Research with Real Photons at DESY – An Overview

Photon science at DESY

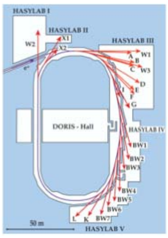
Edgar Weckert
Photon 2009
Hamburg, 13 May 2009

HELMHOLTZ | GEMEINSCHAFT

DESY

Facilities for Research with Photons at DESY

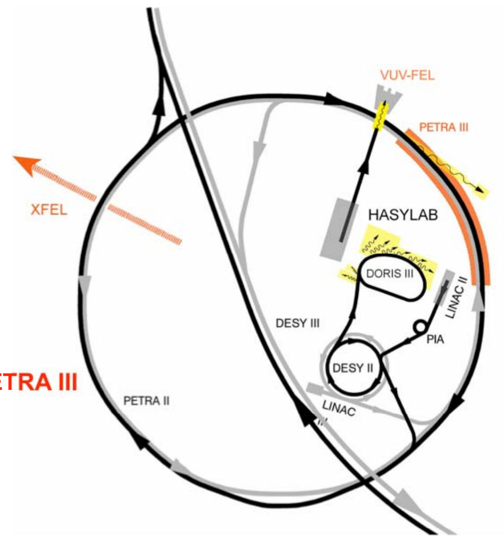
DORIS III



FLASH

PETRA III

European XFEL



Source parameters

Equilibrium characteristics of a storage ring:

- **horizontal emittance:** $\varepsilon_x = \sigma_x \sigma_{x'} \approx E^2/NB^3$

  σ_x: RMS beam size; $\sigma_{x'}$: RMS beam divergence
  E: particle energy; NB: no. of dispersive elements (bending magnets)

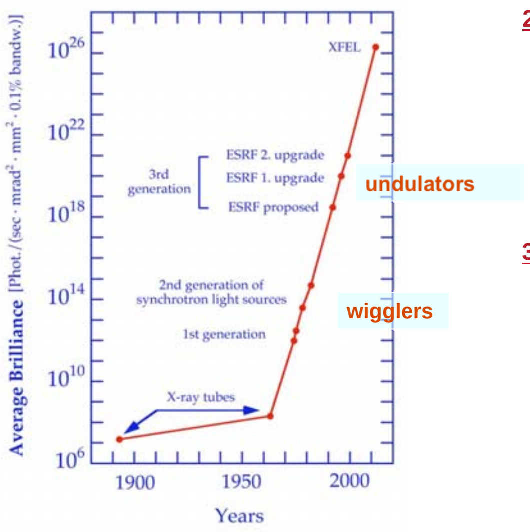
- **vertical emittance:** $\varepsilon_y = \sigma_y \sigma_{y'} = \kappa\varepsilon_x$; κ: horiz./vert. coupling

Radiation source properties:

- **flux:** F [ph/(s 0.1%BW)]
- **brilliance:** $B=F/((2\pi)^2\sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'})$ [ph/(s mm²mrad²0.1%BW)]
- **coherent flux:** $F_c = B(\lambda/2)^2$ [ph/(s 0.1% BW)]

- **'large' samples (mm-size):** flux limited
- **'small' samples or sample areas:** brilliance limited

Brilliance development



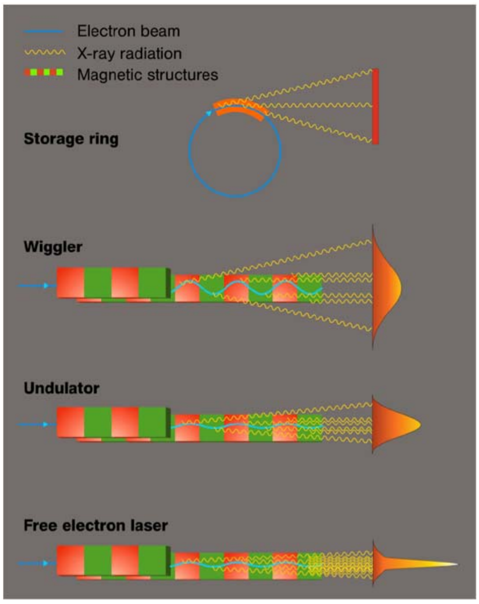
2nd generation: DORIS III

- larger emittance
- high flux
- large beams
- relatively large samples

3rd generation: PETRA III

- small emittance
- high brilliance
- small beams (-focus)
- small (nanoscale) samples

Radiation sources



Bending magnets / Wigglers (60's)

$I \propto n_m \times n_e$

Undulators (60's)

$I \propto n_m^2 \times n_e$

Free-electron-lasers FEL (70's)

$I \propto n_m^2 \times n_e^2$

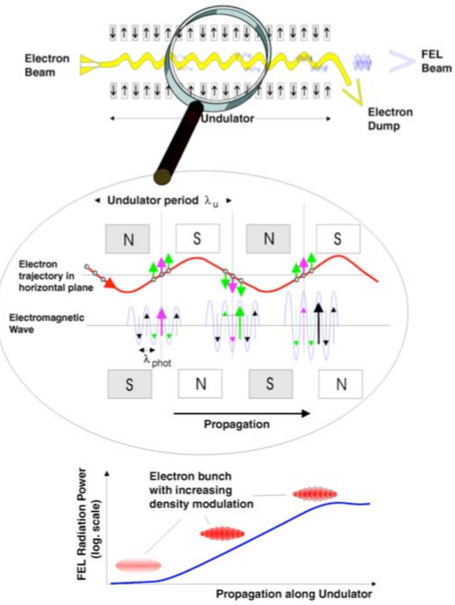
SASE FEL principle

SASE (self-amplified spontaneous emission)

→ electrons in phase with e.m.-wave are retarded ("emit photons"), electrons with opposite phase gain energy ("absorb photons")

→ longitudinal charge density modulation ("micro-bunching") with periodicity equal to λ_{phot}

→ self-amplification of spontaneous emission due to increasingly coherent emission from micro-bunches (like point charge)



PETRA III: Construction

PETRA III: Construction

Start of reconstruction: 2nd July 2007

Foundation stone: 14.9.2007

Topping out ceremony: 26.11.2007

Handover experimental hall: 1.7.2008

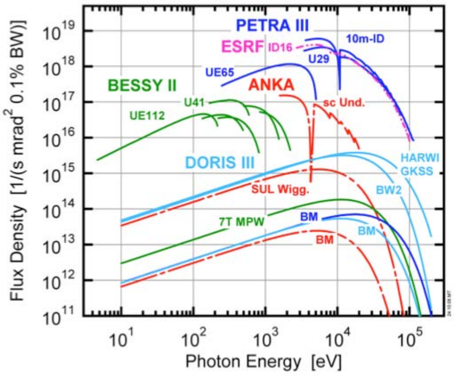
PETRA III: Summary

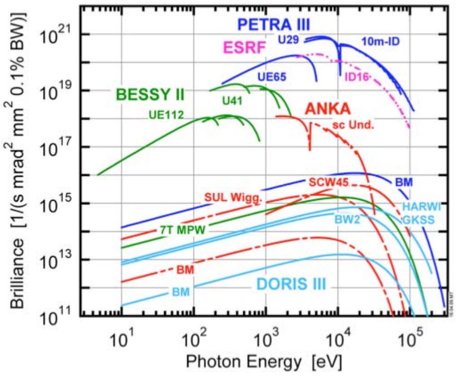
- rebuild of 1/8 of the 2304m circumference
- refurbishment of 7/8 of the storage ring
- refurbishment of pre-accelerator chain (also used by DORIS III)
- construction of a 300m long new experimental hall
- installation of 80m of damping wigglers
- top up operation mode

key parameters:

- particle energy: 6GeV
- current: 100mA (200mA)
- horizontal emittance: 1 nmrad
- No. of undulators: 14 (incl. canted)
- undulator lengths: 2-10(20) m
- no bending magnet beamlines

PETRA III: Performance comparison





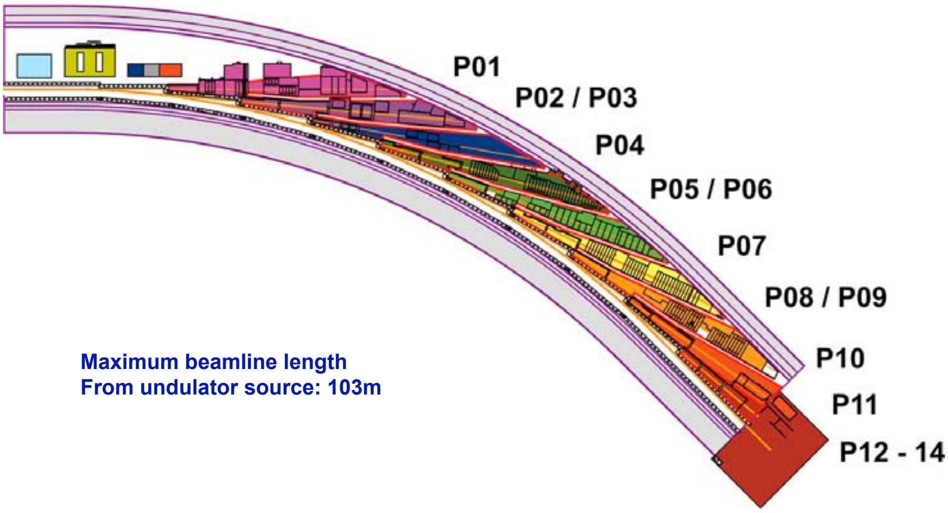
Photon beam parameters at 12keV:

	β_x [m]	β_y [m]	σ_x [μm]	σ_y [μm]	$\sigma_{x'}$ [μrad]	$\sigma_{y'}$ [μrad]	ID-length [m]
low-β 5 m	1.3	3	35.9	5.7	28	5.0	5
high-β 5 m	20	2.38	141	5.2	8.6	5.2	5

coherent flux:
- 12keV (B(λ/2)^2)
- 1×10^{11} ph/s/0.01%BW

Horizontal β-function of each straight section can be selected individually and is changeable (β_x= 1.3m or β_x = 20m)

PETRA III: Layout of the Experimental Hall



Maximum beamline length
From undulator source: 103m

PETRA III: Beamlines

Beamlines for PETRA III were selected according to user demands and driven by novel scientific applications in order to use the high brilliance and capabilities for µ- and nano-focusing in a best possible manner.

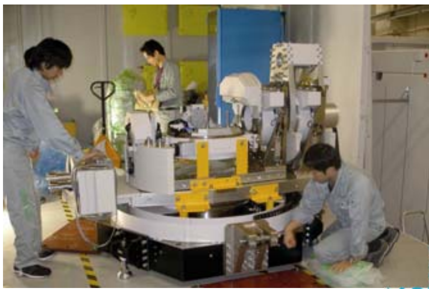
BL	Name	ID-Typ	Energy range	Comment	Contact
P01	NRS, ps-time resolved, IXS	10 m U	6 - 40 keV		H. Franz, DESY
P02	Hard X-ray scattering/diffraction	2 m U23	8 - 100 keV	straight	H.-P. Liermann, DESY
P03	Micro SAXS/WAXS	2 m U29	8 - 23 keV	down	S. Roth, DESY
P04	Variable Polarization XUV	5 m UE65	0.2 - 3.0 keV		J. Viefhaus, DESY
P05	Micro- and nano-tomography / imaging	2 m U29	5 - 50 keV	side	A. Haibel, GKSS
P06	Micro/nano-spectroscopy / fluorescence	2 m U32	2.4 - 100 keV	straight	G. Falkenberg, DESY
P07	High energy materials science and diffraction	4 m U19	50 - 250 keV		N. Schell, GKSS/DESY
P08	High resolution diffraction	2 m U29	5.4 - 30 keV	top	O. Seeck, DESY
P09	Resonant scattering / diffraction	2 m U32	2.4 - 50 keV	straight	J. Strempfer, DESY
P10	Coherence applications	5 m U29	4 - 25 keV		M. Sprung, DESY
P11	MX-diffraction / biological imaging	2 m U32	2.4 -33 keV	side	A. Meents; MPI, HGF, DESY
P12	BioSAXS	2 m U29	4 - 20 keV	straight	M. Rößle, EMBL/GKSS
P13	Macro molecular crystallography I	2 m U29	4 - 17 keV	side	M. Cianci, EMBL
P14	Macro molecular crystallography II	2 m U29	7 - 35 keV	straight	G. Bourenkov, EMBL

high beta section	142x5 µm
low beta section	35x6 µm

PETRA III: Status Storage Ring

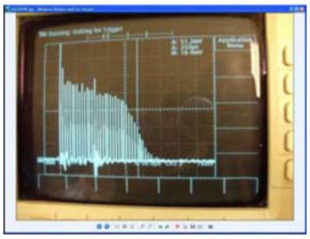
PETRA III: Status Storage Ring

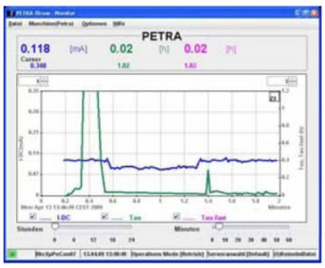
PETRA III: Status

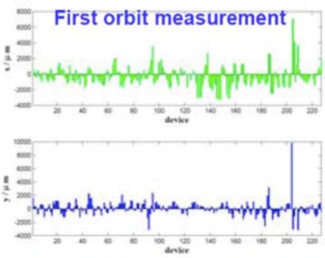


PETRA III: first stored beam

Beam was stored on April 13 (one bunch with 20 µA i.e. about 10^9 e+)
RF – phase right and orbit empirically corrected in the new octant



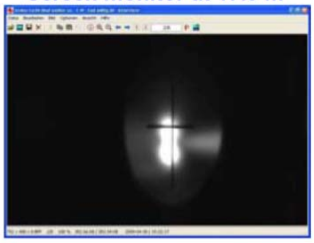




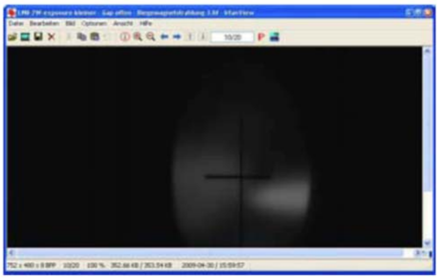
PETRA III: first light in front en

First light on April 30:
- Undulator PU 9 (OL 142m)
- Single bunch 0.5 mA
- Gap closed to 10 mm (foreseen 9.5)
- No effect on machine (orbit / tune)
- Beam centred with horizontal and vertical Bumps
- Power up to 8W

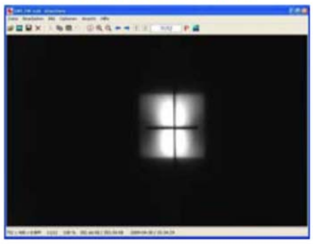
Screen monitor at 17.5 m



Undulator gap open



Screen monitor at 28m



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FLASH: VUV and soft X-ray FEL

FLASH:
VUV free electron laser

electron energy:	1 GeV
wavelength:	6.5-47 nm
average pulse energy:	10-100 µJ
peak pulse energy:	170 µJ
pulse duration:	10-25 fs
average power (700 pulses / s):	20 mW
peak power:	3-10 GW
peak brilliance	$1\text{-}10 \cdot 10^{29}$
divergence (@13nm):	90 µrad
spectral width:	0.7-1%

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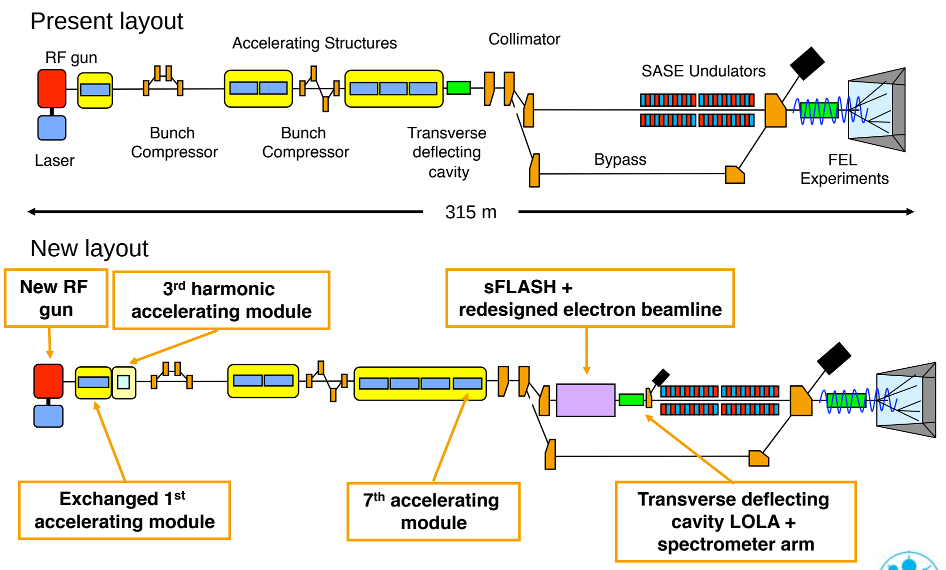
FLASH: layout



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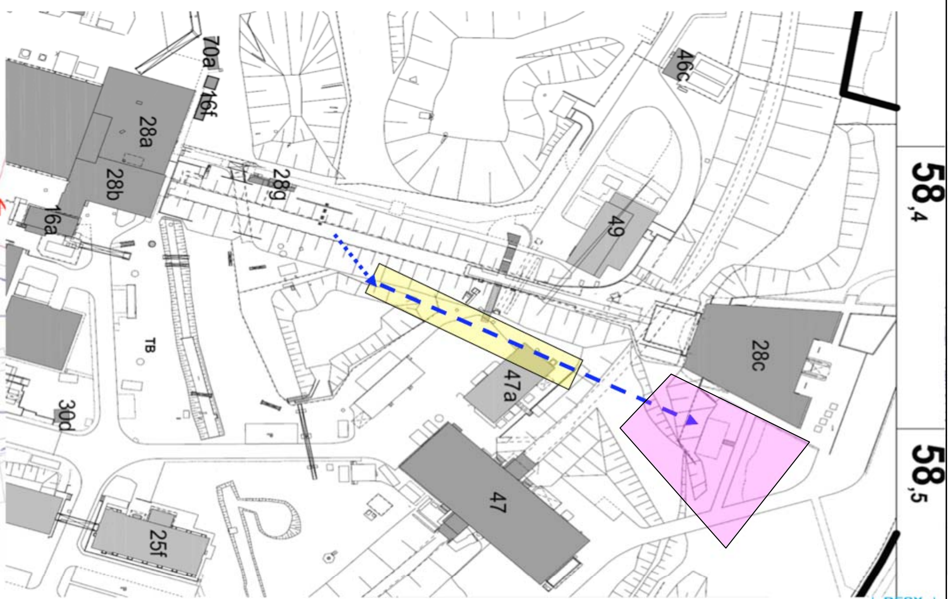
FLASH II proposal

HELMHOLTZ ZENTRUM BERLIN für Materialien und Energie



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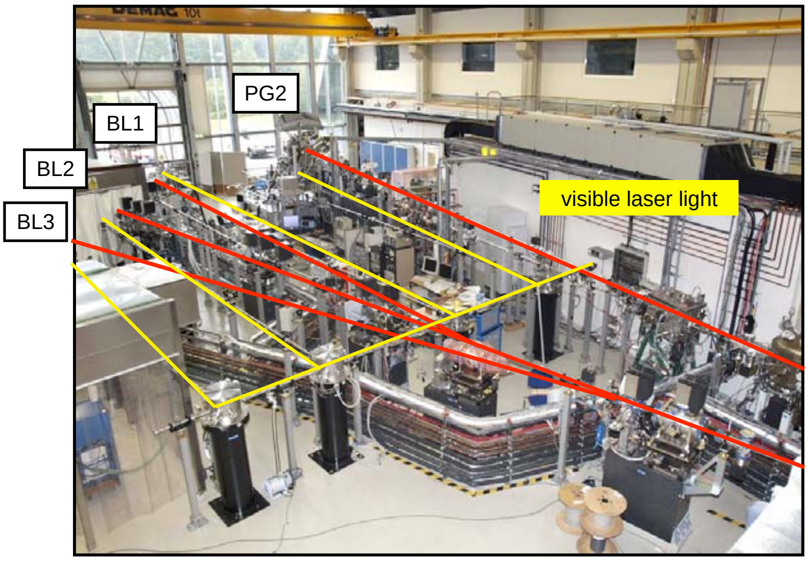
FLASH: experimental hall

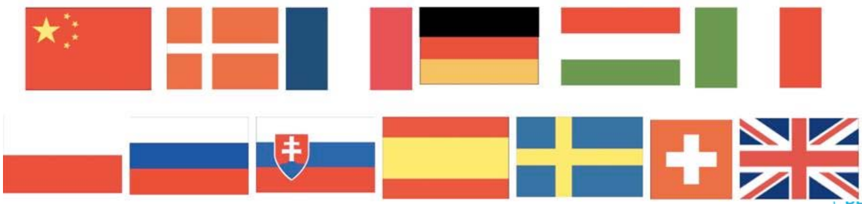


European XFEL Facility

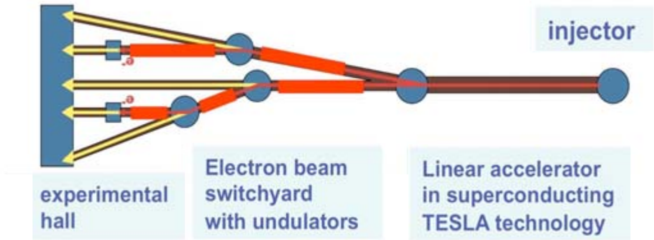
Technical Design Report published in July 2006

Plan approval procedure finished

kick-off at ECRI press conference 5 June 2007



XFEL: Schematic Layout



Linac: 17.5 GeV
min. wavelength: ~1 Å
photons per pulse: ~10^{12}
pulse length: ~100 fs
No. of bunches: 30000 1/s

- 2 X-ray SASE FELs,
- 1 SASE XUV-FELs, and
- 2 beamlines for short pulse physics using spontaneous radiation
- 10 experimental stations

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European XFEL: Status

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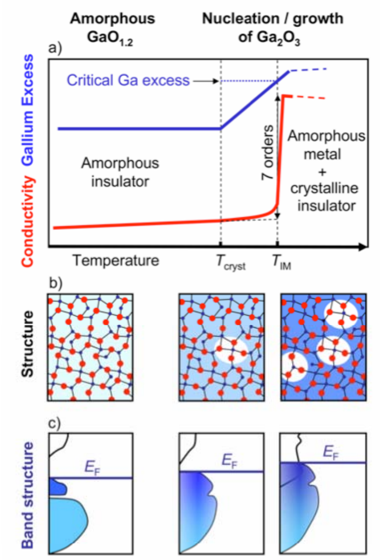
DORIS III: Experiments

J. Dik, K. Jansen, et al., Anal. Chem. (2008)

beige: Sb-fluorescence intensity
red: Hg-fluorescence intensity
Beamline L @ DORIS III

and SAXS X-ray diffraction at BL A2 @ DORIS III
Disentangling different the mechanical properties of crystalline and disordered phases.

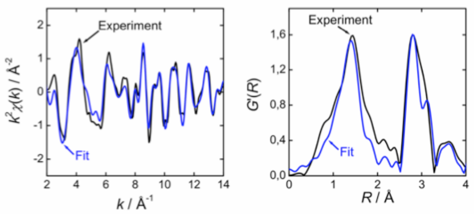
DORIS III: Solid state physics



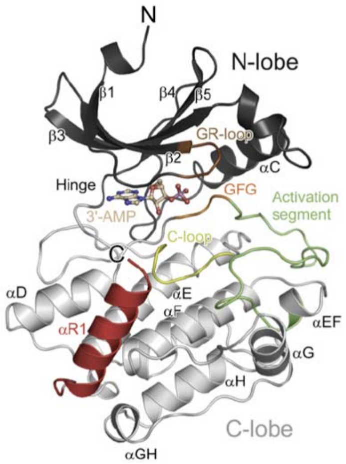
Nagarajan, Souza, Samuelis, Valov, Börger, Janek, Becker, Schmid, Martin, Nature Mat. 7, 391-398 (2008)

Chemical driven metal-insulator transition

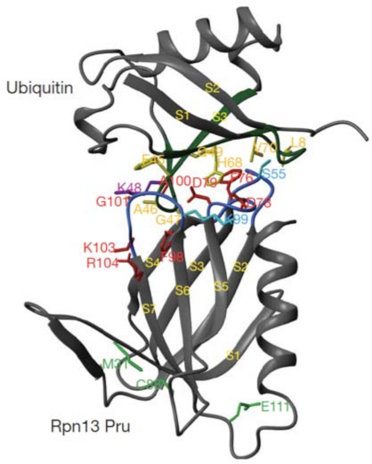
- highly non stoichiometric, amorphous Ga oxid
- conductivity change by 10^7 above 670K
- heterogeneous solid state reaction ➔ crystalline Ga_2O_3 regions ➔ critical Ga conc.
- band gap closed ➔ conductivity
- EXAFS study at BL A1 revealed a significant higher portion of tetrahedral coordinated Ga as compared to β-Ga_2O_3



DORIS III: Structural biology



CASK CaM-kinase (3' AMP)



CASK functions as a Mg^{2+}-independent neurexin kinase, Mukherjee et al., Cell 133 (2008) 328-339

Ubiquitin docking at the proteasome through a novel pleckstrin-homology domain interaction, Schreiner et al., Nature 453 (2008) 548-552

PETRA III: Life sciences/Structural Biology

30S ribosomal subunit: F. Schlünzen, R. Zarivach, J. Harms, A. Bashan, A. Tocilj, R. Albrecht, A. Yonath, Nature 413 (2001) 814-821

Small crystals:

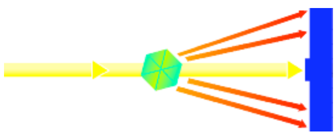
- **Micro focus and still small divergence**

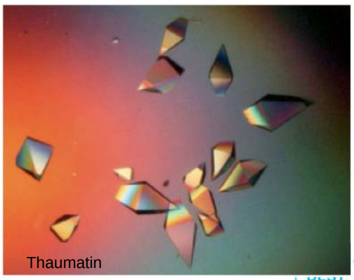
Large complexes:

- **Extremely intense and parallel radiation**

Optimum anomalous signal:

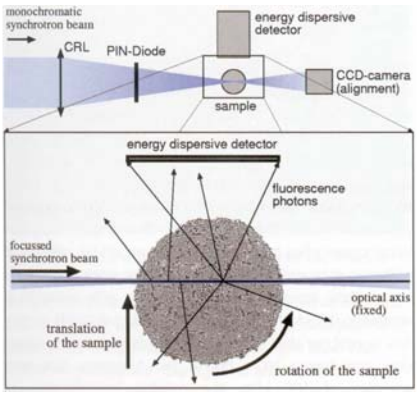
- **High energy resolution and stability**

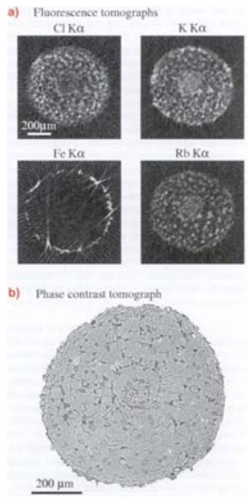




Micro fluorescence tomography

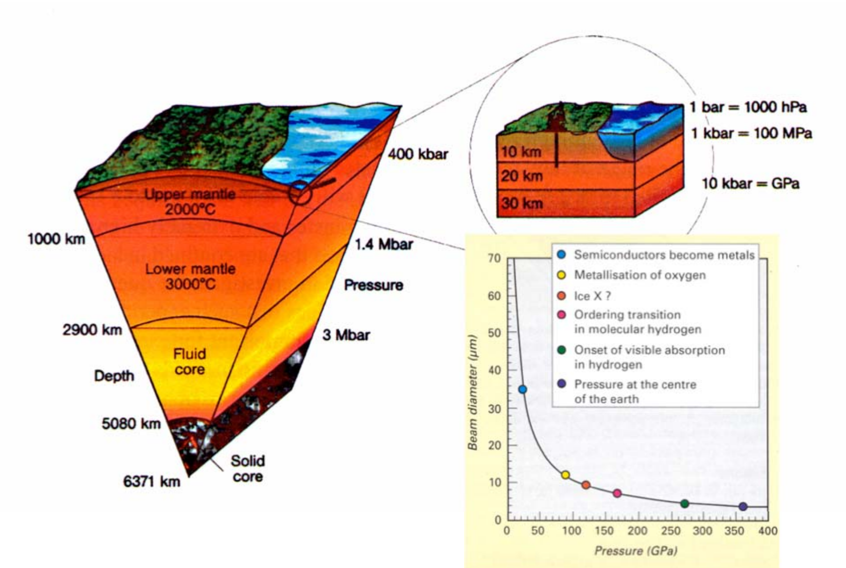
Example: root of mahagoni tree





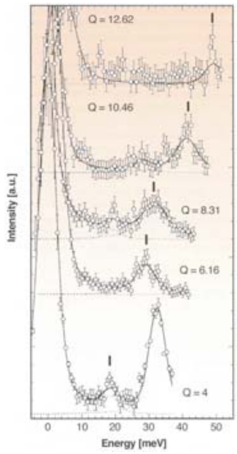
Lengeler et al. JSR, 6, 1153-1167 (1999)

Inelastic scattering under high pressure

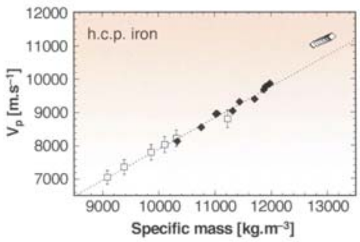


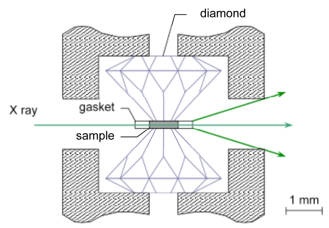
Inelastic scattering under high pressure

Speed of sound of Fe under pressure (ESRF: 2 ph/min)



P=28GPa





G. Fiquet et al., Science 291 (2001) 468

FLASH experiments in imaging

LETTERS

Ultrafast single-shot diffraction imaging of nanoscale dynamics

ANTON BARTY[1,7]*, SÉBASTIEN BOUTET[2,3], MICHAEL J. BOGAN[1], STEFAN HAU-RIEGE[1], STEFANO MARCHESINI[1], KLAUS SOKOLOWSKI-TINTEN[4], NIKOLA STOJANOVIC[4], RA'ANAN TOBEY[5], HENRI EHRKE[5], ANDREA CAVALLERI[5,9], STEFAN DÜSTERER[6], MATTHIAS FRANK[1], SAŠA BAJT[1,8], BRUCE W. WOODS[1], M. MARVIN SEIBERT[3], JANOS HAJDU[3], ROLF TREUSCH[6] AND HENRY N. CHAPMAN[1,7,8]*

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[9]Max Planck Research Group for Structural Dynamics, Center for Free Electron Laser Science, Universität Hamburg at DESY, Notkestraße 85, 22607 Hamburg, Germany
*e-mail: a.barty@llnl.gov; henry.chapman@desy.de

FLASH experiments in imaging

LETTERS

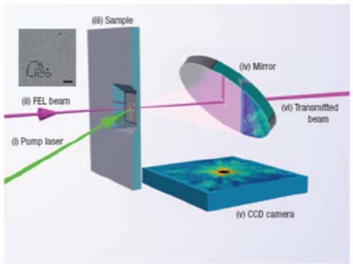
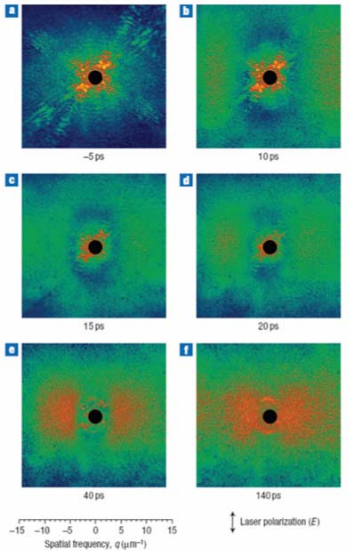
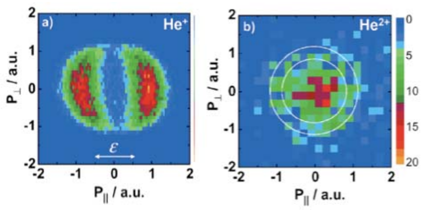


Figure 1 X-ray dynamic diffraction imaging. A visible-light laser beam (i) incident from the left is focused onto the sample (iii) and acts as the excitation pulse. A 10-fs duration soft X-ray pulse at a wavelength of 13.5 nm from the FEL (ii) is focused to a 20-µm spot in the same location as the visible-light laser at a continuously variable delay after the excitation pulse. The X-ray pulse diffracts from the sample, carrying information about the transient sample structure to the CCD detector (v) in the form of a coherent diffraction pattern. A 45° mirror (iv) is used to separate the direct beam from the diffracted light: the direct FEL beam (vi) passes straight through a hole in the mirror and is not detected in the CCD image. A 100-nm-thick zirconium filter over the CCD chip makes the detector blind to the laser excitation pulse. The sample (iii) consisted of a nanometre-resolution pattern etched into a silicon nitride membrane using a focused ion beam (FIB), providing a well-defined control sample so that the time evolution of a known structure could be observed. The path length from sample to CCD is 53 mm and the detected numerical aperture is 0.25, giving a spatial resolution of 27 nm in the sample plane.

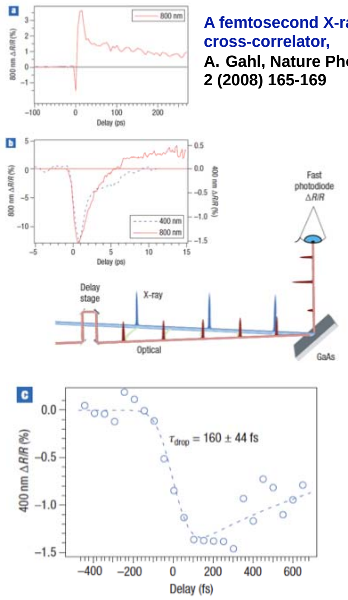


FLASH: Experiments

Exploring the dynamics of the two fundamental two-photon – two-electron reaction pathways: sequential and direct (or non-sequential) absorption of the photons.



Recoil-Ion Momentum Distributions for Two Photon Double Ionization of He and Ne by 44 eV Free-Electron Laser Radiation,
Rudenko et al.,
PRL 73 (2008) 073003



A femtosecond X-ray/optical cross-correlator,
A. Gahl, Nature Photonics 2 (2008) 165-169

XFEL-Applications

Up to now mostly the static structure of matter has been investigated.

The FELs will provide unique opportunities for probing the dynamics of matter for experiments:

- with ultra high (100fs) time resolution in the Å-length wavelength range
- that exploit the transverse coherence of the photon beam
- that demand for the extreme peak brilliance

Time resolved diffraction

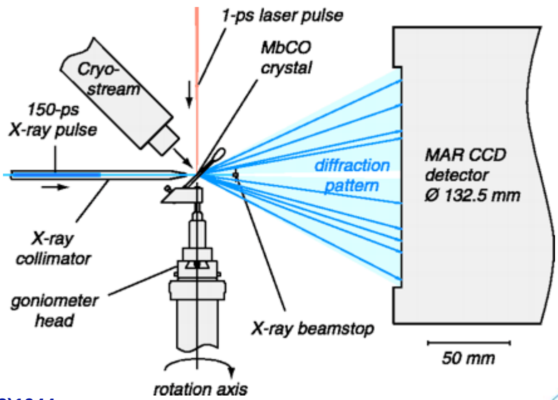
Example:

Time resolved investigation of the photo ionization of CO-myoglobin at ID9 (ESRF):
- pump-probe technique
- X-ray crystallography

Variable delay between laser pump pulse and X-ray probe pulse.

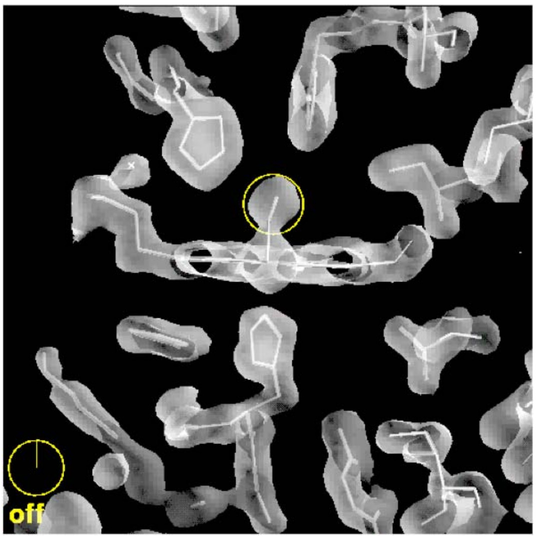
32 exposures per image

'pink' Laue technique, range: 0.72-1.24 Å



Schotte et al., Science 300(2003)1944

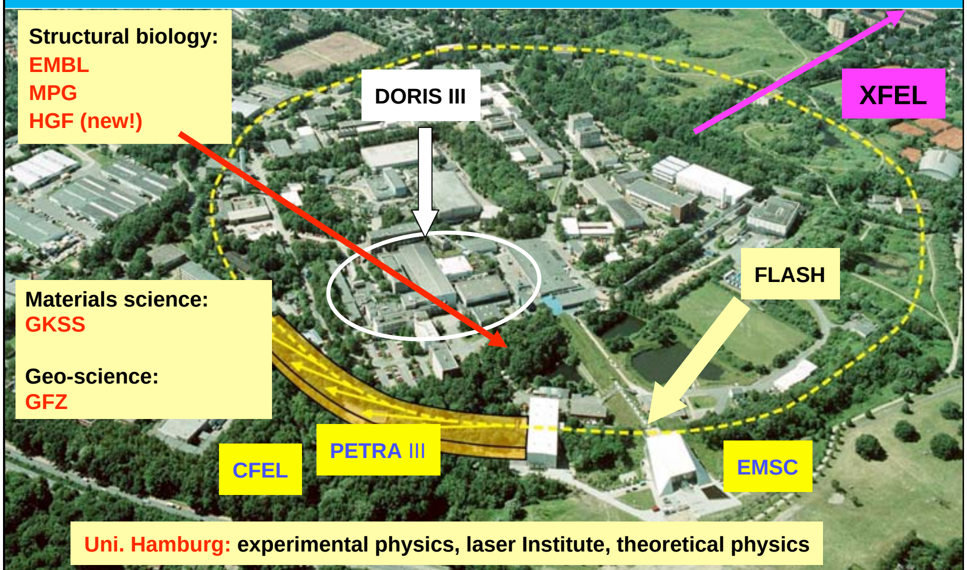
Time resolved crystallography



XFEL: 1000 times better time resolution than today

Schotte et al., Science 300(2003)1944

Facilities at DESY: Concept of Outstations



DESY site in the near future

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Summary

- **brilliant photon beams are excellent tools for studying the structure and dynamics in a wide scientific field**
- **DESY photon sources are very well prepared to match future requirements in the field of photon science**
  - **PETRA III: high energy sources of lowest brilliance for hard X-ray applications with very small focal spot sizes**
  - **FLASH: VUV and soft X-ray FEL for time resolved high brilliance applications**
  - **European XFEL: watching molecules and atoms in real time on their intrinsic length and time scale**
- **DESY: establishment of a fruitful environment of photon based research**

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Thank you for your attention