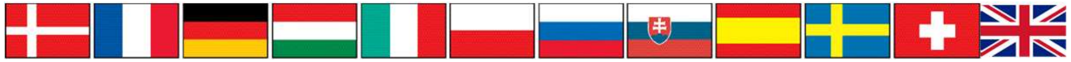
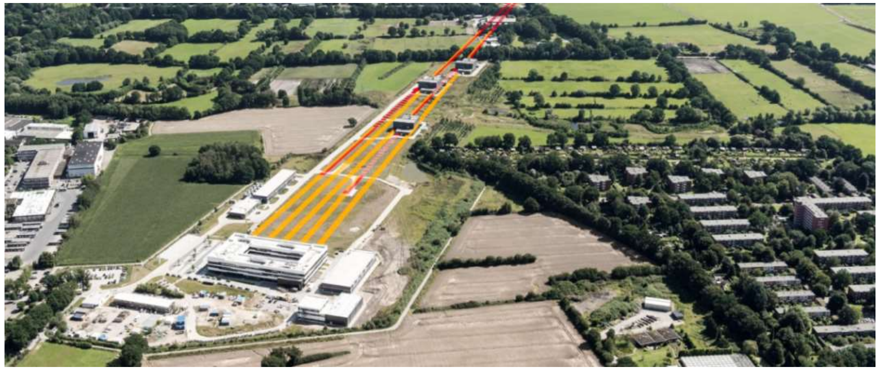


European XFEL

Prof. Robert Feidenhans’l
Chairman of the European XFEL Management Board

European
XFEL

European XFEL



Management Board and Council Chair

European XFEL

European XFEL

Prof. Robert Feidenhans’l
Chairman of the European XFEL Management Board

- What is European XFEL
- History of FELS
- How does a XFEL work
- What Science can be done
- Outlook

A Free Electron Laser - the overall Principle

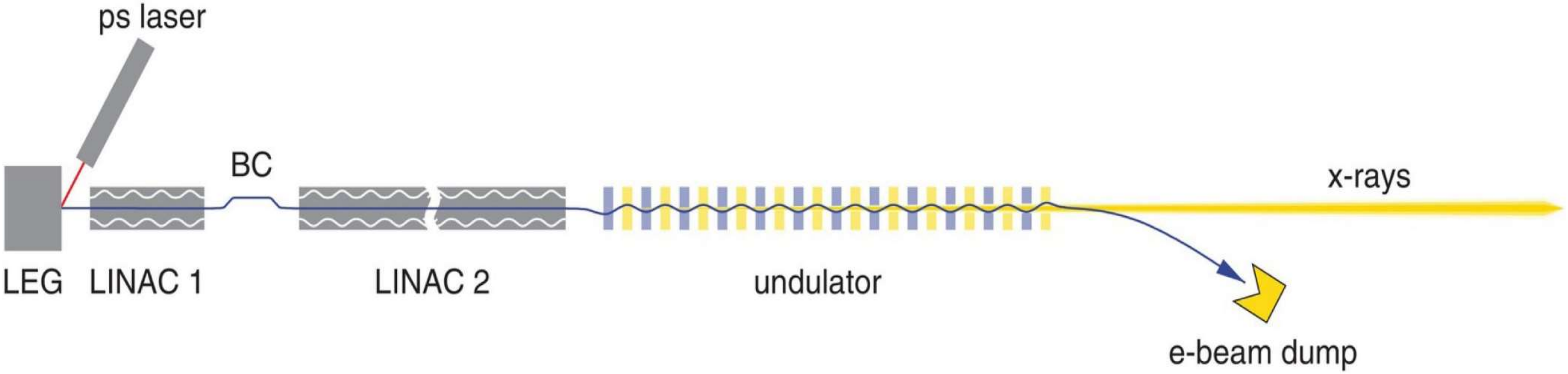
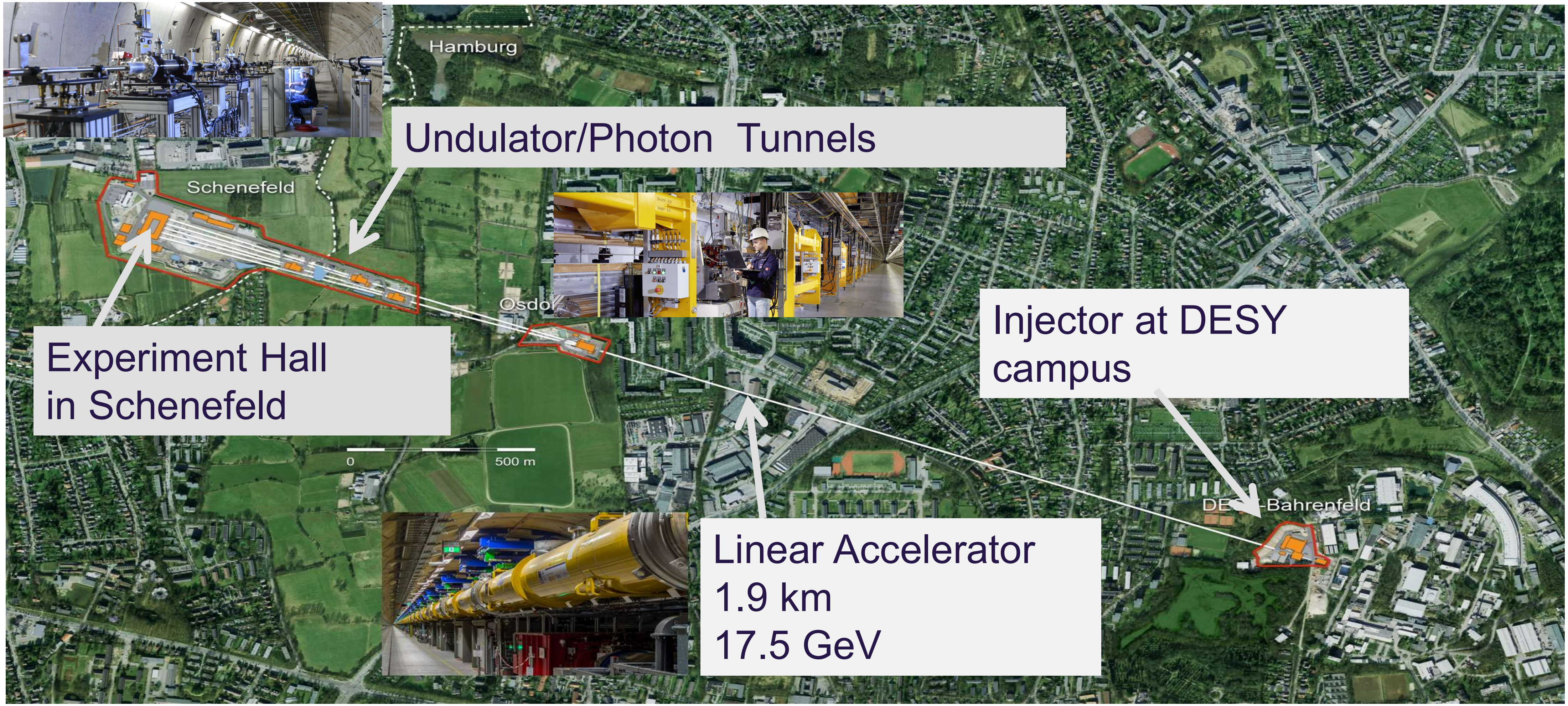


Figure 4.2 Schematic of XFEL facilities. Electron bunches are emitted from a low-emittance gun (LEG) irradiated by picosecond laser pulses. They are then accelerated in a short LINAC (LINAC 1), compressed longitudinally using one or more bunch-compressor magnet chicanes (BC), then further accelerated using a much longer LINAC (LINAC 2) before entering a long undulator, typically a few hundred metres in length. The SASE process along the undulator produces highly intense x-ray pulses with durations of the order of 50 fs. The electrons are deflected after the undulator using a bending magnet and subsequently dumped.

General layout of the European X-ray Free Electron Laser



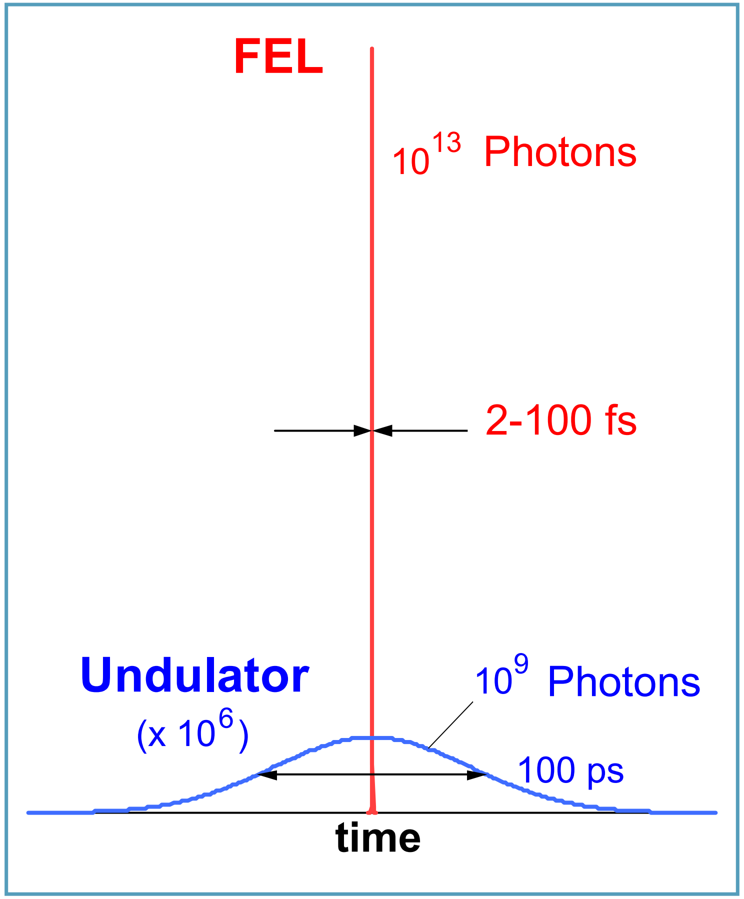
Undulator/Photon Tunnels

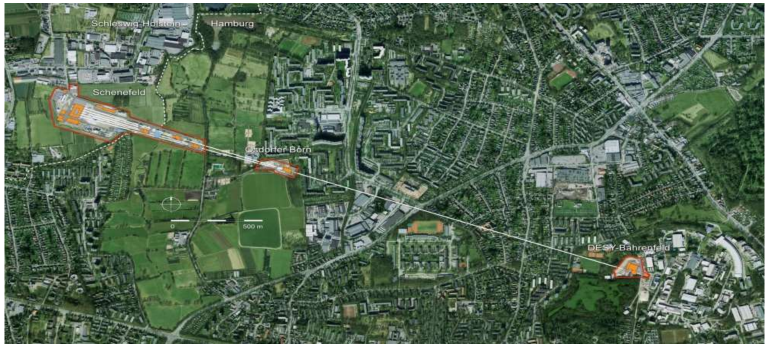
Experiment Hall
in Schenefeld

Injector at DESY
campus

Linear Accelerator
1.9 km
17.5 GeV

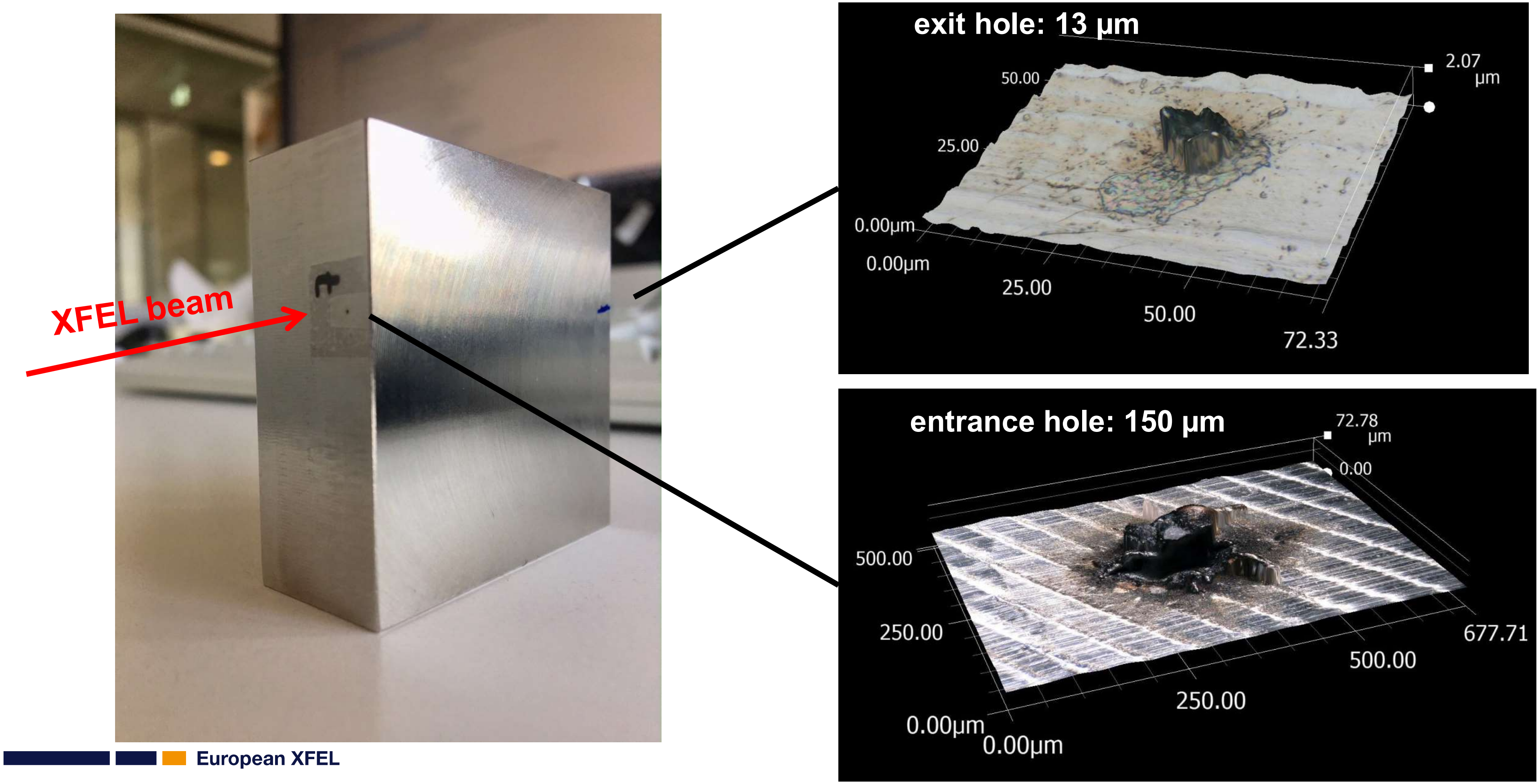
What is the difference between Synchrotron Radiation and X-ray Lasers?





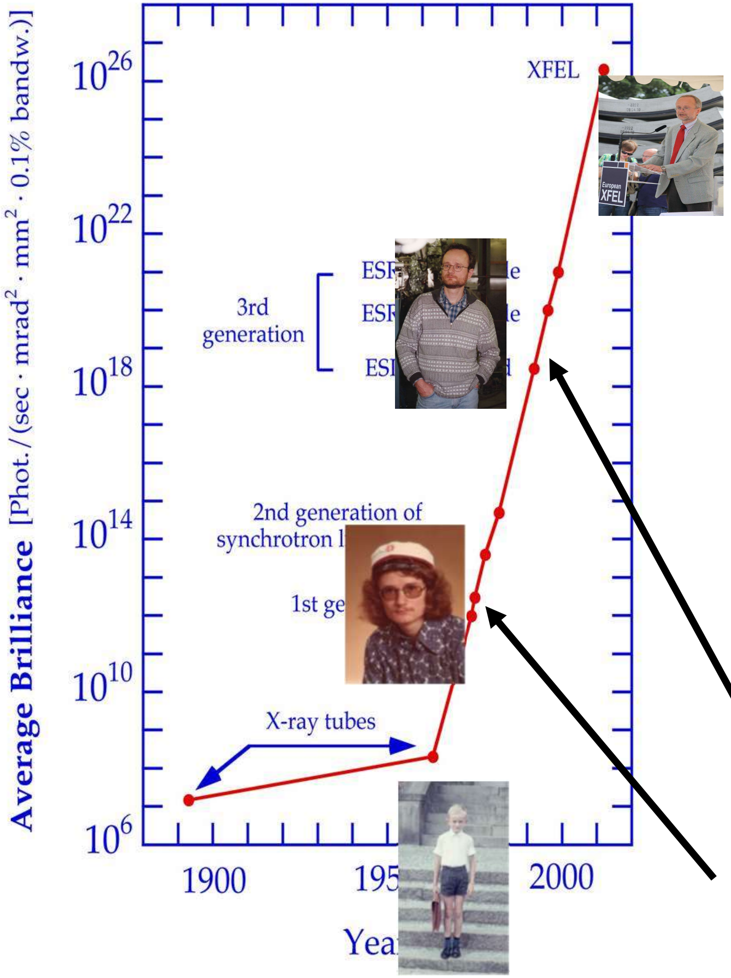
Courtesy Harald Sinn

We have an exceptionally strong beam: Drilling with XFEL beam through 50 mm of steel in 26 seconds

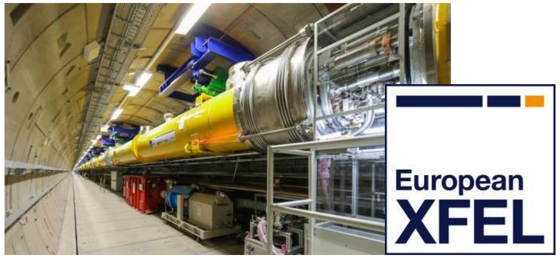


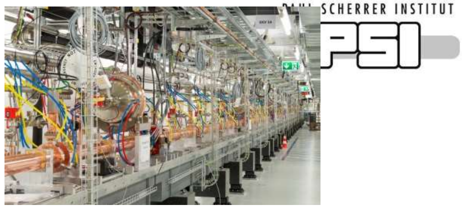
Development of X-ray Science

Synchrotron Radiation



Free Electron Lasers





Faster than Moore's Law !!

I joined X-ray Science in 1981
Fantastic Experience

FP14

About the European XFEL

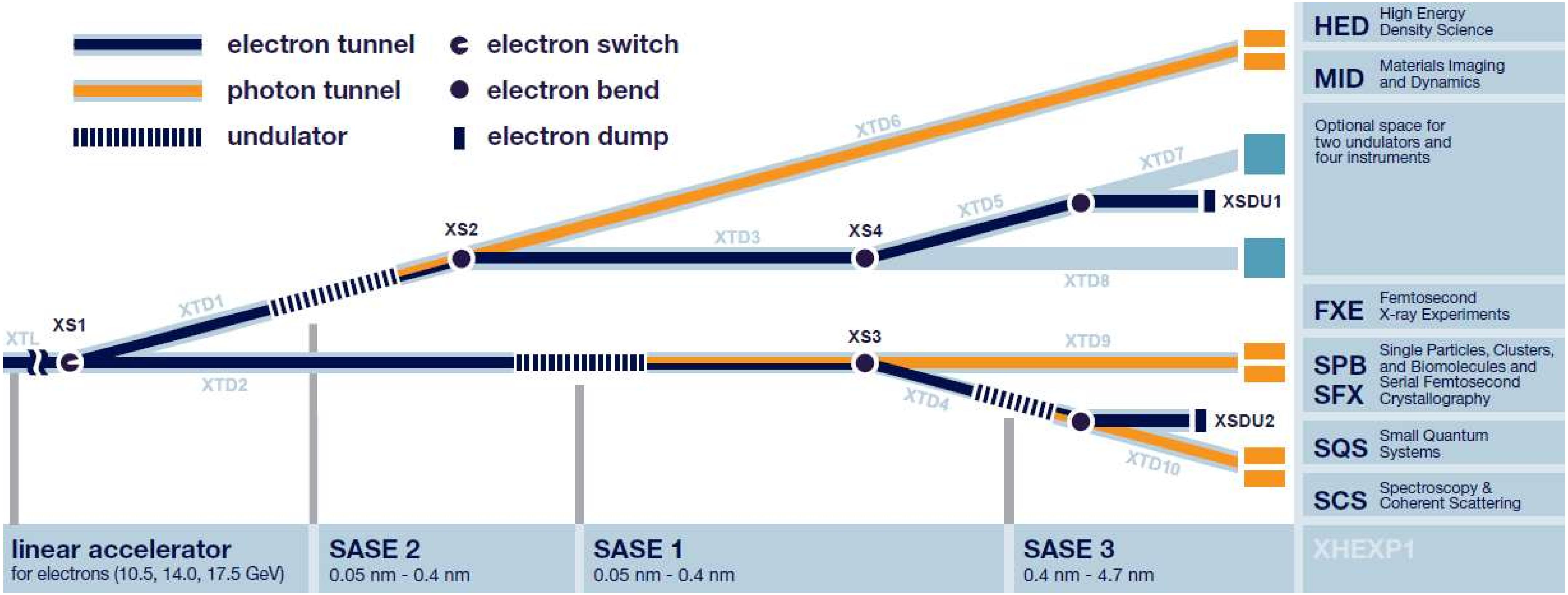
- Start 2009
- Task : *Construction*, *operating* and *development* of the X-ray Laser Facility
- Germany 58%, Russia 27 %, others 1–3%
- DESY operates the accelerator
- Staff XFEL about 500, Staff @ DESY about 250
- Start of operation 1. July 2017
    - 1,54 Brd. € (2018 prices) construction cost
    - 50% in cash, 50% in-kind
    - Yearly running costs 135 Mio € (2021)

Slide 8

FP14 Flaggenleiste mit HH und S-H? Gerade wegen letzterem.
Poppe, Frank; 30-01-2017

- Six Experimental Stations
  - Typically running in 12 hour mode
  - 3 Experiments run simultaneously

Experimental Hall



European XFEL

The Users Community

One Experiment takes about
5 days (60 hours)
Experiments are based on excellence

Free Electron Lasers

SASE – Self-Amplified Spontaneous Emission

Kondratenko, Saldin (1979)
Bonifacio, Pellegrini, Narducci (1984)

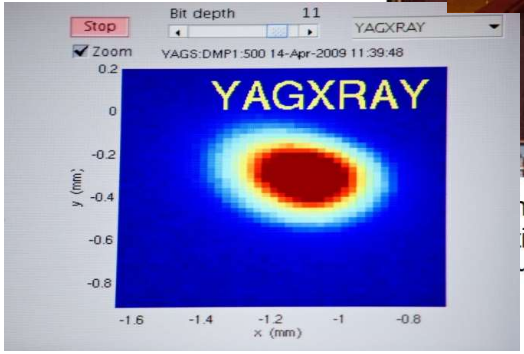

FLASH 2005


SLAC NATIONAL ACCELERATOR LABORATORY

April 21, 2009 - New Era of Research Begins as W
Hard X-ray Laser Achieves "First Light"

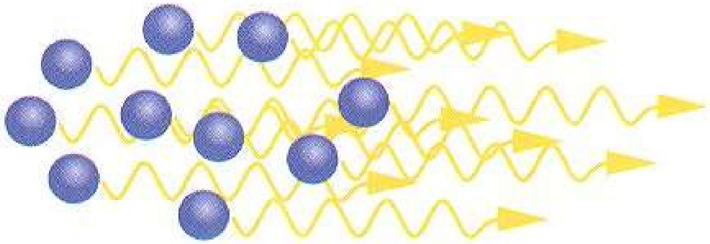
X-Ray laser pulses of unprecedented energy and brilliance produced at S


European XFEL 2009

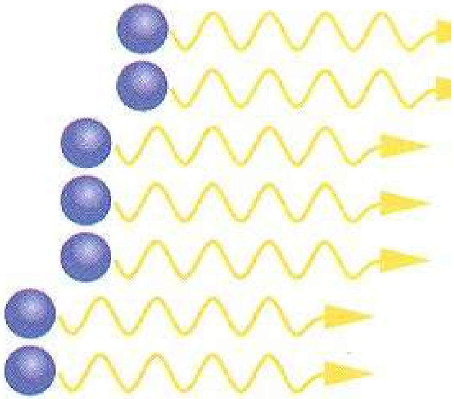


and E. Saldin get FEL prize this year
ions to the SASE FEL (Saldin started
25 years ago)

Emission of Light – „aligment“ of electrons



Noncoherent bunch

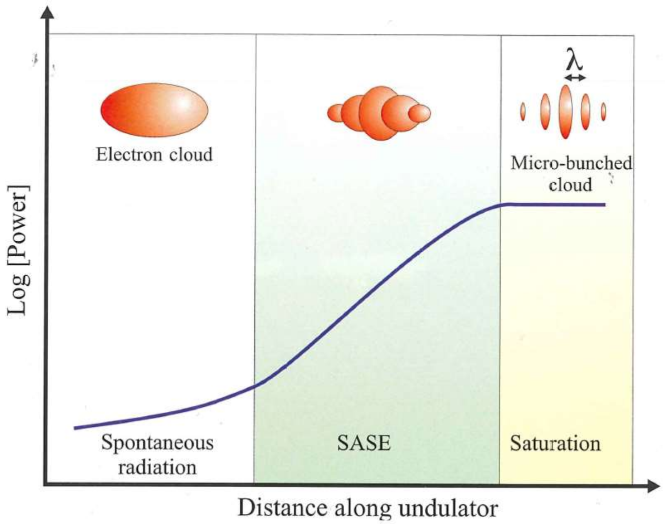


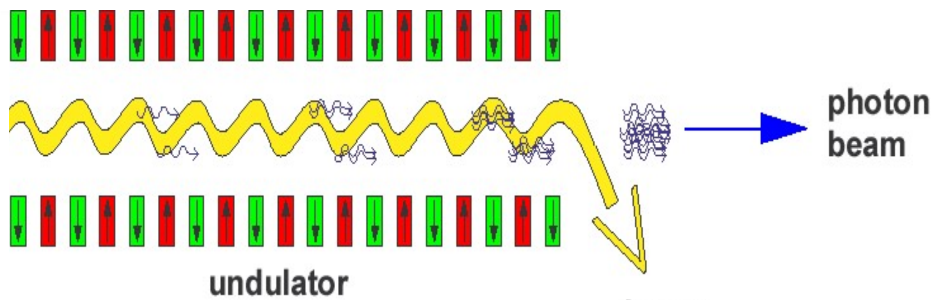
Coherent bunch

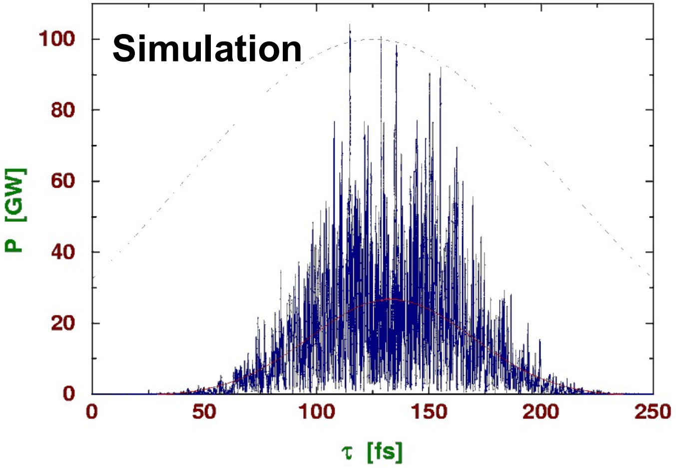
Lasing in one Pass : Self Amplified Spontaneous Emission (SASE)

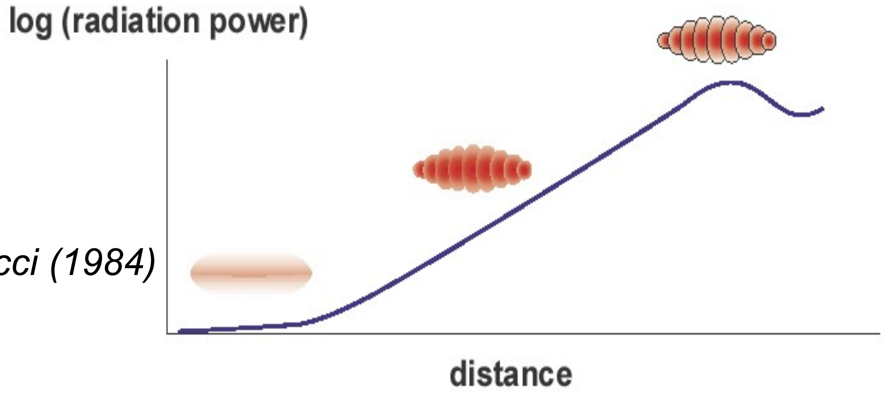
Tightly collimated (low emittance) electron beam in a long undulator: coherent emission results from microbunching, produced by amplification of shot-noise density fluctuations at the resonant

s it progresses through the bunch.









Kondratenko, Saldin (1979)
Bonifacio, Pellegrini, Narducci (1984)

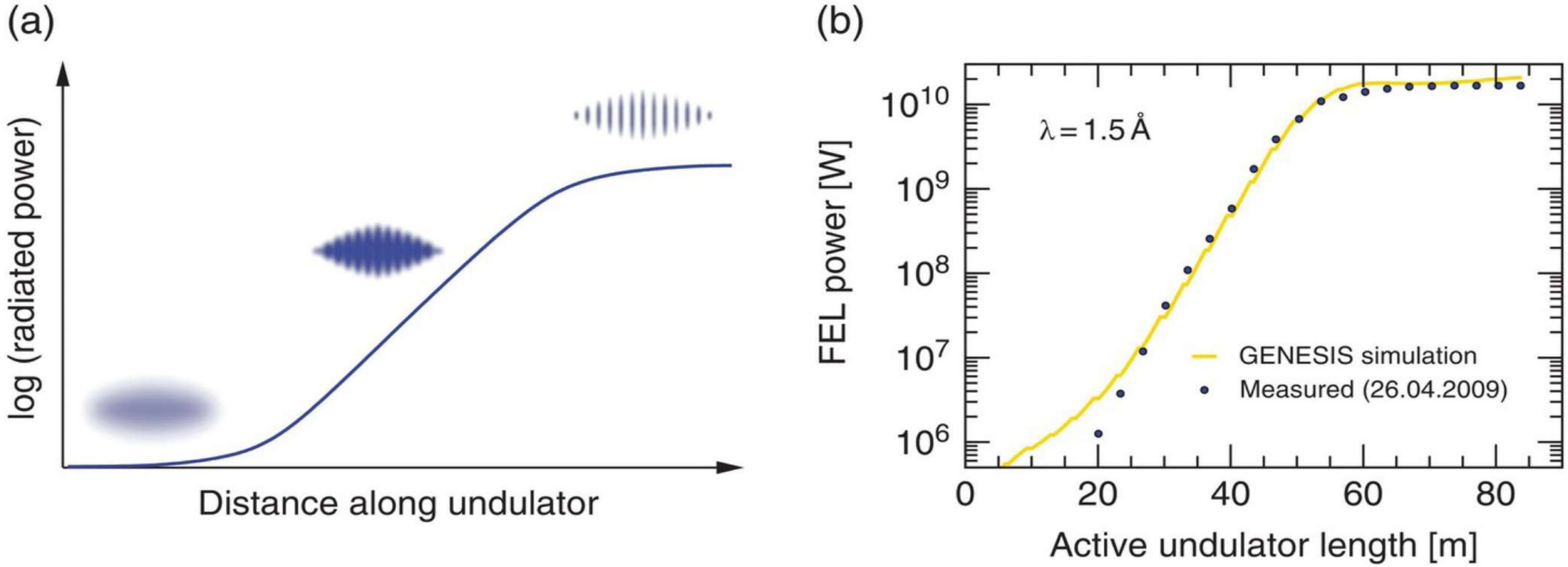
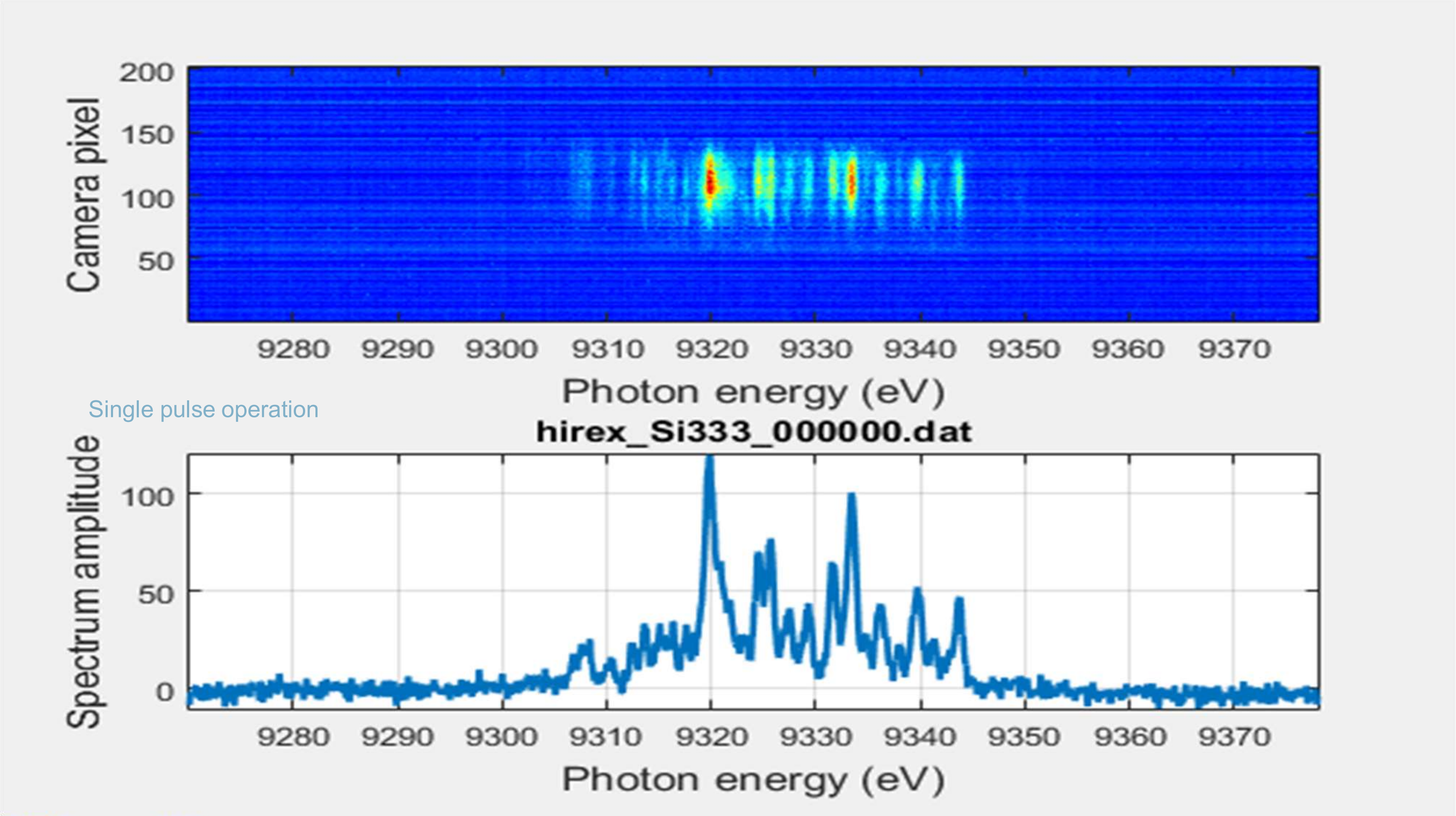


Figure 4.6 The self-amplification spontaneous-emission (SASE) process in an XFEL undulator. (a) Because of the interaction of the electrons with the synchrotron radiation they emit, a longitudinal density modulation (microbunching) develops together with a resulting exponential growth of the radiation power along the undulator. Note that in reality the number of microbunches within a conventional electron bunch is much larger than shown here ($\geq 10^5$ for x-ray FELs). (b) The gain/saturation curve measured at the LCLS in April 2009, along with the theoretically expected curve, calculated using the GENESIS simulation package. Reprinted from [12] courtesy Paul Emma and John Galayda, SLAC National Accelerator Laboratory, with permission of Macmillan Publishers Ltd.

Spectrum from Si111 crystal with 333 reflection with 200 shots



Single pulse operation

Courtesy Naresh Kujala

Kujala, SRI2018

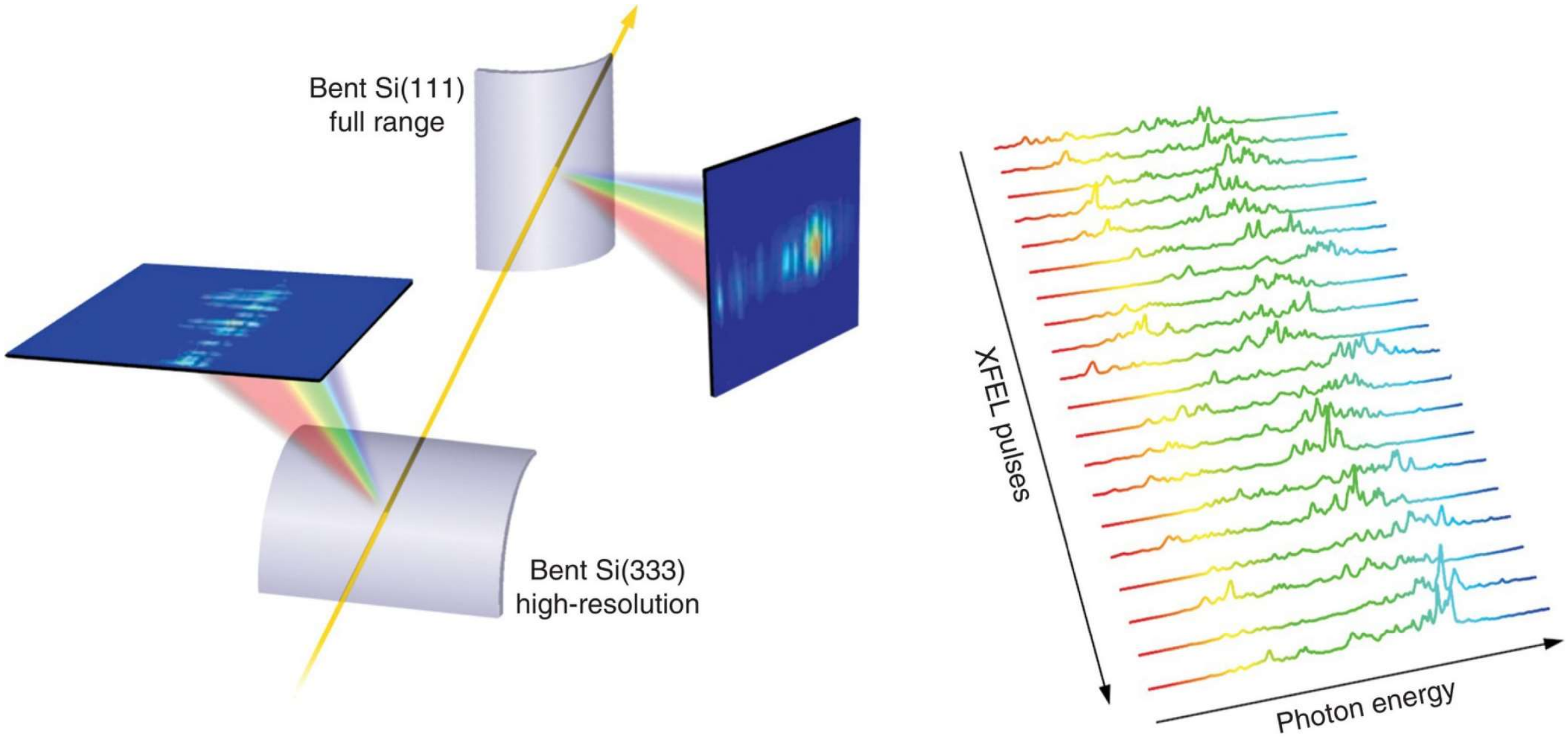
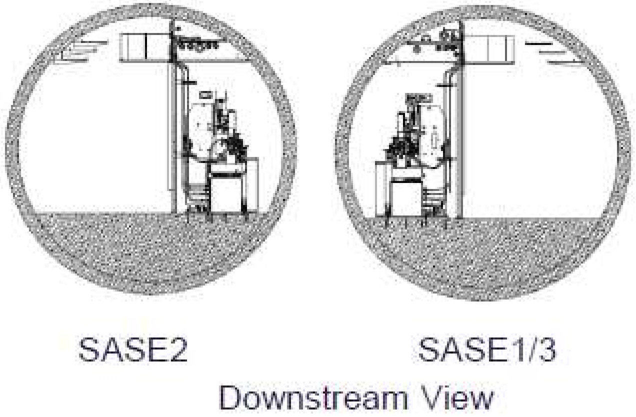


Figure 4.8 In-line spectral diagnostics for hard x-ray FEL pulses. Left: by bending thin single-crystal wafers of Si(111), the SASE spectral features can be spatially dispersed onto an area detector. The bent Si(111) crystal used for the full-range diagnostics provides a resolution of $\Delta E/E \approx 1.3 \times 10^{-4}$, or $\Delta E = 1$ eV at 8 keV. The Si(333) crystal, on the other hand, has a resolution of 9×10^{-6}, or 0.07 eV at 8 keV, sufficiently narrow to resolve individual SASE spikes, which are typically separated at 8 keV by approximately 0.2 eV. Right: the SASE spectra can fluctuate significantly from shot to shot, not least regarding the photon energy for which the maximum intensity is found. Adapted from [16] with permission of the American Institute of Physics.

Kujala, SRI2018

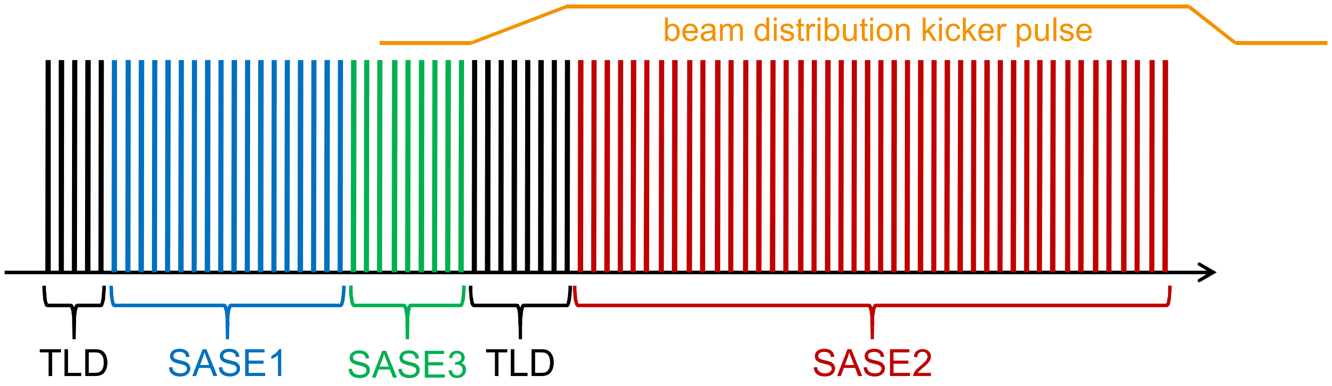
FEL undulators

- 2 hard & 1 soft x-ray devices
- 91 segments of undulator, phase shifter, air coils
- Conventional technology
  - NdFeB magnets, 10 mm



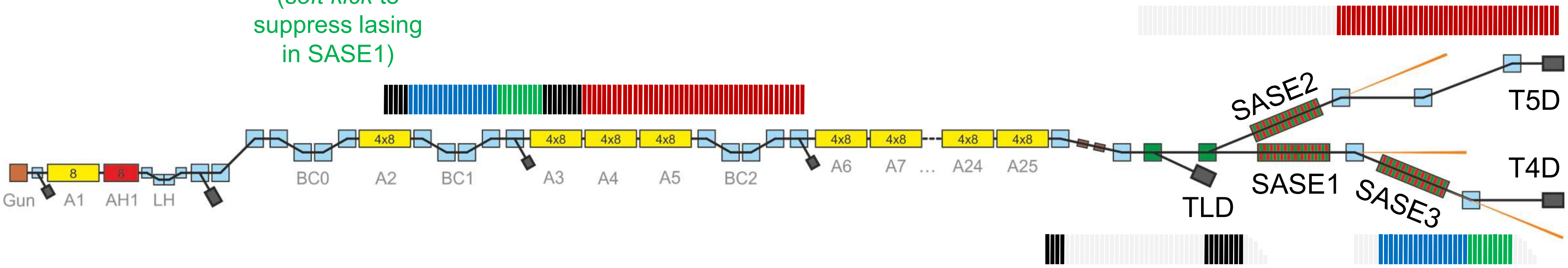
450 m total magnetic length, periods 40&68 mm ➔ ~40.000 single magnets

A Typical Bunch Pattern for User Operation



(*soft kick* to suppress lasing in SASE1)

© J.P. Lon / CC BY-SA 3.0
(via Wikimedia Commons)



Slide by L. Fröhlich (DESY)

Screeshot Machine Status : Note the measurement is pulse energy

Accelerator: **Studies**

2019-06-11 07:11

2019-06-09 10:38

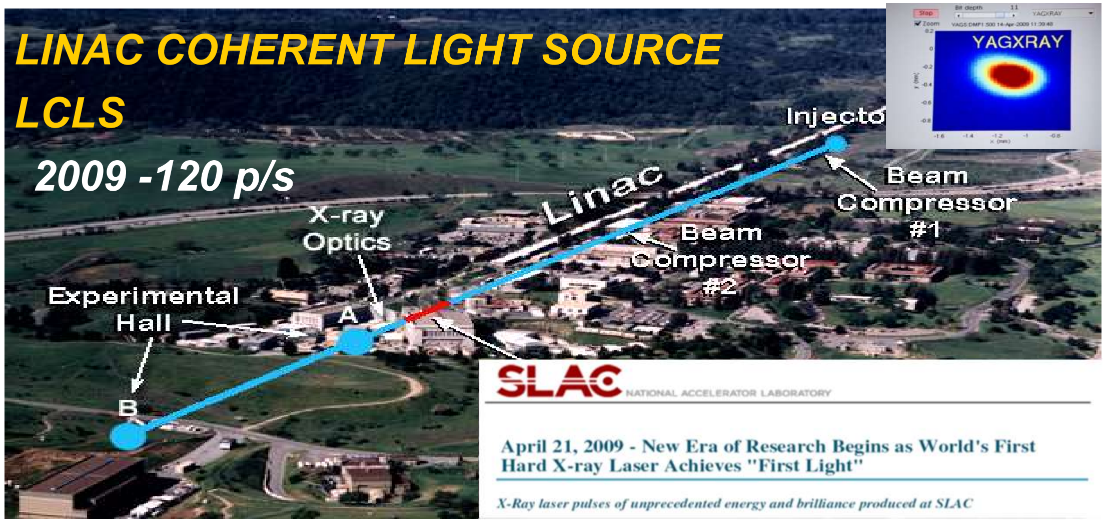
SASE1:

SASE2:

SASE3:

SASE3: **SCS**

The European XFEL in the International Context : Hard X-ray FELS



LINAC COHERENT LIGHT SOURCE

LCLS

2009 -120 p/s

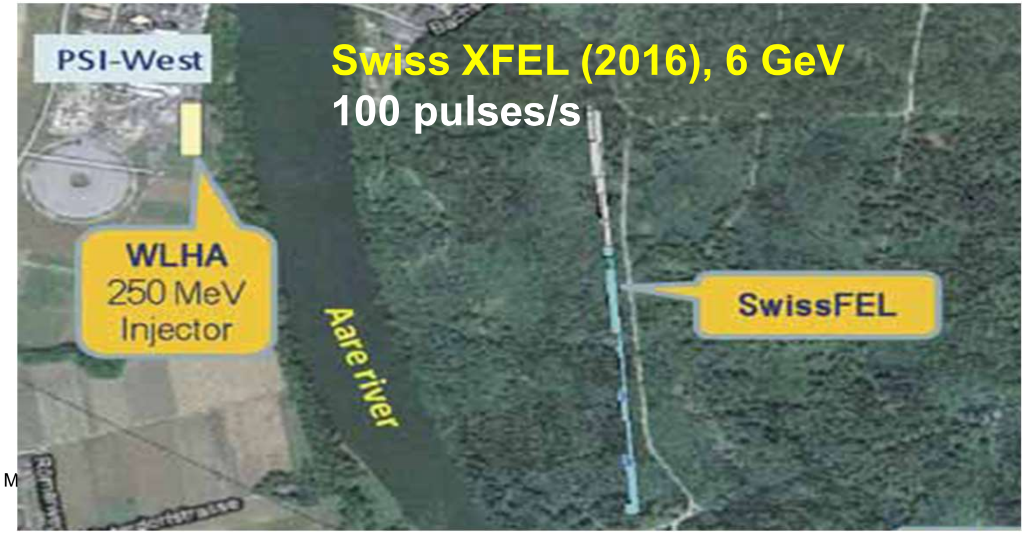
April 21, 2009 - New Era of Research Begins as World's First Hard X-ray Laser Achieves "First Light"

X-Ray laser pulses of unprecedented energy and brilliance produced at SLAC

2011-60 p/s

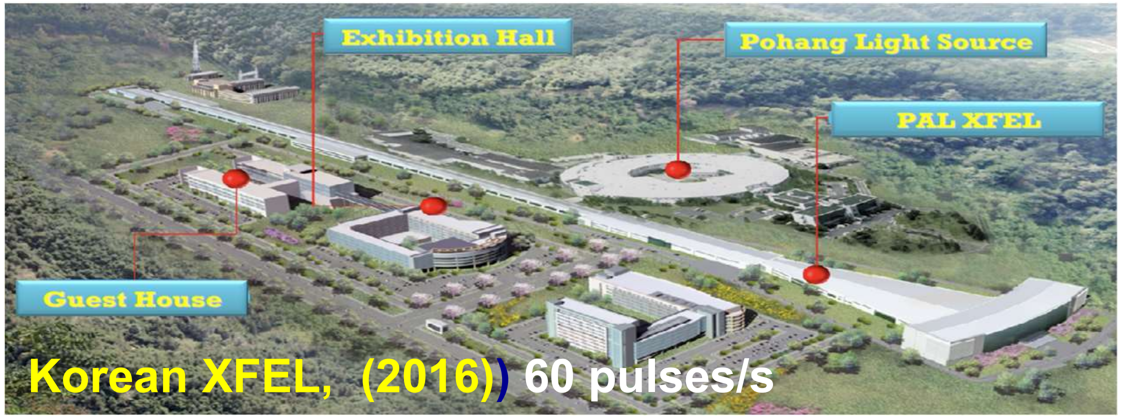
SACLA

SPring-8 Angstrom Compact LAser



Swiss XFEL (2016), 6 GeV

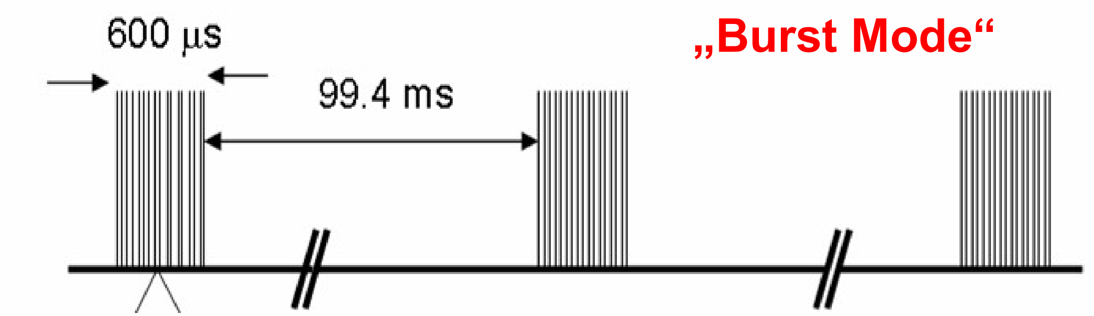
100 pulses/s



Korean XFEL, (2016)) 60 pulses/s

Key parameters of European XFEL (*Superconducting Accelerator*)

Parameter	Value
Electron Energy	8.5 – 17.5 GeV
Photon energy	0.26 - >25 keV
Pulse duration	2 – 100 fs
Seeding	In preparation
# of pulses	27000 /s
# of FELs	3
# of instruments	6
Start of operation	2017

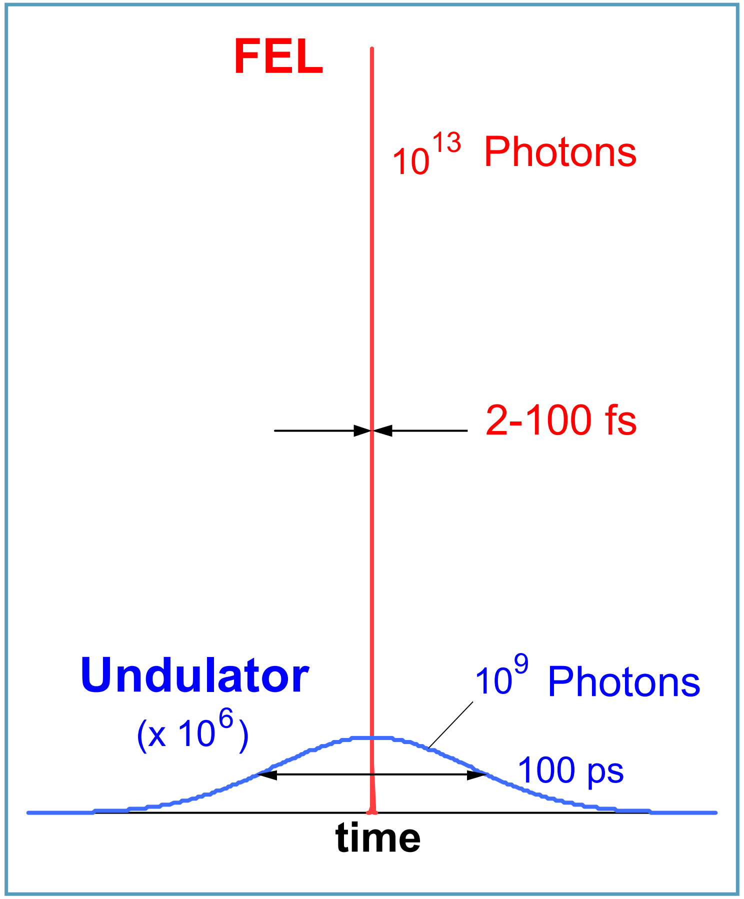


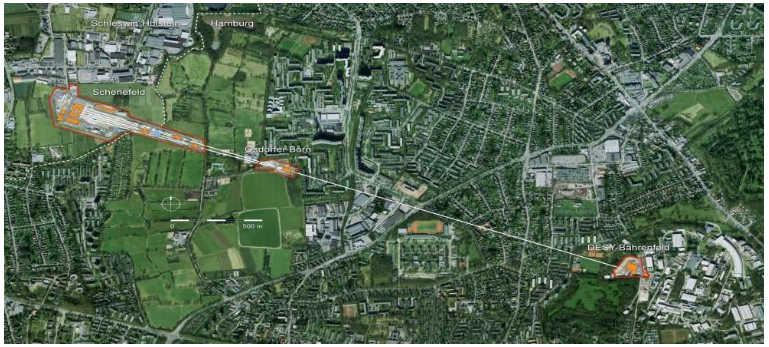
„Burst Mode“

- Specific electron & x-ray beam delivery pattern
  - Follows from pulsed RF system
  - Trains of e-/x-ray pulses
  - Max. = 2.700 per train / 27.000 per sec

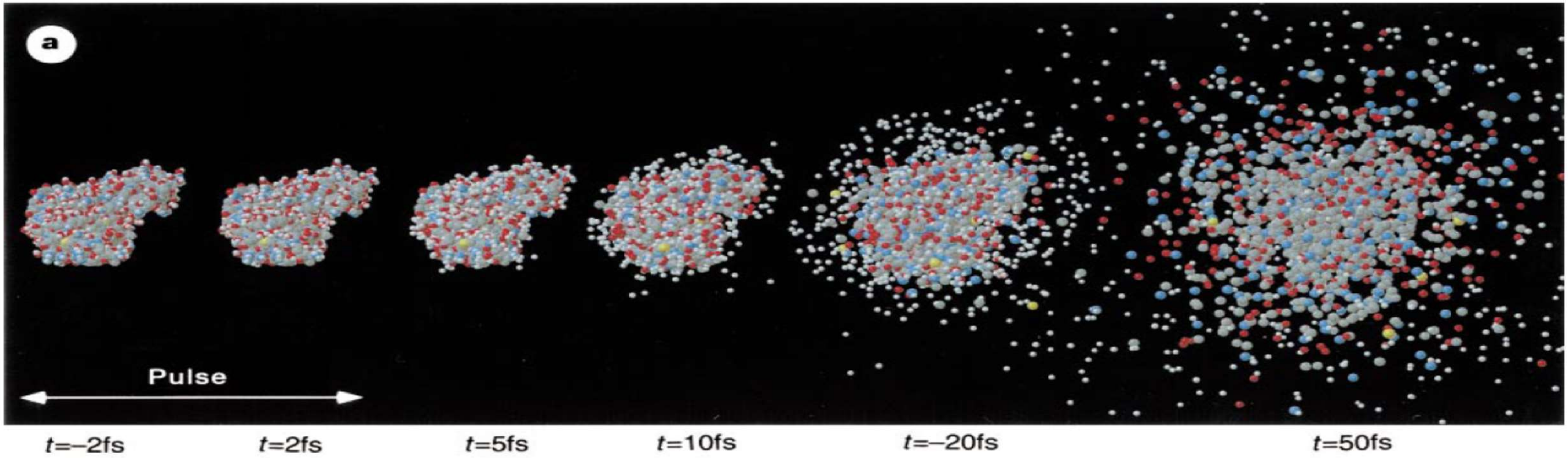
  - High average brilliance
  - Feedback & time and space stabilization
  - Dedicated pulse delivery

What is the difference between Synchrotron Radiation and X-ray Lasers?



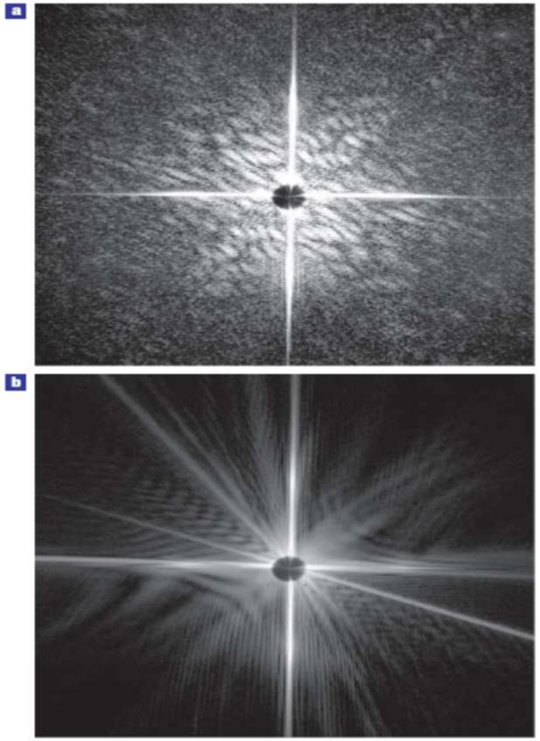


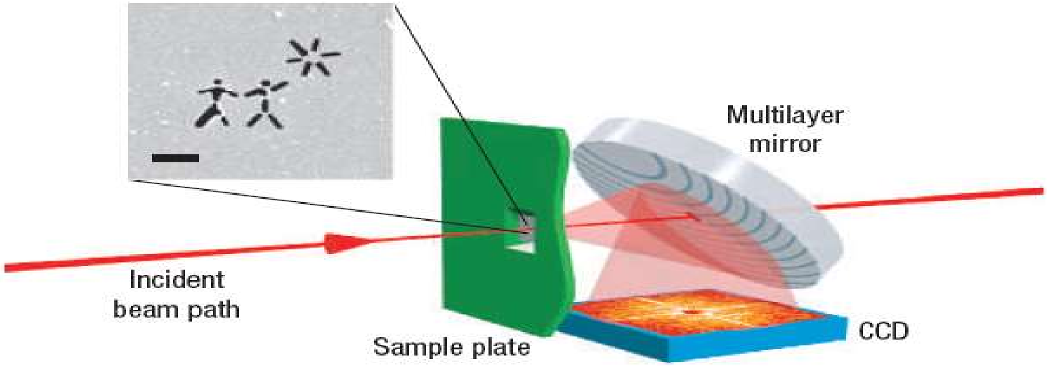
The exploding protein

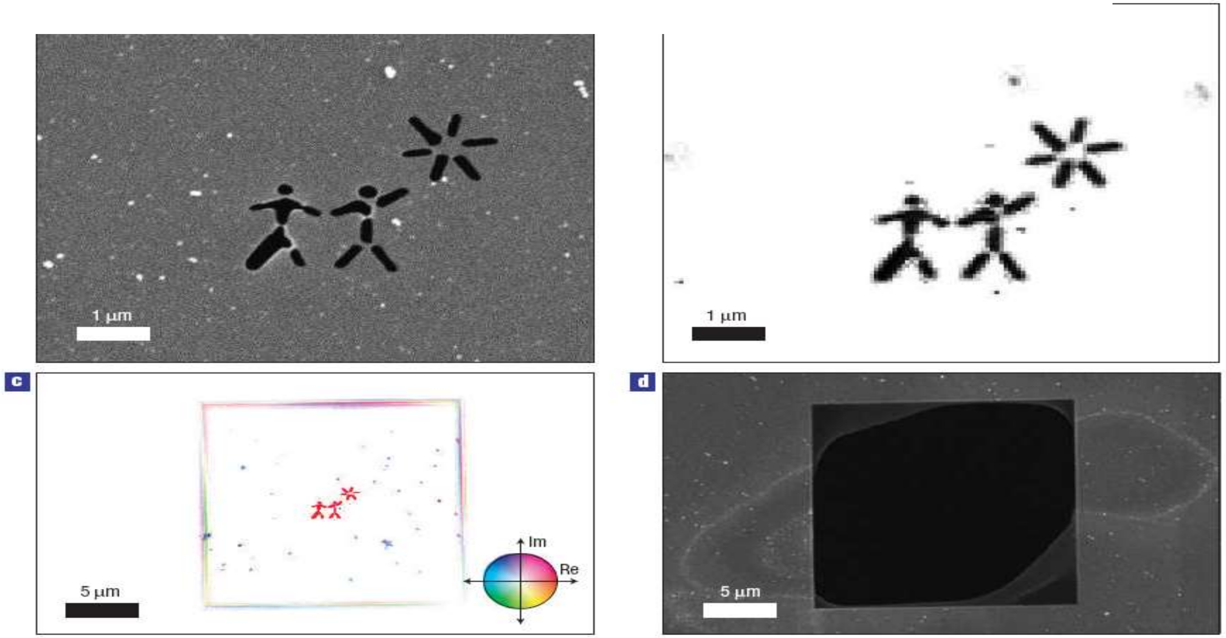


*R.Neutze, R. Wouts, D. Van der Spoel, E. Weckert, J Hajdu, Nature **406**, 2000*

First groundbreaking experiments at FLASH

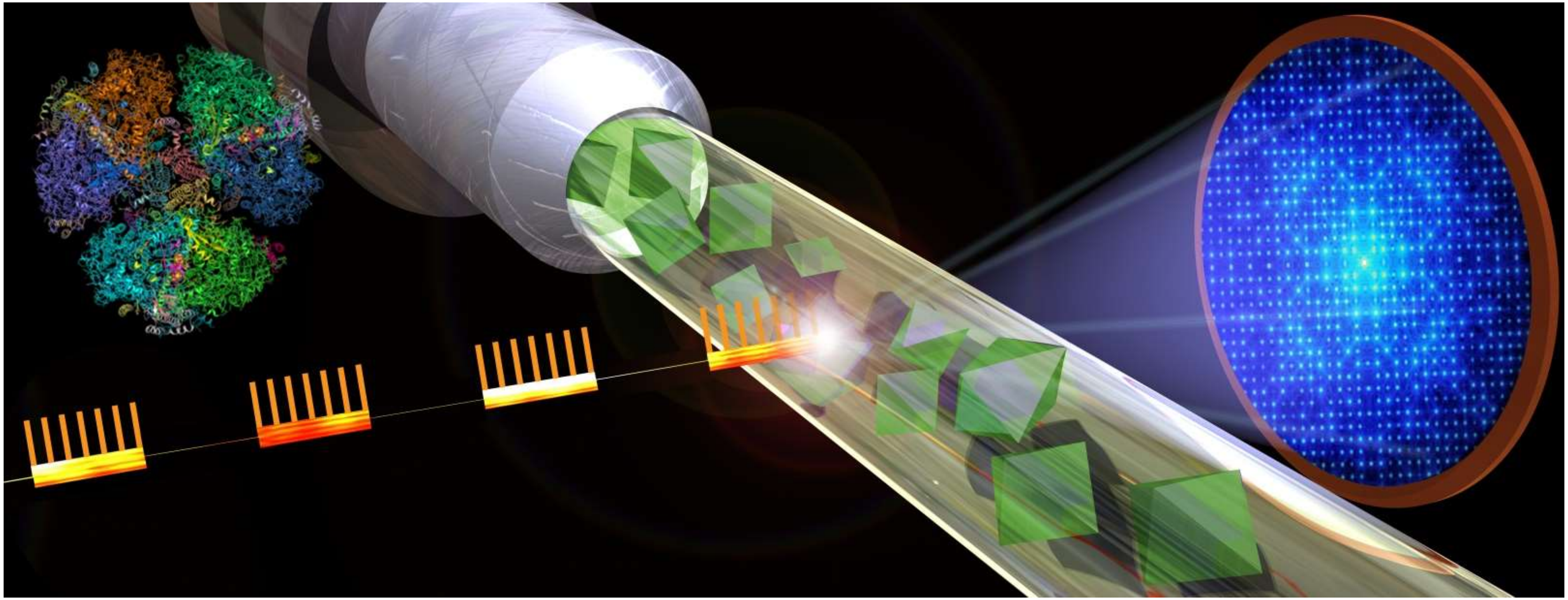






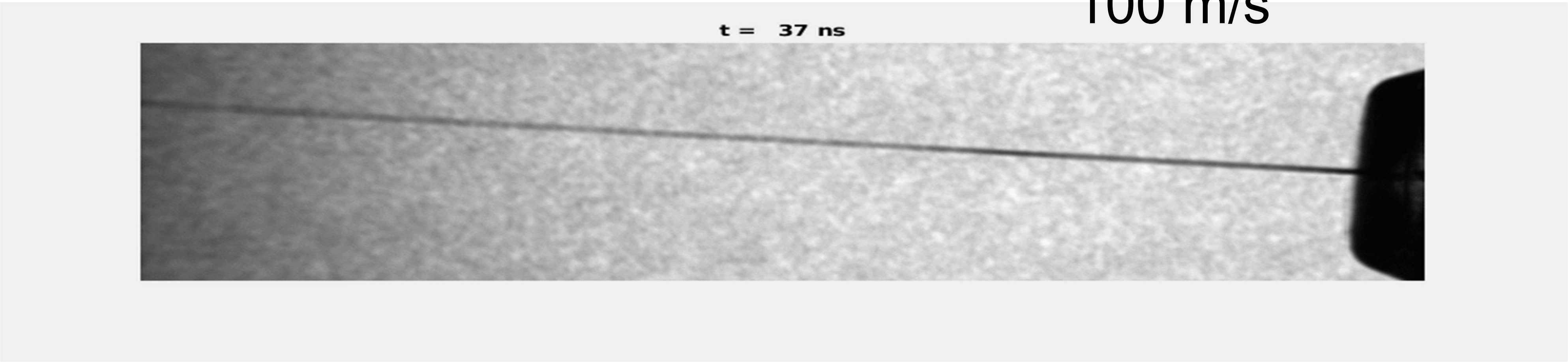
Chapman et al
Nature Physics 2006

Experiments are typically done in a radial different manner



Jets - Sample delivery

100 m/s



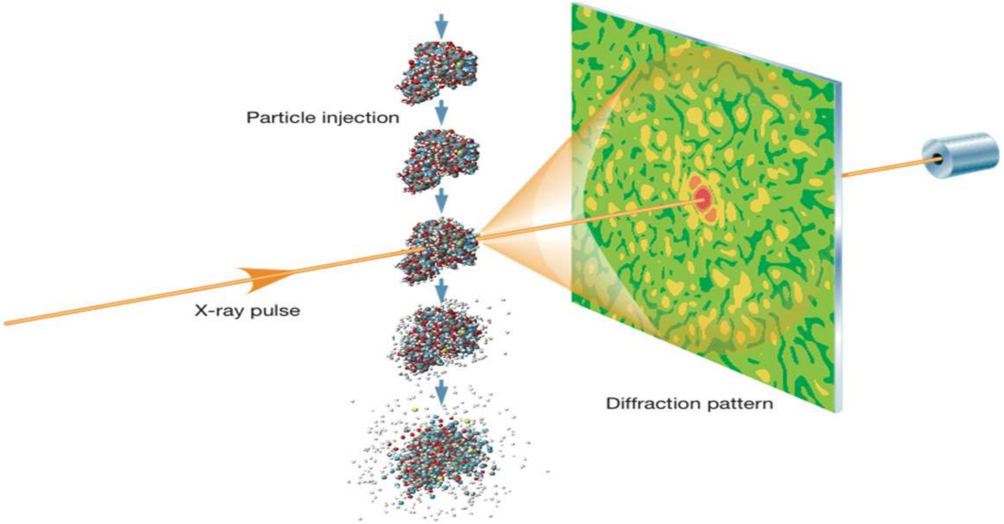
Max Wierdorn, Claudio Stan

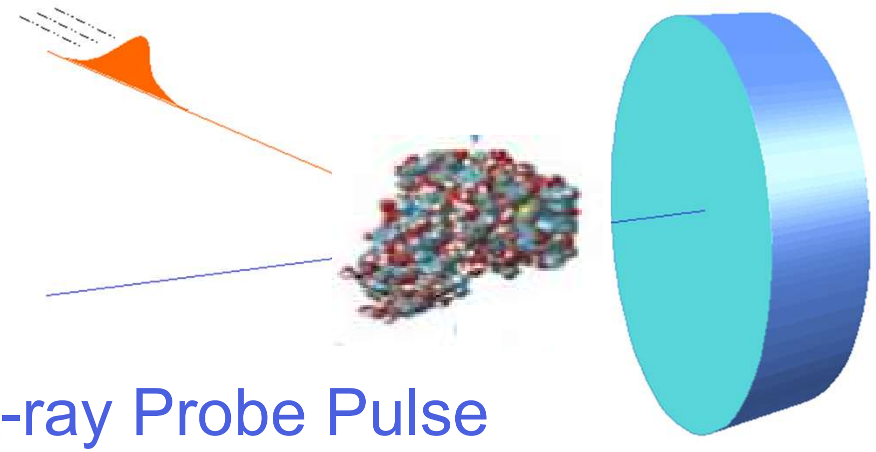
European XFEL

(courtesy A. Barty, H. Chapman)

CFEL SCIENCE

Science Case : Making Molecular Movies

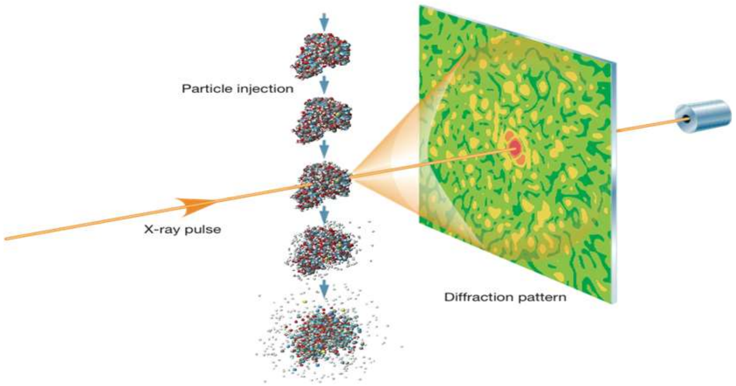


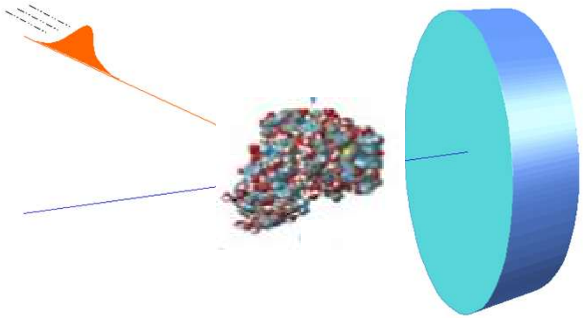


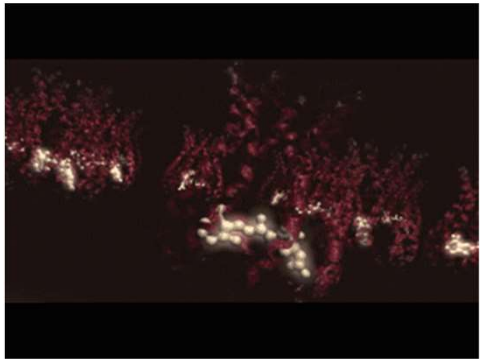
Optical Laser Pump Pulse

X-ray Probe Pulse

Making Molecular Movies

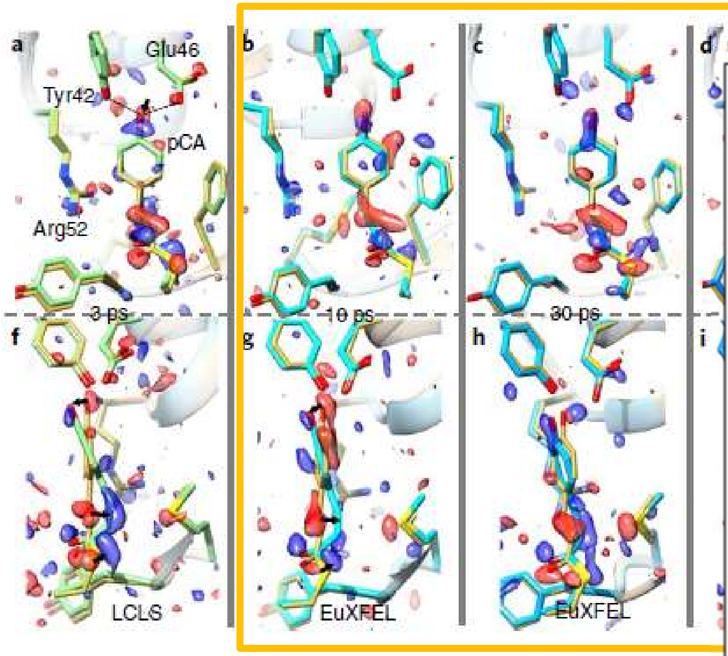


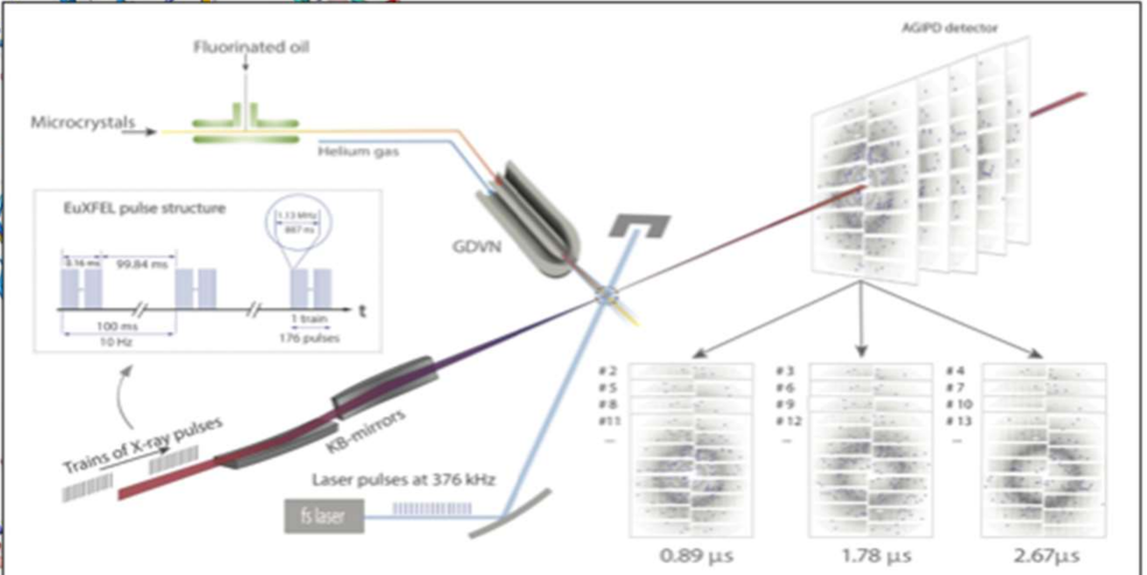




TR-SFX at the pico second time scale.

NATURE METHODS ARTICLES





Extended Data Fig. 1 | Setup of a MHz TR-SFX experiment at the EuXFEL (modified from Wiedorn et al., 2018). X-ray pulses arrive in 1.13 MHz bursts which repeat every 100 ms. There are 176 X-ray pulses in the burst. The KB-mirror system focuses the X-ray beam to a 2 – 3 µm focal spot. The fs-laser delivers 376 kHz pulses (λ=420 nm, blue) synchronized to the X-ray pulses. The laser focus is 42 µm Ø in the X-ray interaction region (dotted circle). The microcrystals are mixed with fluorinated oil and injected by a GDVN. The jet produced by the GDVN, the laser beam as well as the X-ray pulses precisely intersect. The time-resolved diffraction patterns are collected by the AGIPD. Diffraction patterns with common time-delays were separated based on the pulse ID (see also Fig. 2b) and combined to datasets.

Time series of TRX data from 3 ps to 100 ps at LCLS
and difference electron density of the photocycle of

Synchrotron **XFEL**

Dynamic Phenomena

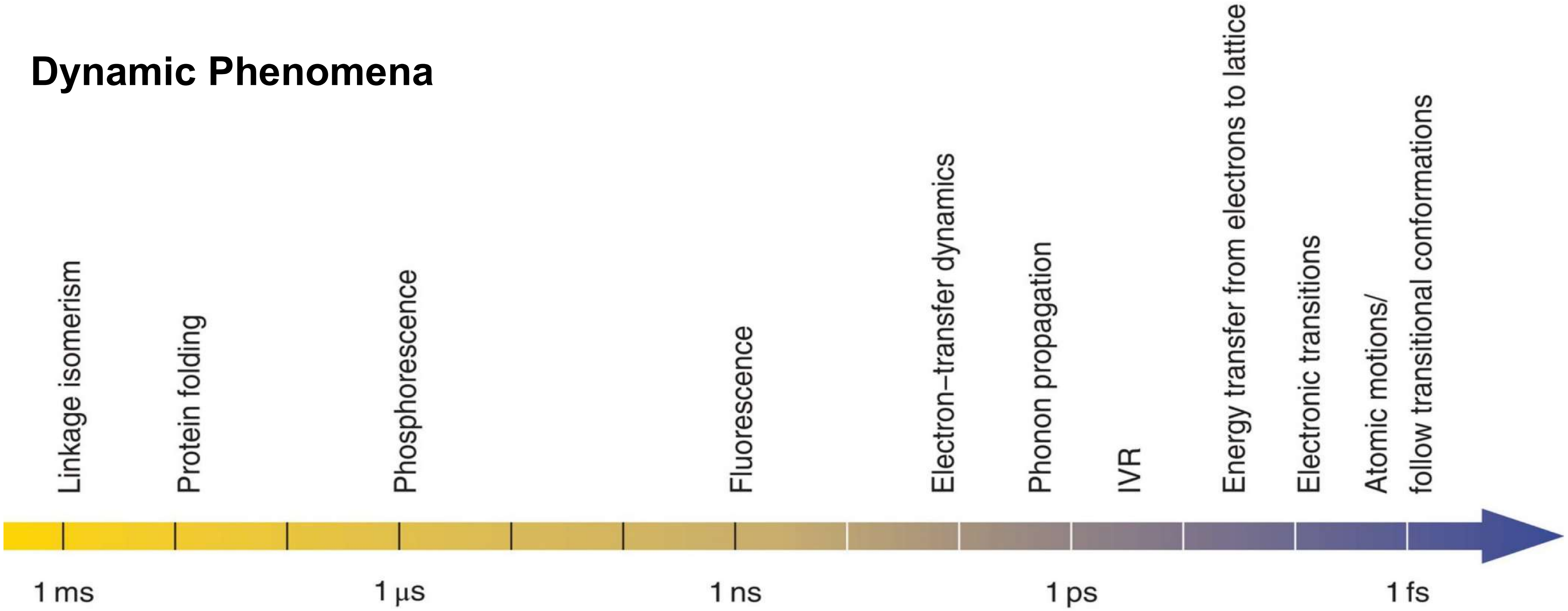
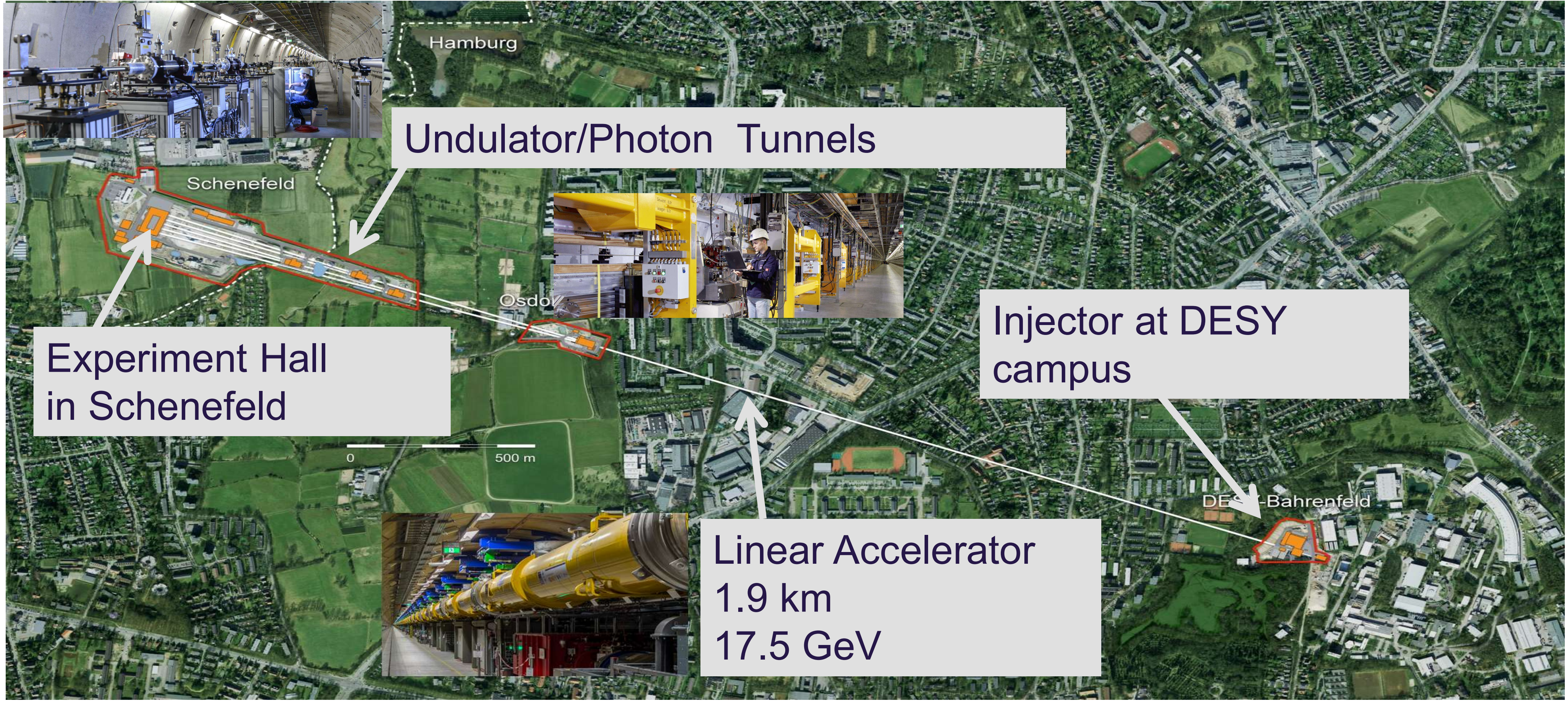


Figure 4.1 Typical time-scales for different dynamical processes in matter. IVR = intramolecular vibrational energy redistribution. The position of any one process is only meant to be representative, and may in reality span a broader range, depending on the details of the system; for example, protein folding is known to cover approximately eight decades, from minutes to microseconds.

General layout of the European XFEL



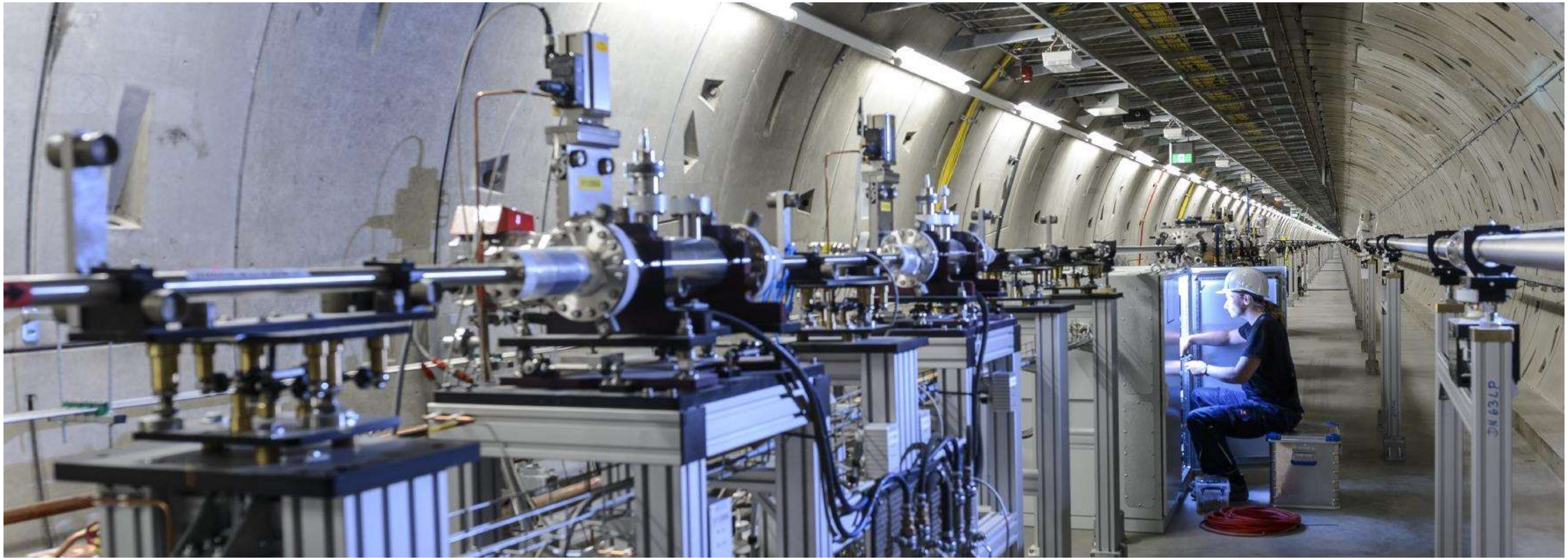
Undulator/Photon Tunnels

Experiment Hall
in Schenefeld

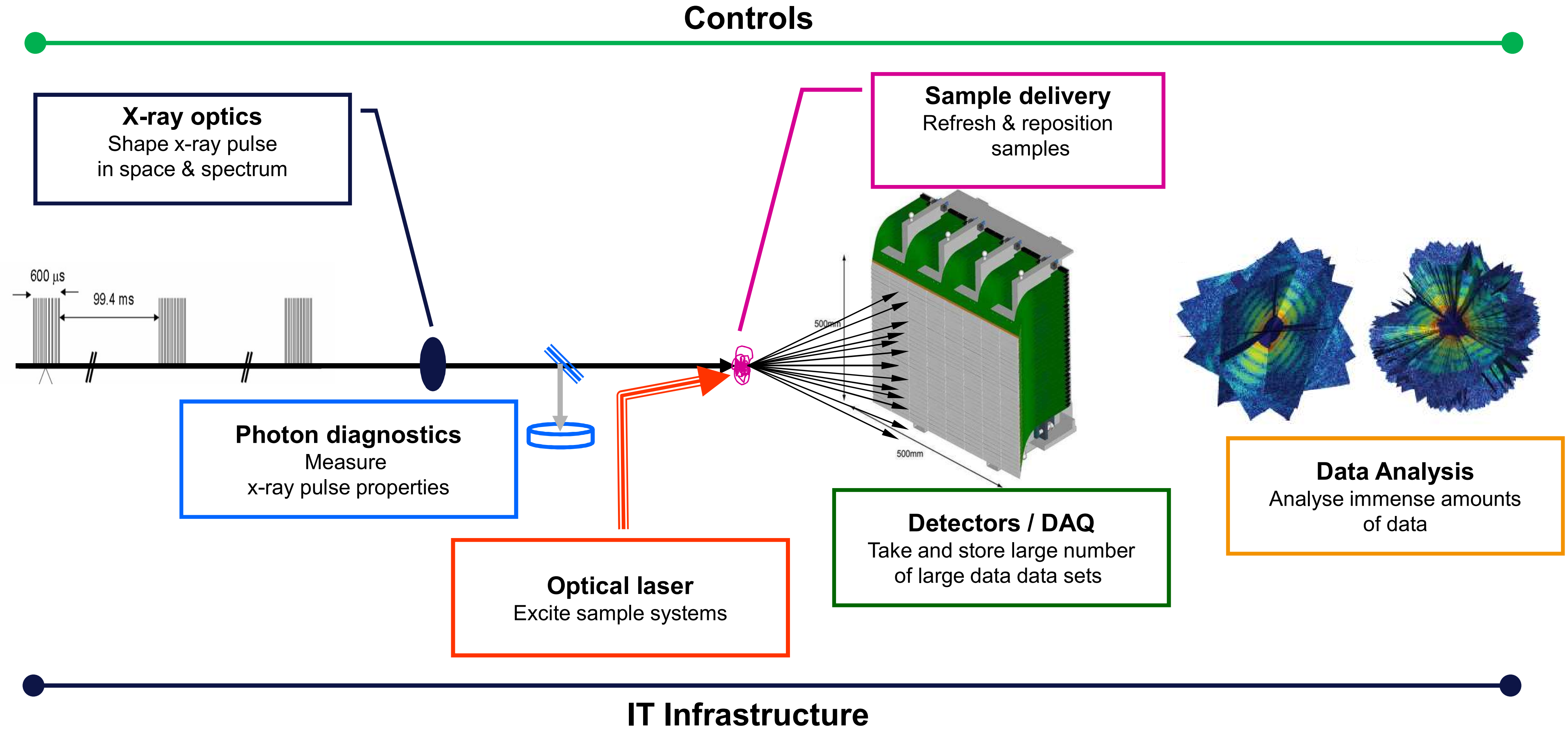
Injector at DESY
campus

Linear Accelerator
1.9 km
17.5 GeV

Photon beamlines (~ 900 m)



Complexity of Experiments:



Controls

X-ray optics
Shape x-ray pulse
in space & spectrum

Sample delivery
Refresh & reposition
samples

Photon diagnostics
Measure
x-ray pulse properties

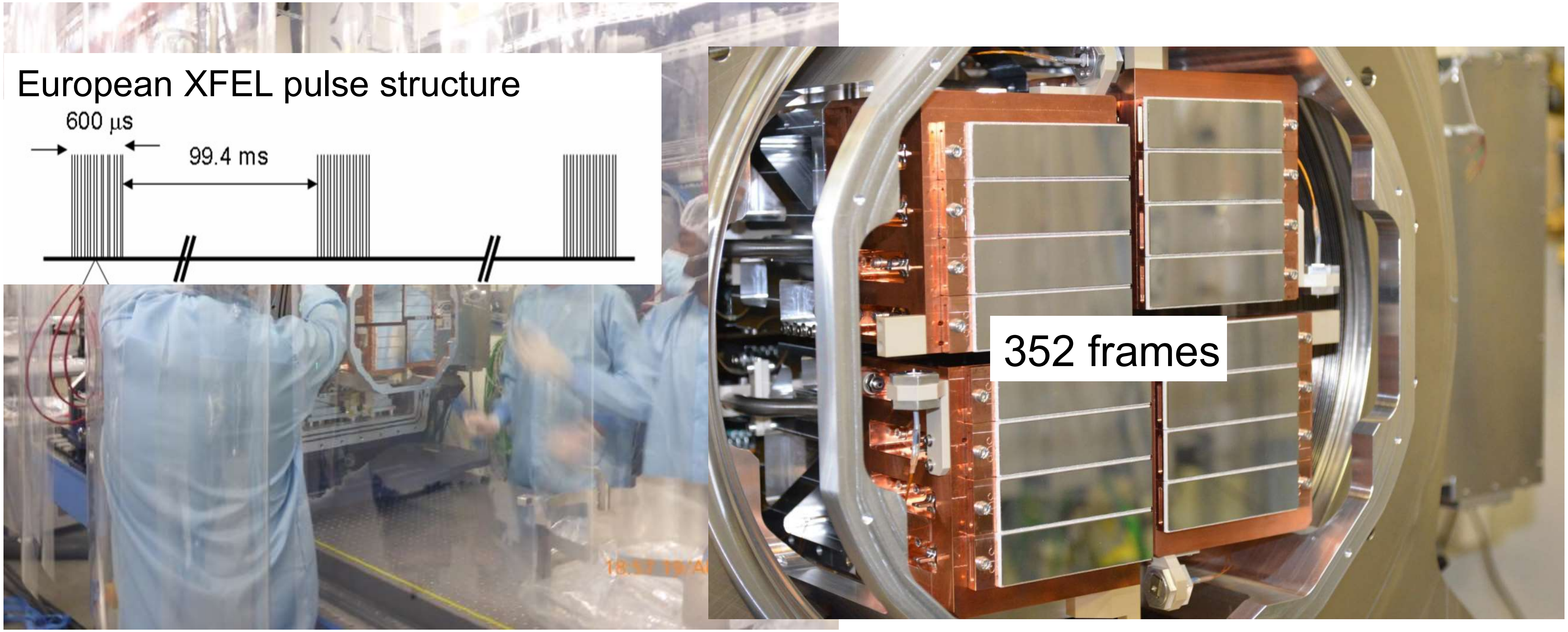
Data Analysis
Analyse immense amounts
of data

Detectors / DAQ
Take and store large number
of large data data sets

Optical laser
Excite sample systems

IT Infrastructure

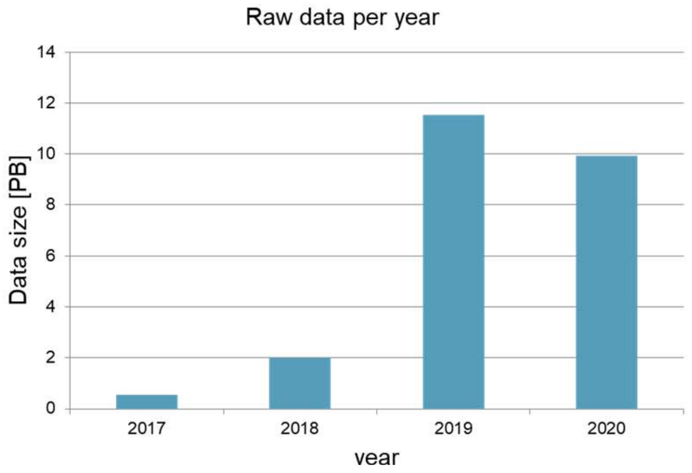
AGIPD Detector at SPB/SFX : Adaptive gain detector



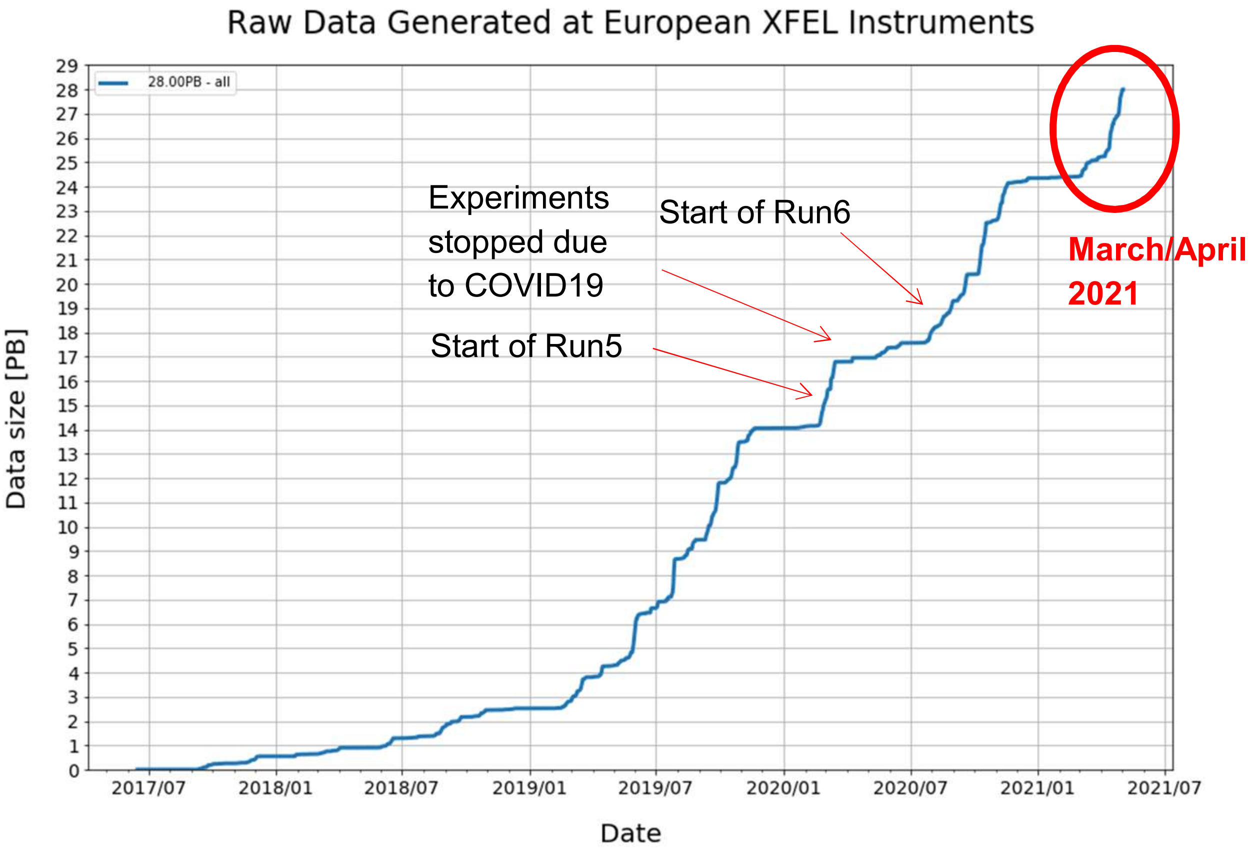
Courtesy Adrian Mancuso

Collection of Data.

- 10 PB of raw data collected in 2020 (despite pandemic)



- 500 pulses per train &1 Mpixel detector
- → 10^6 x 500 x 10 x 60 x 60 x 24 x 2bytes = 864 TB ~ 1PB *per day*



Experiments stopped due to COVID19

Start of Run6

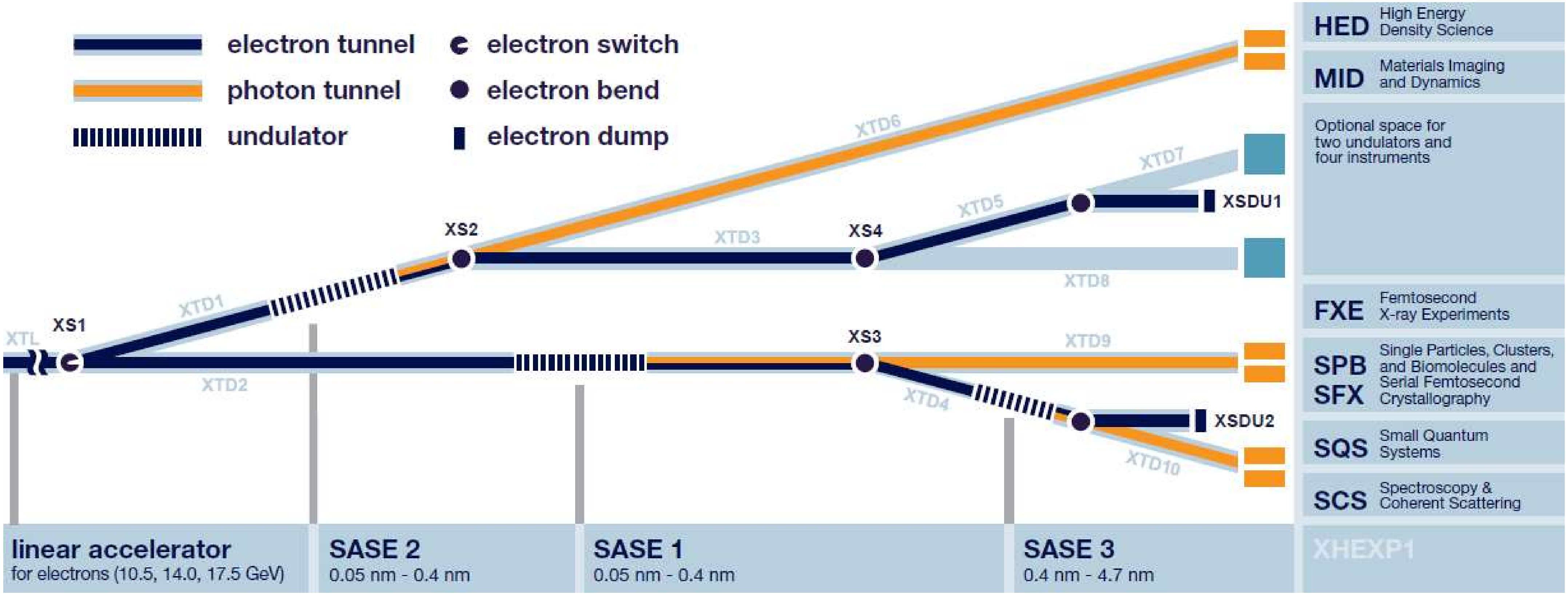
Start of Run5

March/April 2021

The Instruments

Experimental Hall

- Six Experimental Stations
- Typically running in 12 hour mode
- 3 Experiments run simultaneously



Scientific instruments

SASE1

FXE (Femtosecond X-ray Experiments)

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

Team: D. Khakhulin et al.

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

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

Team: A. Mancuso et al. / **SFX UC** (H. Chapman et al.)

SASE2

MID (Materials Imaging & Dynamics)

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

Team: A. Madsen et al.

HED (High Energy Density science)

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

Team: U. Zastrau et al. / **HiBEF UC** (T. Cowan et al.)

SASE3

SQS (Small Quantum Systems)

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

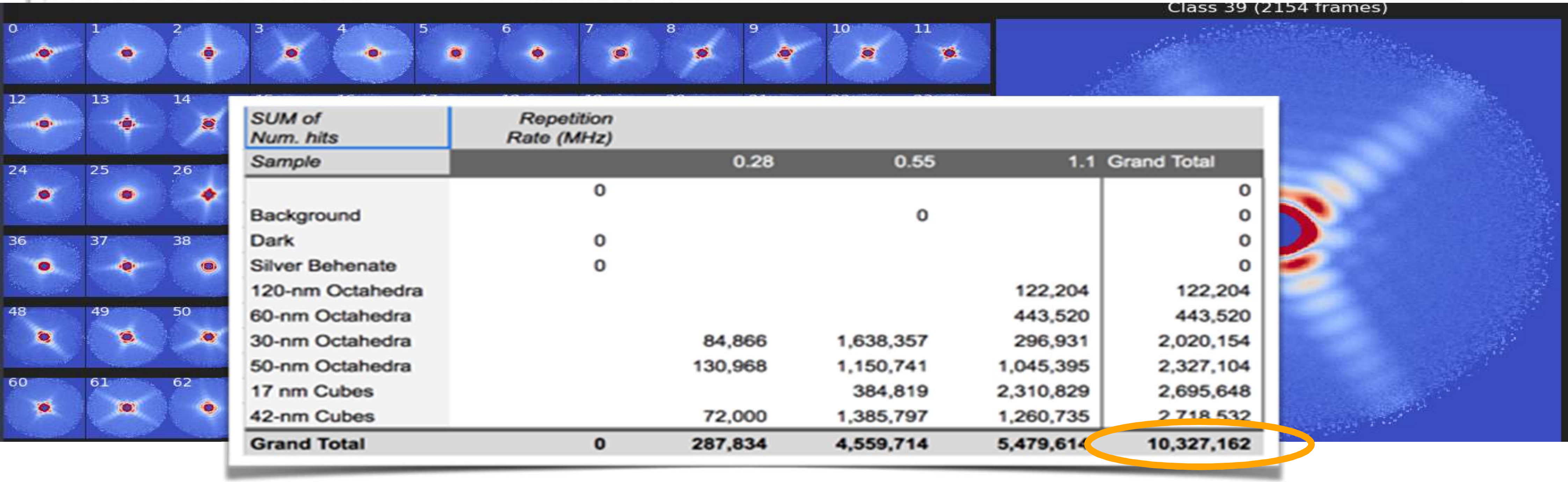
Team: M. Meyer et al.

SCS (Spectroscopy & Coherent Scattering)

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

Team: A. Scherz et al. / **hRIXS** UC (A. Föhlisch et al.)

SPB/SFX : Scattering from many many Au particles, radical new type of experiment

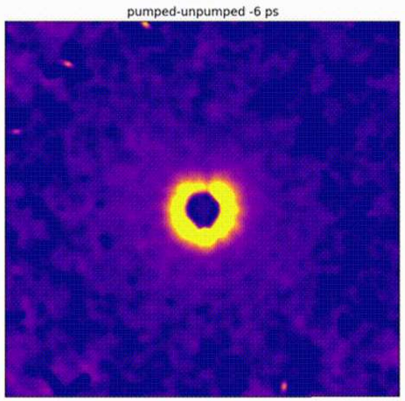


SUM of Num. hits	*Repetition Rate (MHz)*				
Sample		0.28	0.55	1.1	Grand Total
	0				0
Background			0		0
Dark	0				0
Silver Behenate	0				0
120-nm Octahedra				122,204	122,204
60-nm Octahedra				443,520	443,520
30-nm Octahedra		84,866	1,638,357	296,931	2,020,154
50-nm Octahedra		130,968	1,150,741	1,045,395	2,327,104
17 nm Cubes			384,819	2,310,829	2,695,648
42-nm Cubes		72,000	1,385,797	1,260,735	2,718,532
Grand Total	**0**	**287,834**	**4,559,714**	**5,479,61**	**10,327,162**

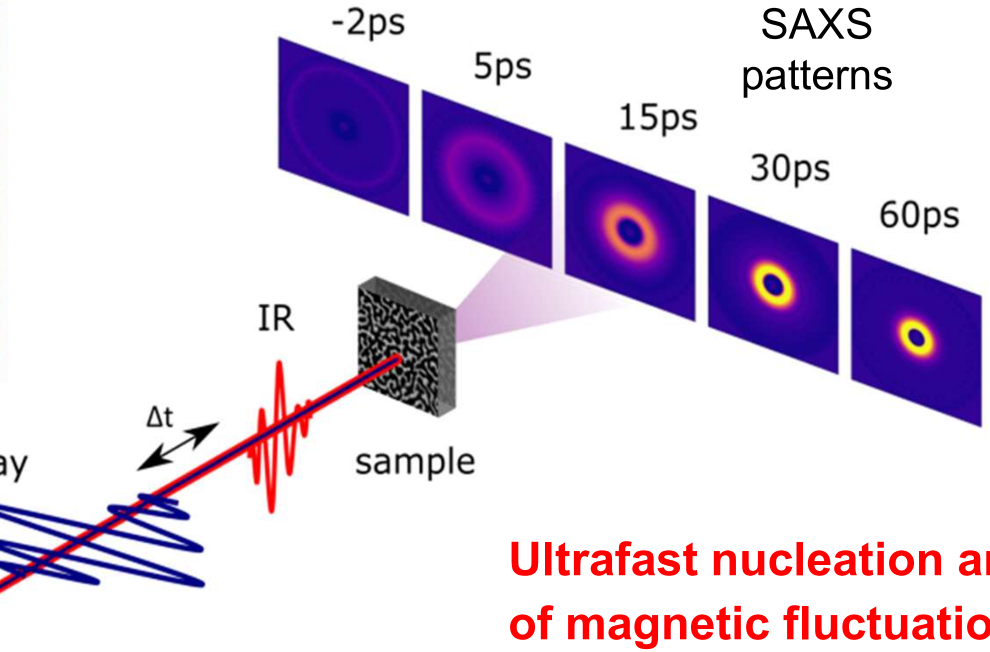
PI: Ayyer, experiment #2160

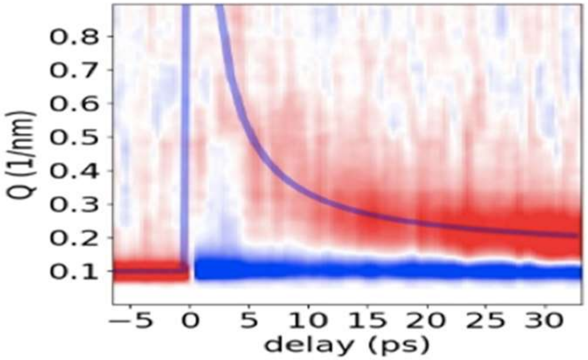
SCS: Magnetic fluctuations in ferromagnetic multilayers (I. Pronin, U ITMO, St. Petersburg)

- Experiment:
  - Nanosize Co/Pt multilayers with perpendicular magnetization
  - Pump-probe experiment in transmission geometry at SCS station
  - Resonant magnetic scattering at the Co L_3 edge
  - SAXS acquisition with ultrafast two-dimensional DSSC detector



SAXS vs delay time





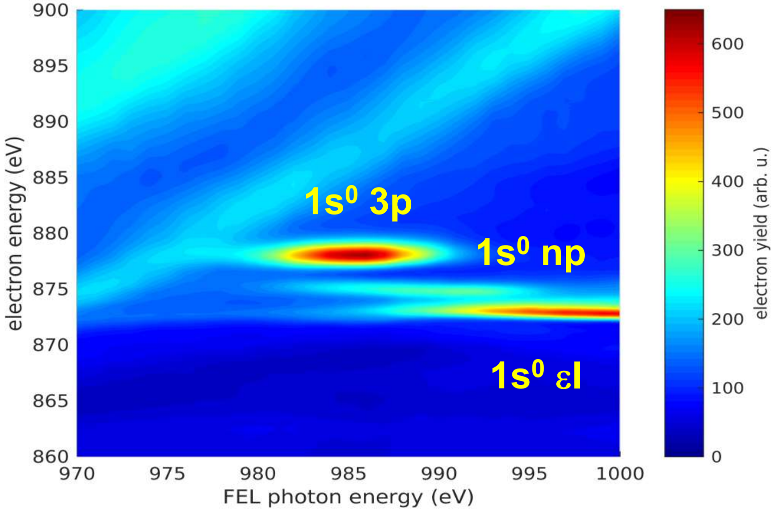
Ultrafast nucleation and subsequent coalescence of magnetic fluctuations occurs at ps time scale

SQS (Small Quantum Systems)

All experimental stations are operational !!!

AQS
(multi-photon spectroscopy)

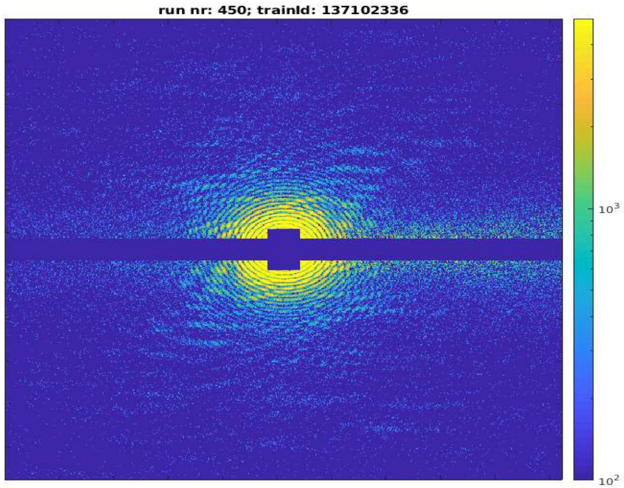
Non-linear electronic interaction of atoms with x-rays
PI: T. Mazza et al. (SQS)



Neon

NQS
(imaging)

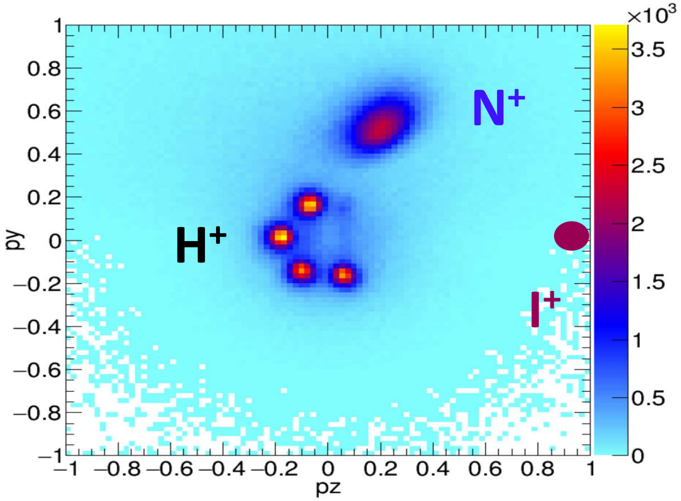
Doped He nanodroplets imaging
PI: R. Tanyag, D. Rupp (TU/MBI Berlin)



Xe-doped He droplet

SQS-REMI
(coincidences)

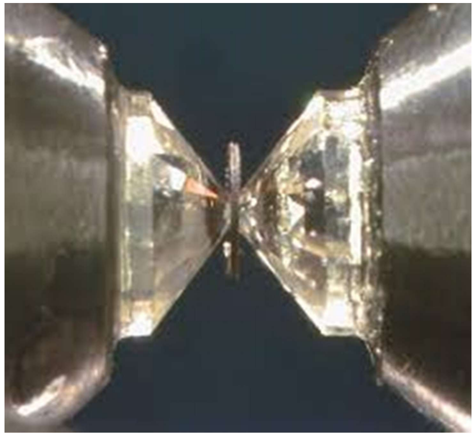
Charge transfer and Coulomb explosion initiated by fs X-ray pulses
PI: R. Boll et al. (SQS)



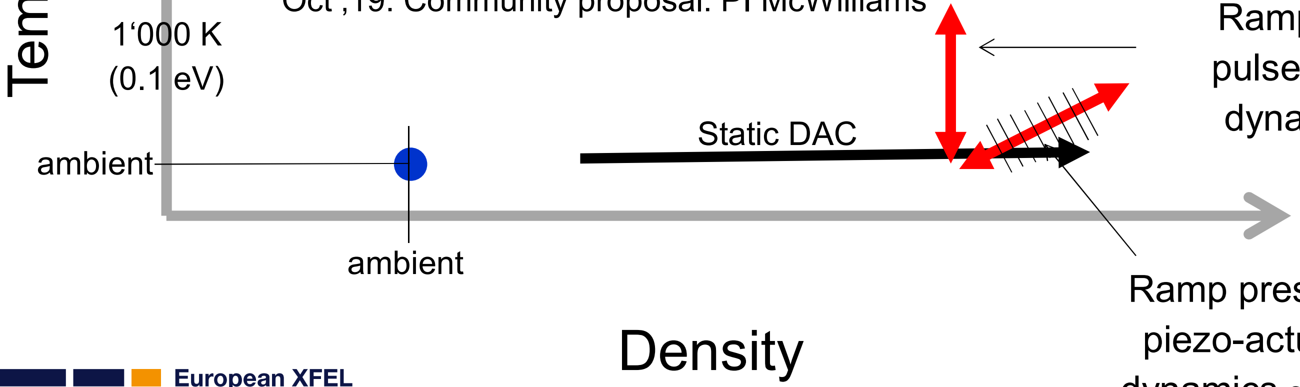
Iodopyridine

Diamond Anvil Cells at HED
static pre-compressed samples

Oct ,19: Community proposal: PI McWilliams



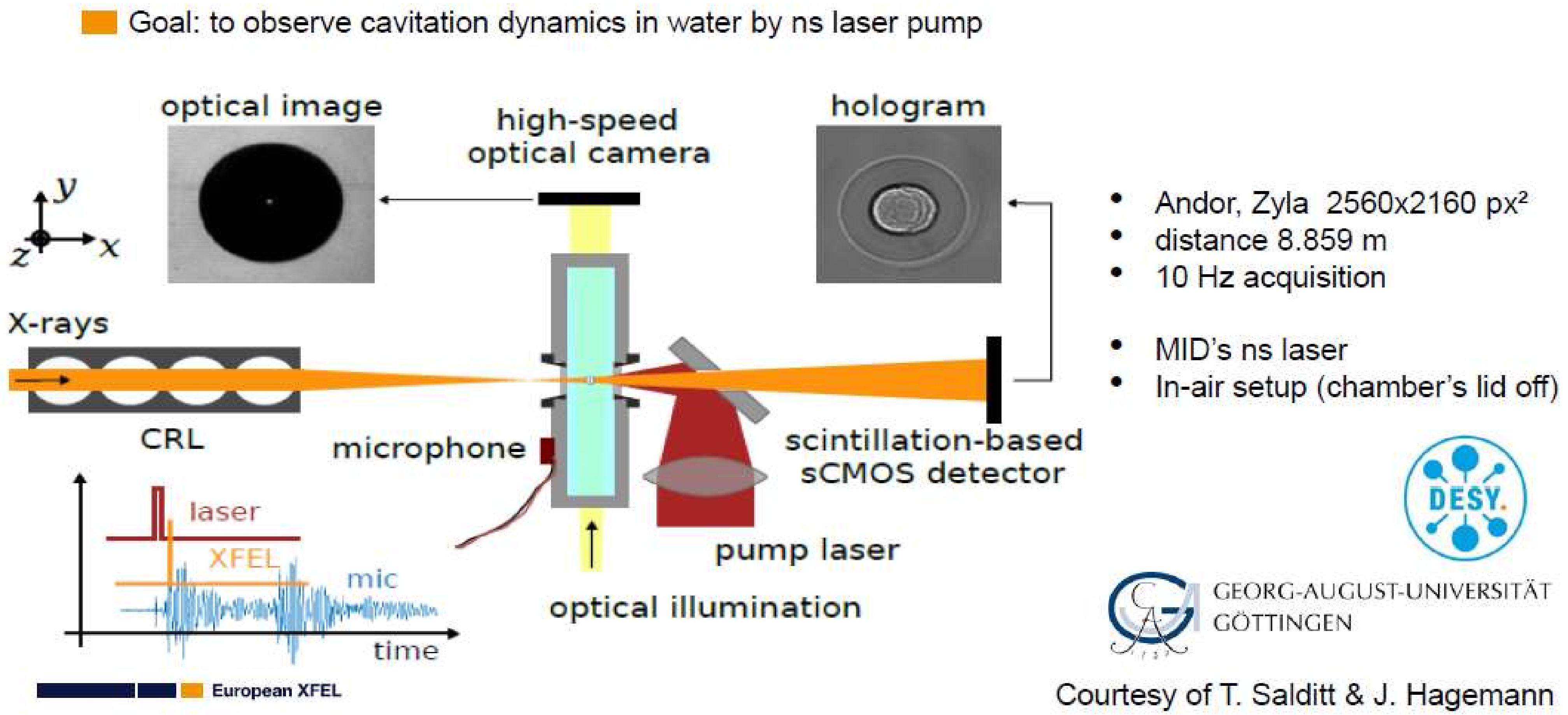
Pressures
up to
several Mbar



Ramp temperature:
pulsed laser heating
dynamics ~ few ns

Ramp pressure:
piezo-actuator
dynamics ~ 1 ms

MID: Time resolved Holography (*User Experiment Tim Salditt, Uni Göttingen*)



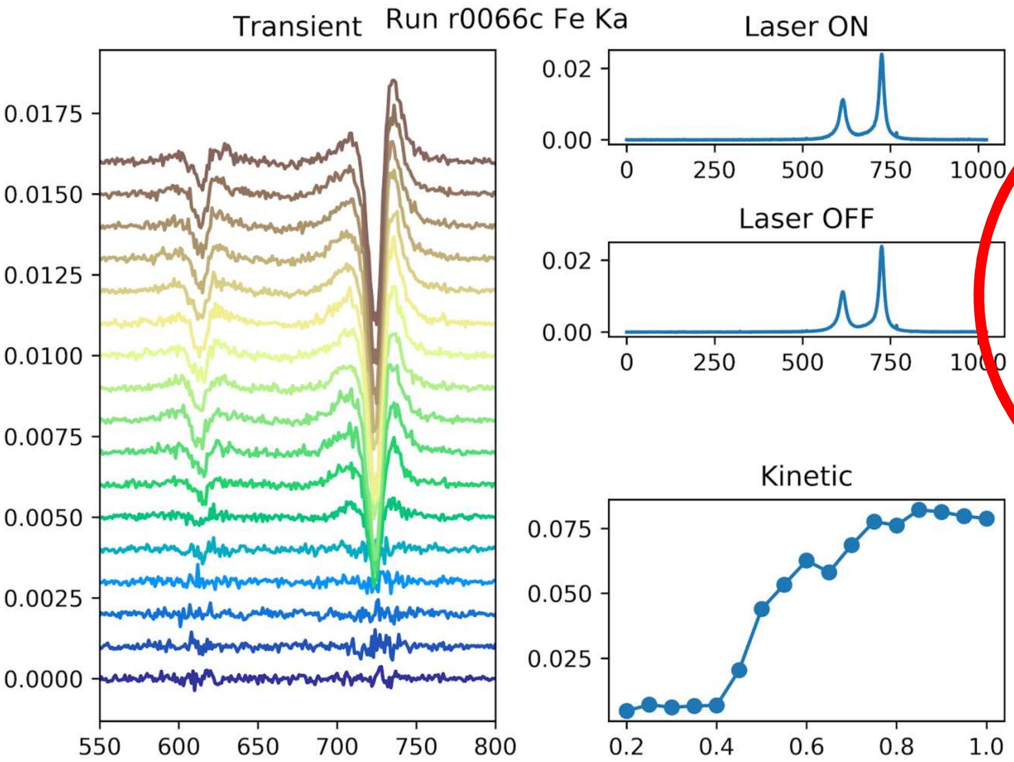
- Goal: to observe cavitation dynamics in water by ns laser pump

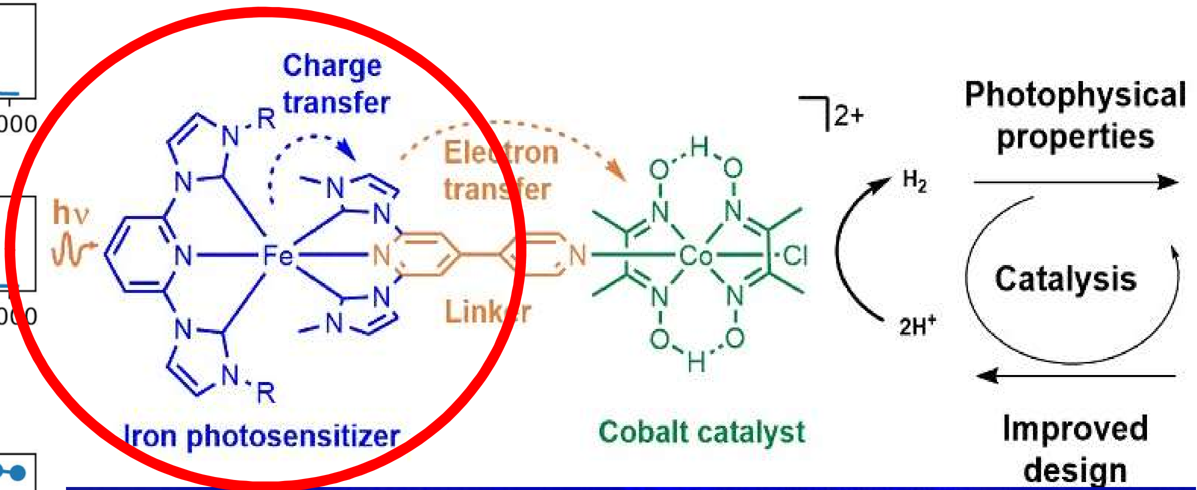
- Andor, Zyla 2560x2160 px²
- distance 8.859 m
- 10 Hz acquisition

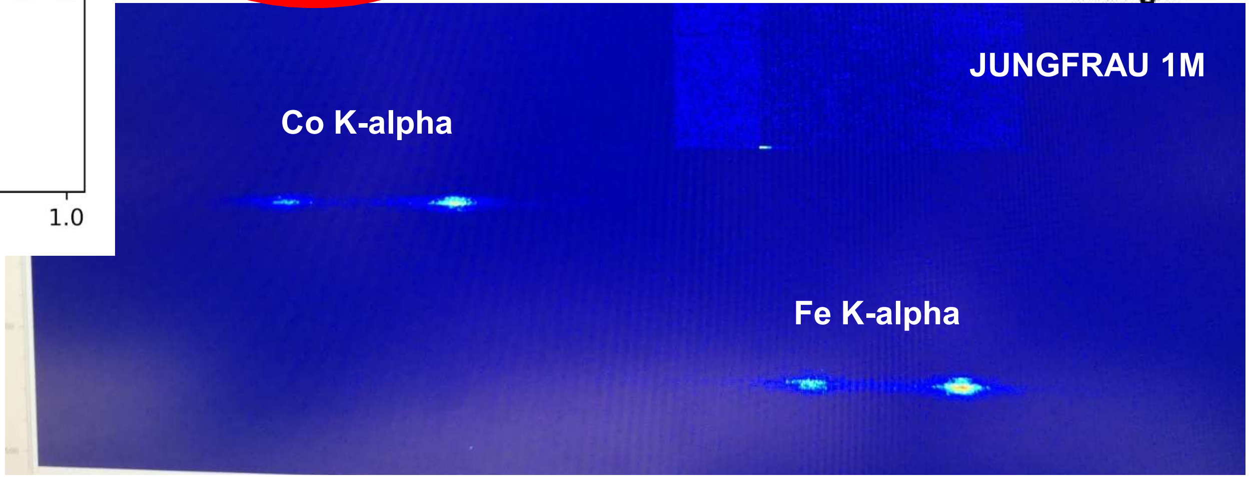
- MID's ns laser
- In-air setup (chamber's lid off)

Courtesy of T. Salditt & J. Hagemann

FXE: Recent User Experiment (Matthias Bauer, Uni. Paderborn)







How to take part in the activities?

- Come to our Users Meeting in January (27-31 Jan)
  - Many parallel sessions at the users meeting

- Engage with European XFEL
  - Many parallel sessions at the users meeting
  - Sabbatical
  - Joint PhD positions?

- Before writing a proposal
  - Contact one of the scientist of the instruments you are interested in (**or contact me!)**
  - Investigate the possibility to join a community proposal
  - Discuss your idea with a scientist at the instrument
  - Make test and sample preparation in our Bio laboratories (XBI)

- Write an appealing and exciting proposal
  - Proposal Review Panel consist of external Experts
  - Rejection rates are high

All six Instruments are in Users Operation

Adrian Mancuso

SPB/SFX (Start September 2017)

Andreas Scherz

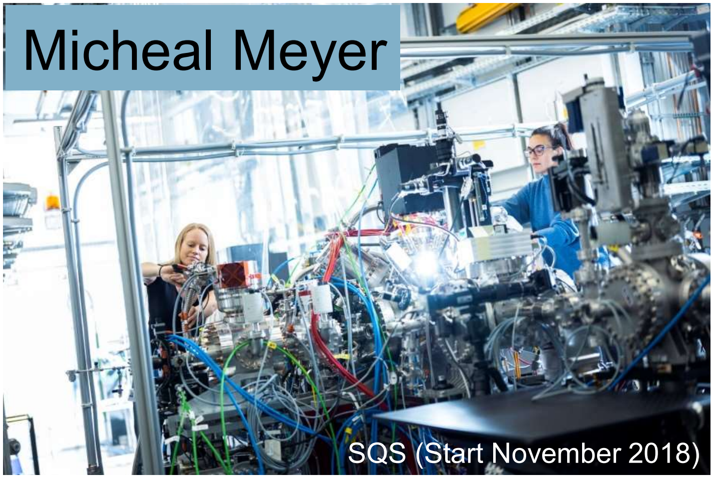
SCS (Start November 2018)

Anders Madsen

MID (Start April 2019)

Dmitry Khakhulin

FXE (Start September 2017)



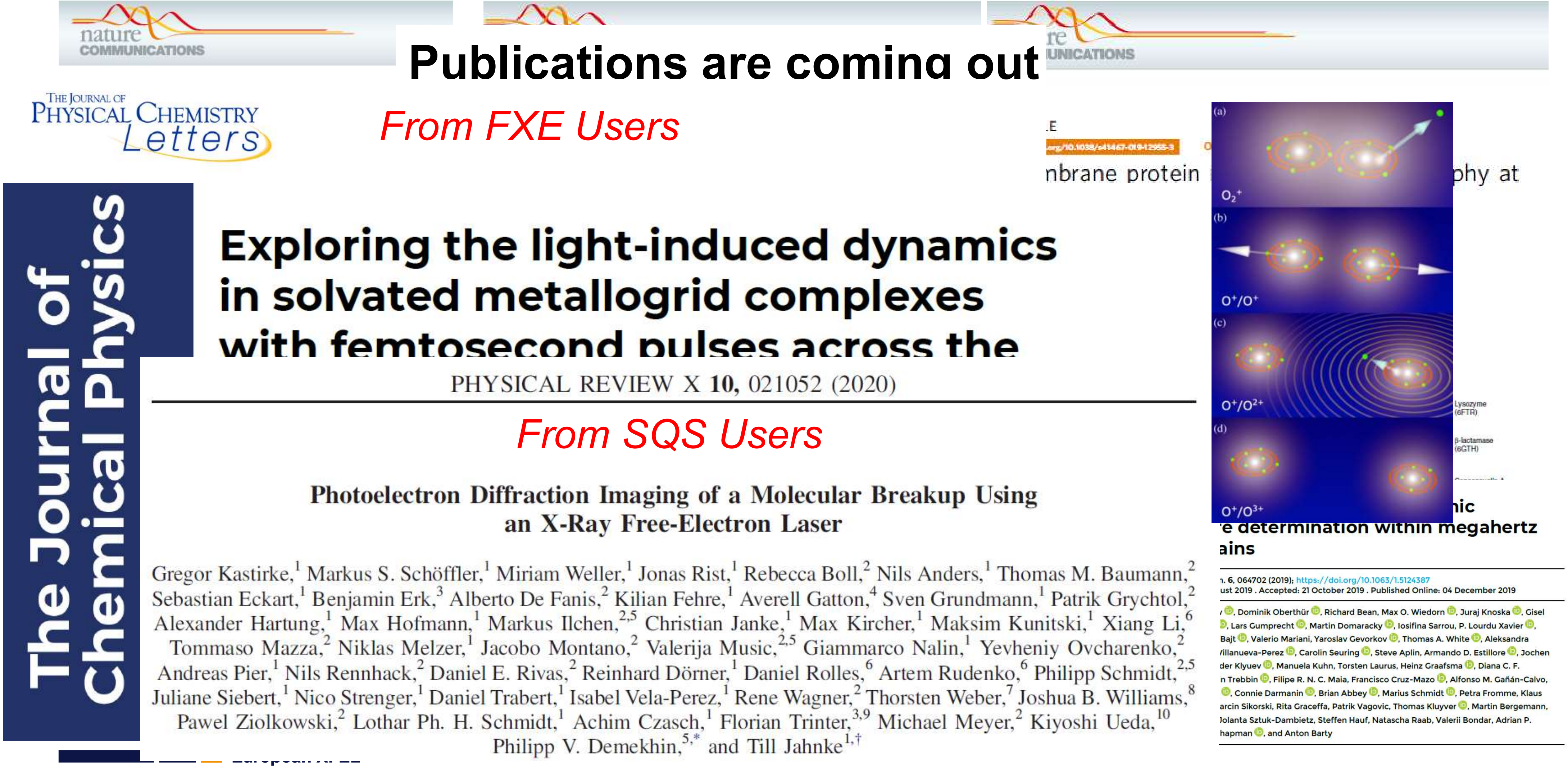
Micheal Meyer

SQS (Start November 2018)

Ulf Zastrau

HED (Start April 2019)

Publications are coming out



From FXE Users

Exploring the light-induced dynamics in solvated metallogrid complexes with femtosecond pulses across the

PHYSICAL REVIEW X **10,** 021052 (2020)

From SQS Users

Photoelectron Diffraction Imaging of a Molecular Breakup Using an X-Ray Free-Electron Laser

Gregor Kastirke,[1] Markus S. Schöffler,[1] Miriam Weller,[1] Jonas Rist,[1] Rebecca Boll,[2] Nils Anders,[1] Thomas M. Baumann,[2] Sebastian Eckart,[1] Benjamin Erk,[3] Alberto De Fanis,[2] Kilian Fehre,[1] Averell Gatton,[4] Sven Grundmann,[1] Patrik Grychtol,[2] Alexander Hartung,[1] Max Hofmann,[1] Markus Ilchen,[2,5] Christian Janke,[1] Max Kircher,[1] Maksim Kunitski,[1] Xiang Li,[6] Tommaso Mazza,[2] Niklas Melzer,[1] Jacobo Montano,[2] Valerija Music,[2,5] Giammarco Nalin,[1] Yevheniy Ovcharenko,[2] Andreas Pier,[1] Nils Rennhack,[2] Daniel E. Rivas,[2] Reinhard Dörner,[1] Daniel Rolles,[6] Artem Rudenko,[6] Philipp Schmidt,[2,5] Juliane Siebert,[1] Nico Strenger,[1] Daniel Trabert,[1] Isabel Vela-Perez,[1] Rene Wagner,[2] Thorsten Weber,[7] Joshua B. Williams,[8] Pawel Ziolkowski,[2] Lothar Ph. H. Schmidt,[1] Achim Czasch,[1] Florian Trinter,[3,9] Michael Meyer,[2] Kiyoshi Ueda,[10] Philipp V. Demekhin,[5,*] and Till Jahnke[1,†]

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.org/10.1038/s41467-019-12955-3

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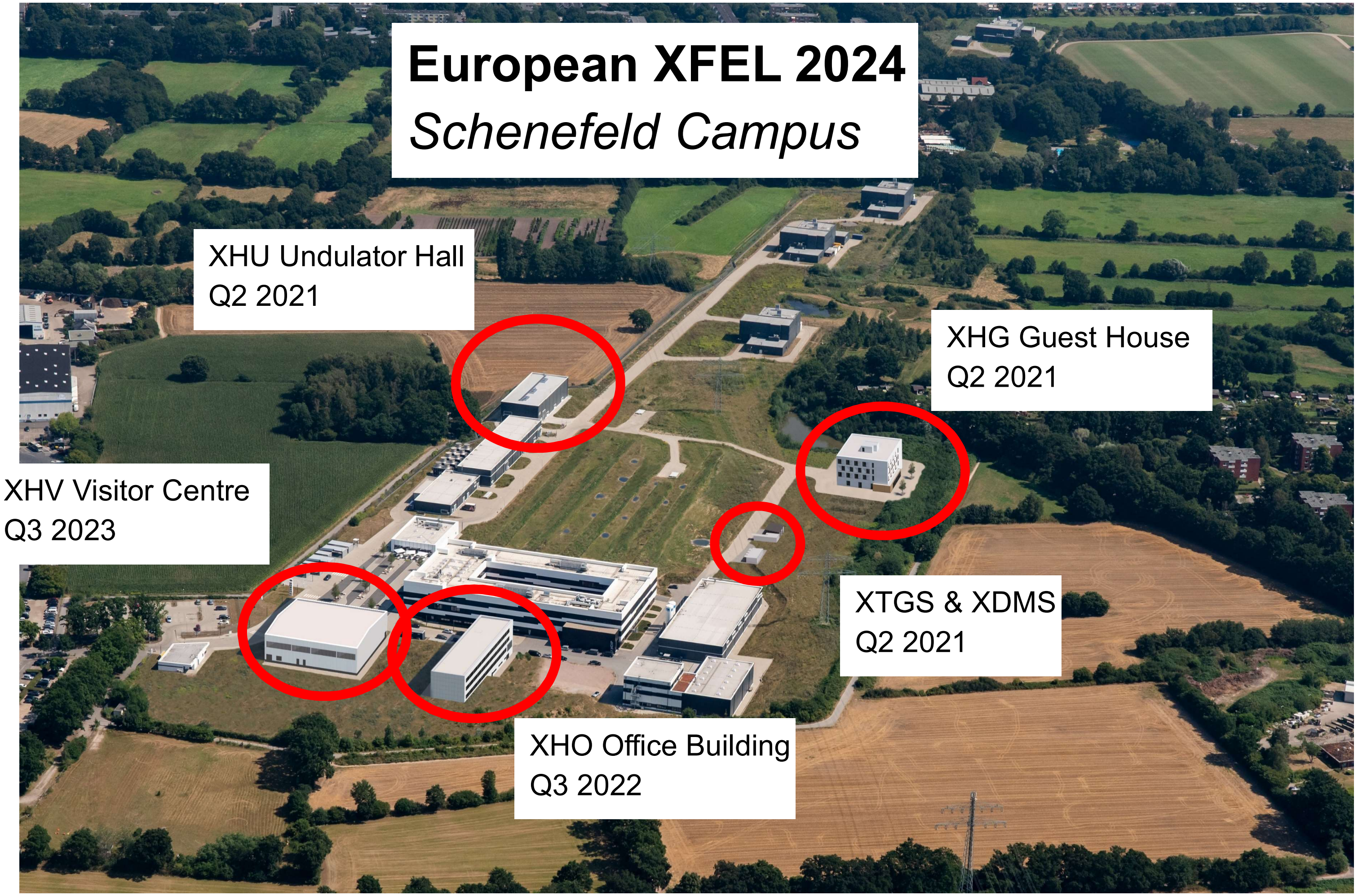
1. 6, 064702 (2019); https://doi.org/10.1063/1.5124387
ust 2019 . Accepted: 21 October 2019 . Published Online: 04 December 2019

, Dominik Oberthür, Richard Bean, Max O. Wiedorn, Juraj Knoska, Gisel
, Lars Gumprecht, Martin Domaracky, Iosifina Sarrou, P. Lourdu Xavier,
Bajt, Valerio Mariani, Yaroslav Gevorkov, Thomas A. White, Aleksandra
Villanueva-Perez, Carolin Seuring, Steve Aplin, Armando D. Estillore, Jochen
der Klyuev, Manuela Kuhn, Torsten Laurus, Heinz Graafsma, Diana C. F.
n Trebbin, Filipe R. N. C. Maia, Francisco Cruz-Mazo, Alfonso M. Gañán-Calvo,
, Connie Darmanin, Brian Abbey, Marius Schmidt, Petra Fromme, Klaus
arcin Sikorski, Rita Graceffa, Patrik Vagovic, Thomas Kluyver, Martin Bergemann,
Jolanta Sztuk-Dambietz, Steffen Hauf, Natascha Raab, Valerii Bondar, Adrian P.
hapman, and Anton Barty

HAPPY USERS in 2019



European XFEL 2024
Schenefeld Campus

XHU Undulator Hall
Q2 2021

XHG Guest House
Q2 2021

XHV Visitor Centre
Q3 2023

XTGS & XDMS
Q2 2021

XHO Office Building
Q3 2022

Thank you for your attention