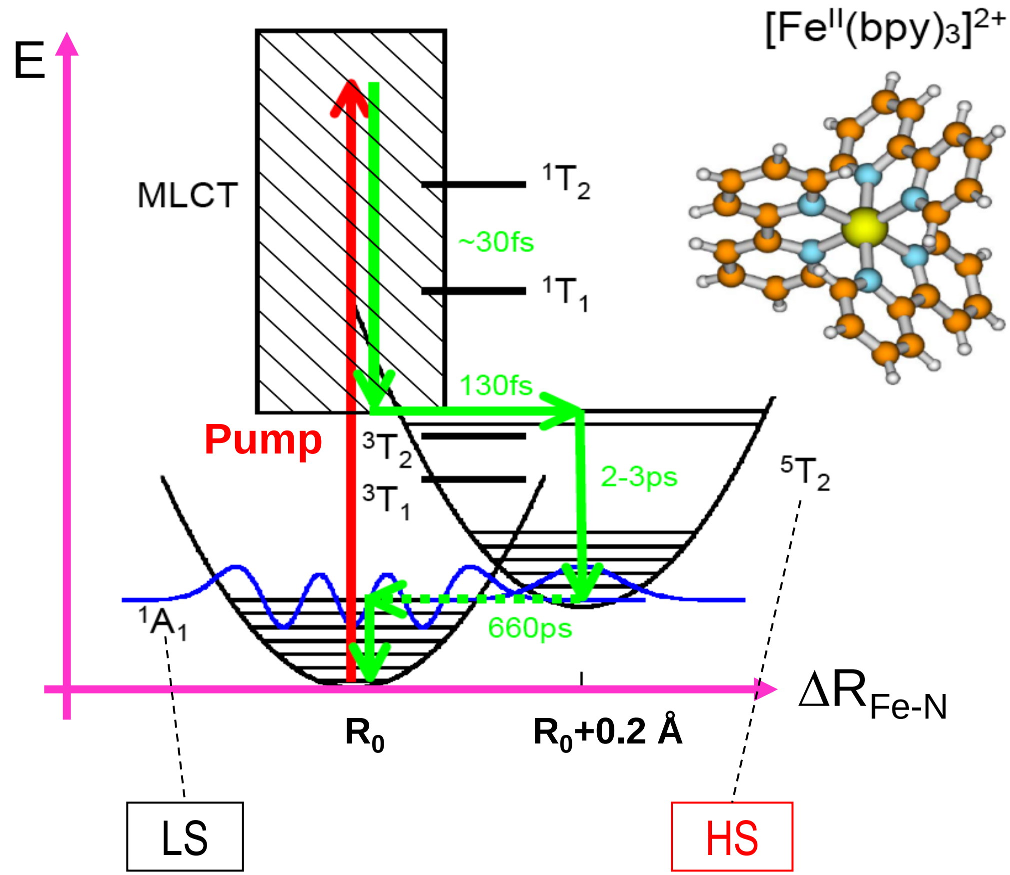
Pump-probe XAS







W. Gawelda *et al.*, JACS **129**, 8199−8206 (**2007**)

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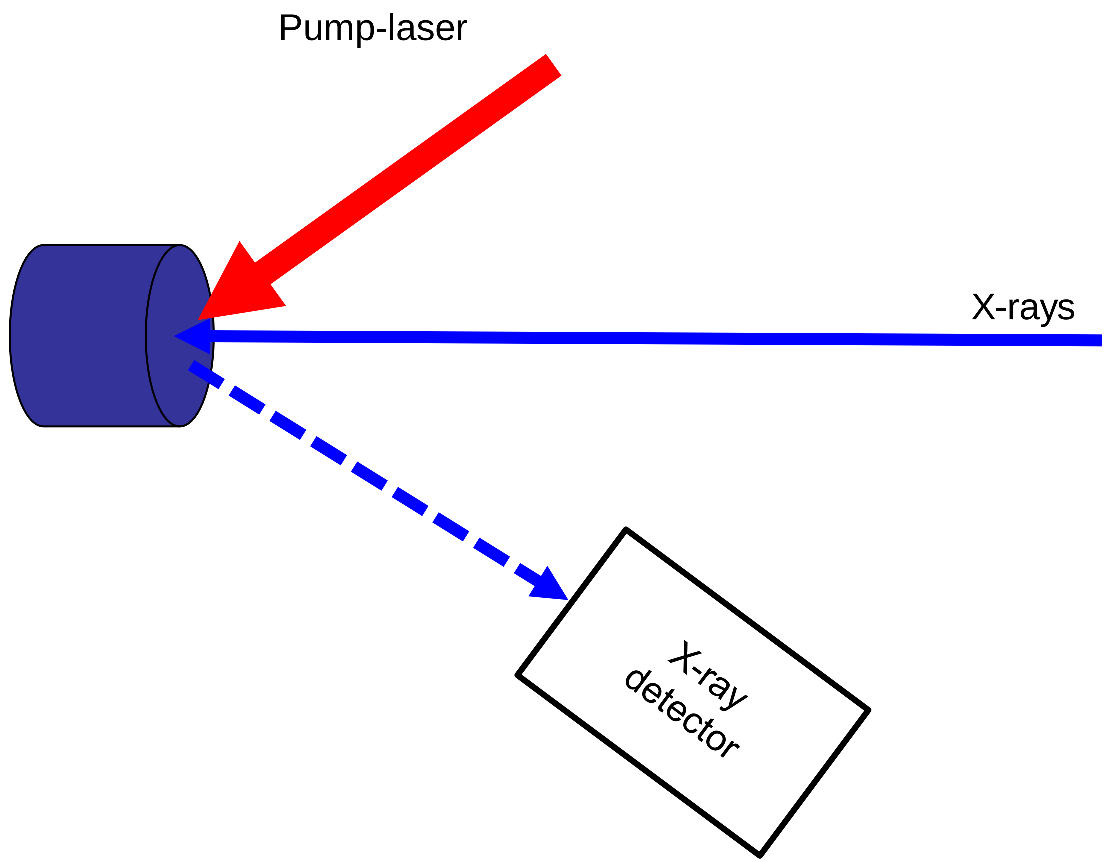
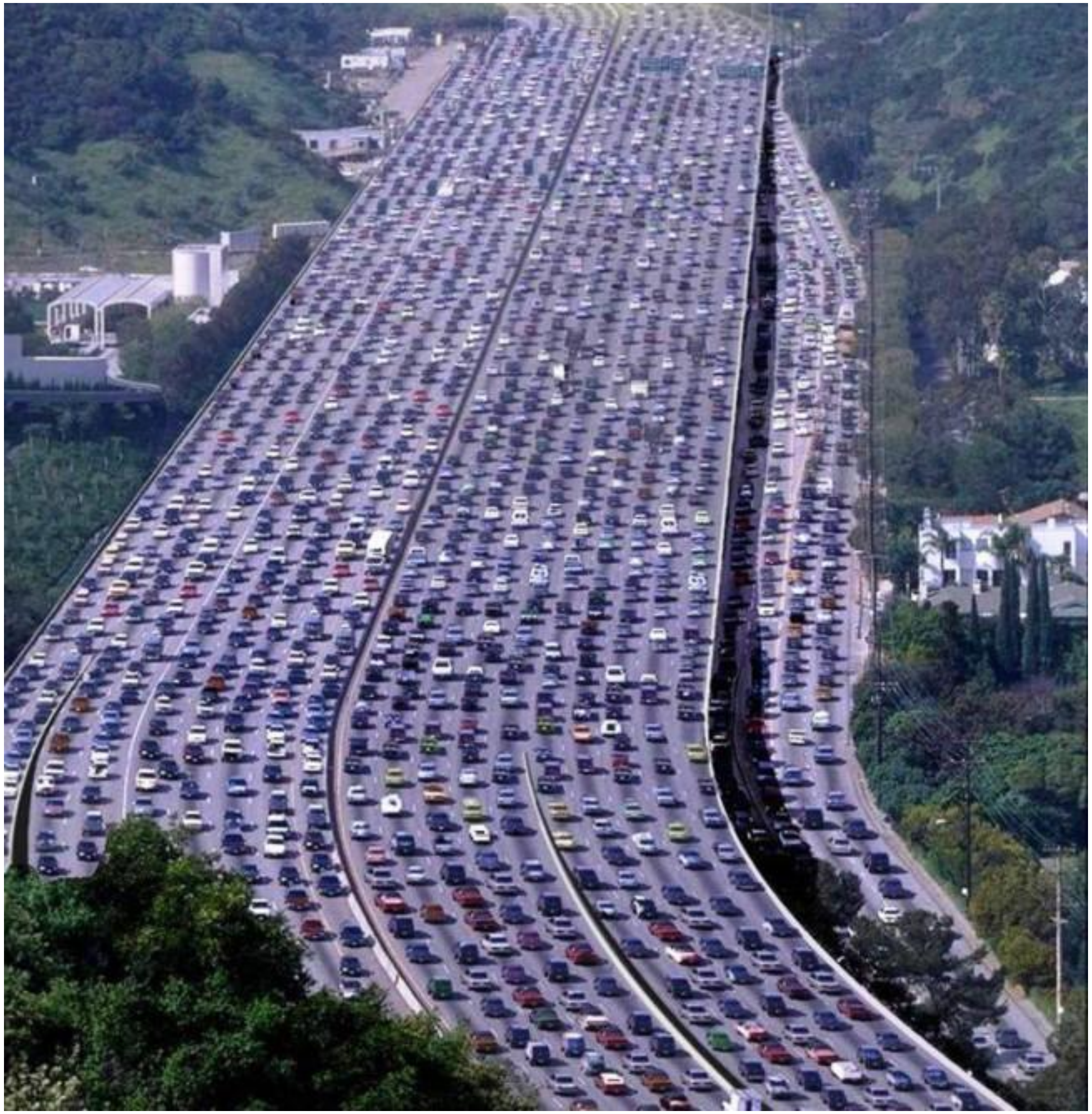
W. Gawelda *et al.*, J. Phys. Chem. **130**, 124520 (**2009**)

C. Bressler *et al.*, Science **323**, 489−492 (**2009**)

Pump-probe



Correlated Systems



Modern electronic properties of condense mater:

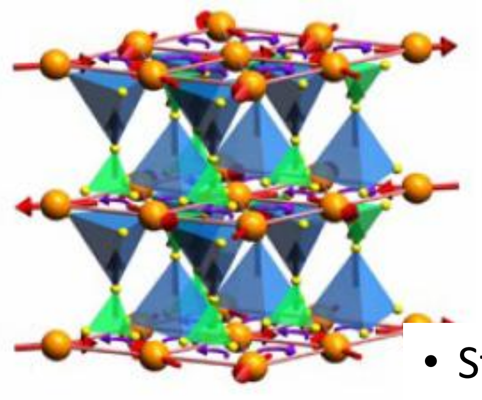
-High temperature Superconductivity

-Giant magnetoresistance

Study weak and strong correlated electron systems in the time domain

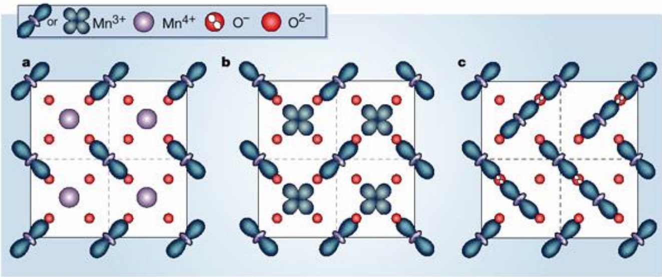
Lattice, Charge, Spin and Orbital orders

Lattice $\tau l < 1ps$



$\tau el < 1ps$

Charge $\tau e < 100fs$

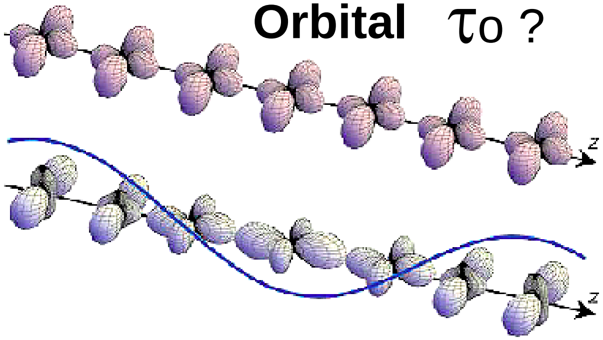


- Strong correlations among spin, charge, orbital, and lattice degrees of freedom.
- Disentangle energy and time scales are the key for understanding these complex phenomenon.

τol ?

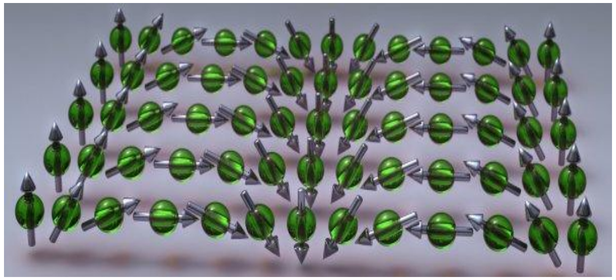
τes ?

Orbital τo ?

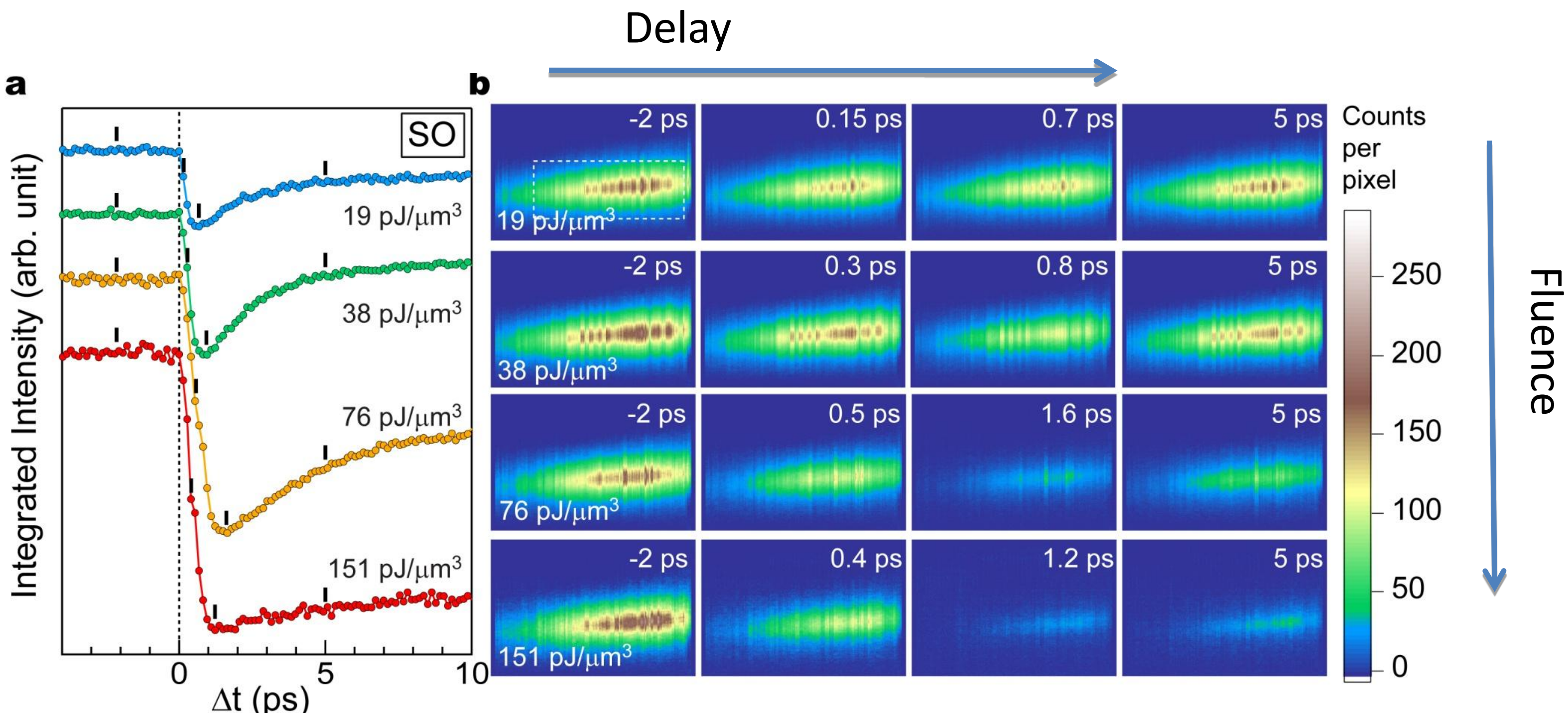


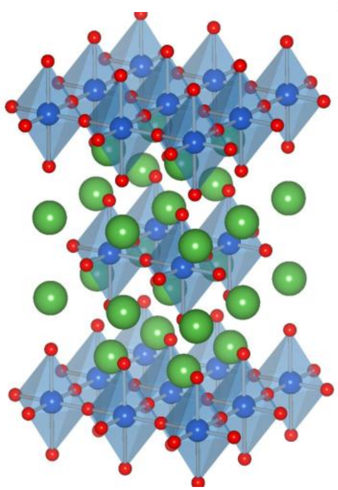
τos ?

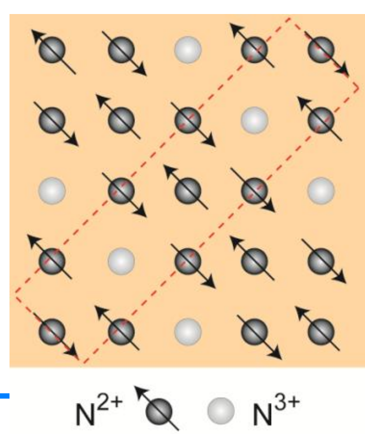
Spin τs ?



Femtosecond resonant soft x-ray scattering experiment Stripe state of $La_{2-x}Sr_xNiO_4$







RXS Experiments in the SXR- Station at LCLS (Stanford)
(Collaboration: Stanford, SLAC, ALS, PSI,...)

W.-S. Lee, Nature Com. (2012)

Experiment types

Pump-Probe
(Laser) - (X-ray)

Time resolution, laser-x-ray synchronisation

XAS, XES, RXD, RIXS,…..

- Nano-particules, single molecules
- Catalytic process
- Correlated system

Diffraction/Imaging

"very photon hungry"
structure directly (from diffraction)

XD, CXS

- serial 3D nano-crystallography
- 2D "membrane" crystallography

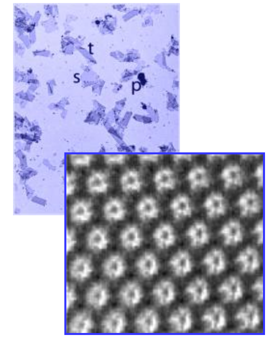
Diffraction

SYN | **FEL**

Diffract and destroy

3D crystallography

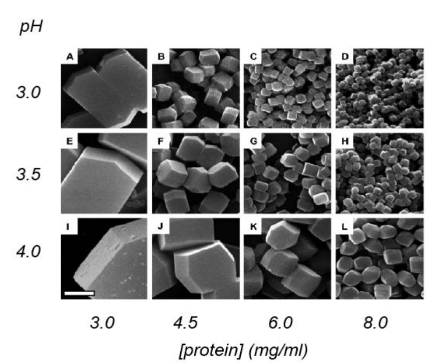
2D “membrane” crystallography



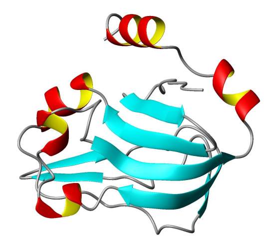
Orientation fixed

Orientation random

3D nano-crystallography



Single molecule



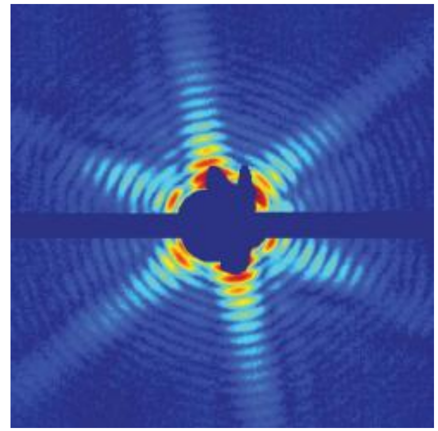
Diffract & destroy

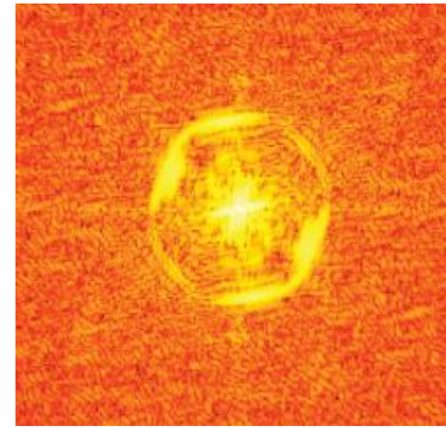
SYN | **FEL**

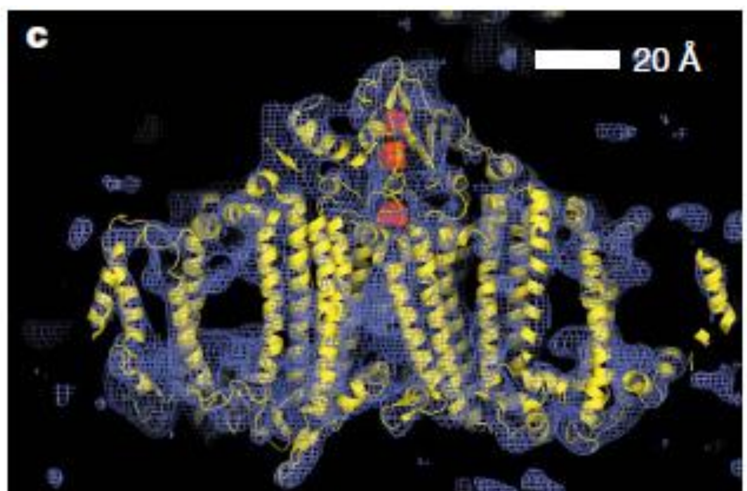
3D
crystallography

M. M. Seibert *et al*., Nature **470**, 78−81 (**2011**)

Virus
LCLS, 6.9 Å







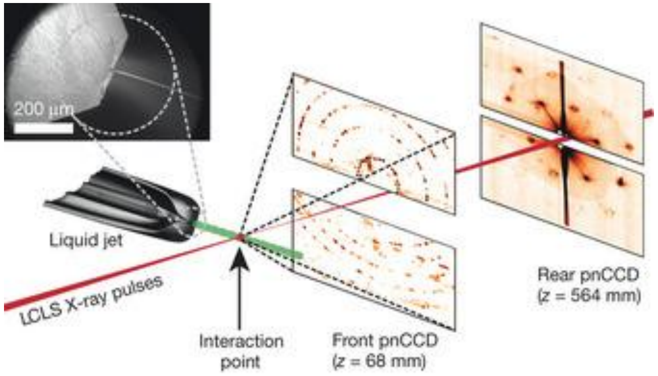
3D-nanocrytals
LCLS, 6.9 Å

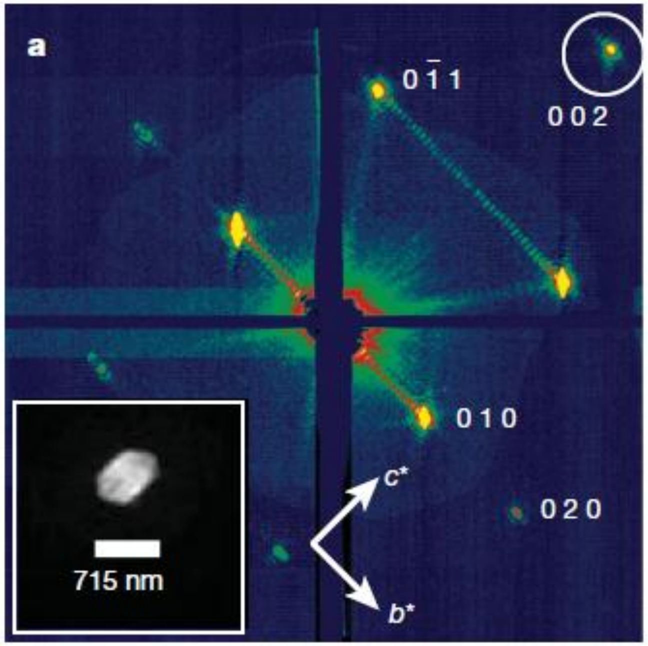
H. Chapman *et al*.,
Nature **470**
73−78 (**2011**)

[protein] (mg/ml)

3D nano / 2D «mem»

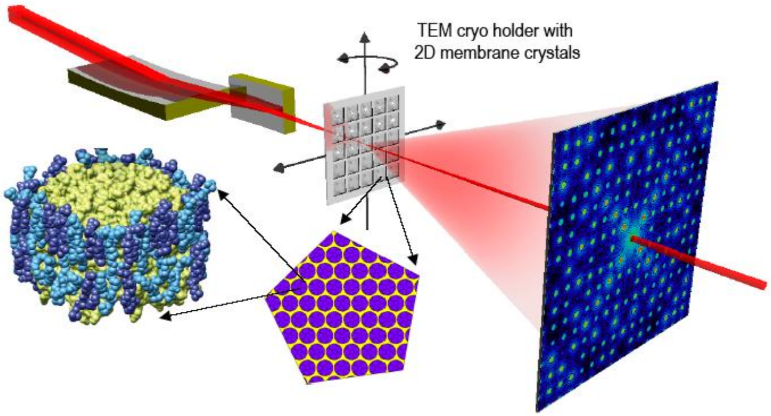
3D nano-crystallography

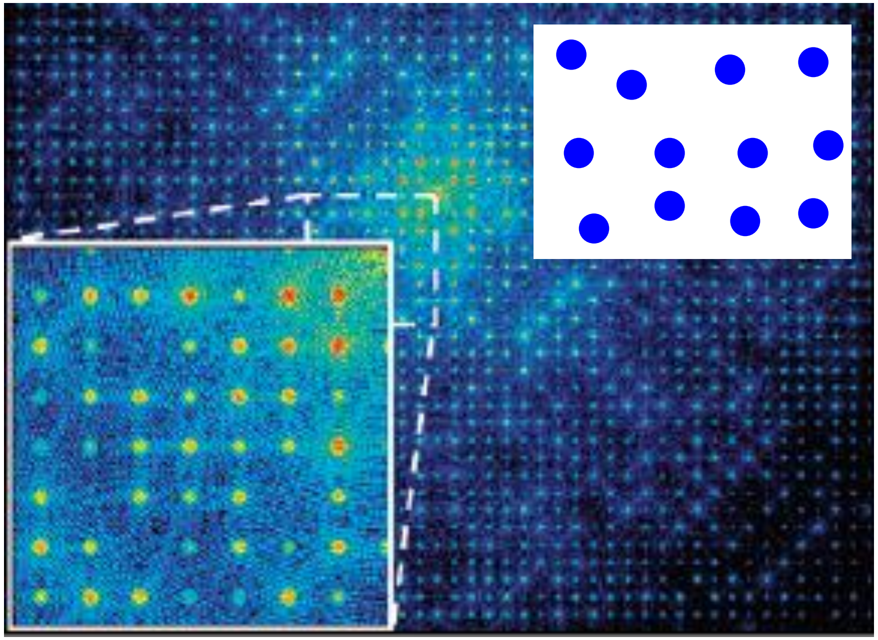




H. Chapman *et al*., Nature **470**, 73−78 (2011)

2D "membrane" crystallography





K. Kewish *et al*., New J. Phys. **12**, 035005 (2010)

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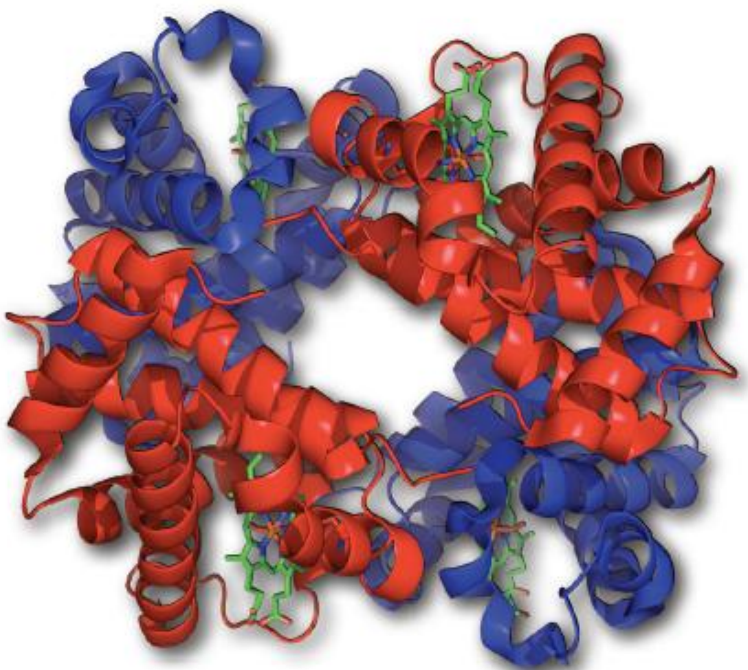
Is function structure or dynamics ?

Structure

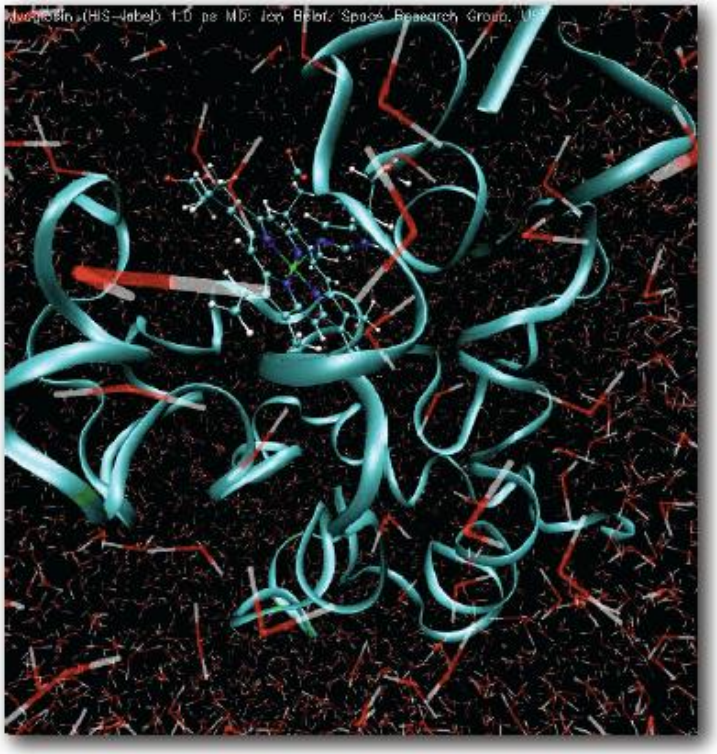
- X-ray crystallography
- electron microscopy
- atomic force microscopy
- electron diffraction
- X-ray absorption spectroscopy
- NMR



Protein structure of human hemoglobin in the T-state with oxygen bound at all 4 hemes (from PDB 1GZX Wikipedia)

Dynamics

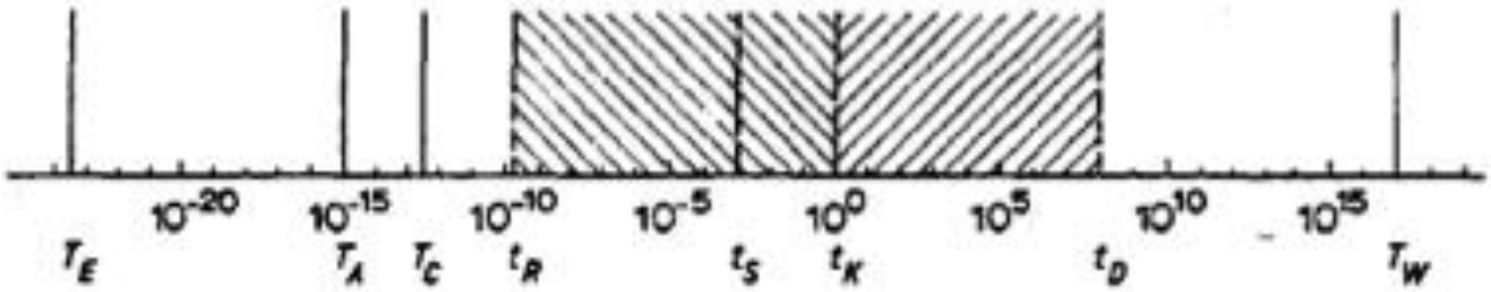
- Laser spectroscopy
- NMR
- time-resolved diffraction
- X-ray absorption spectroscopy



Rotating hydrated myoglobin molecule
http://chemweb.rc.usf.edu/faculty/data/space/
B. Space & J. Belof (University of South Florida)

Molecular Movies

1967 M. Eigen Nobel Price Chemistry *:*
Immeasurably Fast Reactions



1999 A. Zewail Nobel Price Chemistry:
Femtochemistry: Atomic-Scale Dynamics of the Chemical Bond

20XX ?