X-ray photon diagnostics at the European XFEL

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Hamburg, Germany

www.xfel.eu

Foundation of the European XFEL GmbH

- European XFEL GmbH registered on Oct.8, 2009
- Non-profit company to:
  - Construct
  - Commission the XFEL machine
  - Operate
- International Convention was signed on Nov.30,2009

Management Board

Managing Directors (= "Geschäftsführer" in the sense of the GmbHG)

Chairperson of the Management Board: M. Altarelli

Administrative Director *K. Witte*	Scientific Director *S. Molodtsov*	Scientific Director *A. Schwarz*	Scientific Director *T. Tschentscher*
Human Resources	WP-74 Photon Diagnostics	Accelerator Liaison and WP-71 Undulators	WP-73 X-Ray Optics
Finance and Accounting	WP-79 XHEXP1, Sample Environment	WP-75 Detectors	WP-78 Optical Lasers
Procurement and Contracts, Customs	WP-85 Scient. Instrument SQS	WP-76 DAQ & Controls	WP-81 Scient. Instrument FDE
Law Office	WP-86 Scient. Instrument SCS	Civil construction including WP-31 Site & Civil Construction WP-41/42/43 Lots 1-3 WP-44 Site Engineering WP-45 AMTF Hall	WP-82 Scient. Instrument HED
Central Services incl. Library, User Administration, Travel Office	Technical Support Services, Mechanics, Electronics Workshops		WP-83 Scient. Instrument MID
		IT, Computing Services	WP-84 Scient. Instrument SPB

MB Assistant, Secretariat

Safety, Radioprotection

Communication, PR

IKC Coordinator, Controlling, Internal Audit

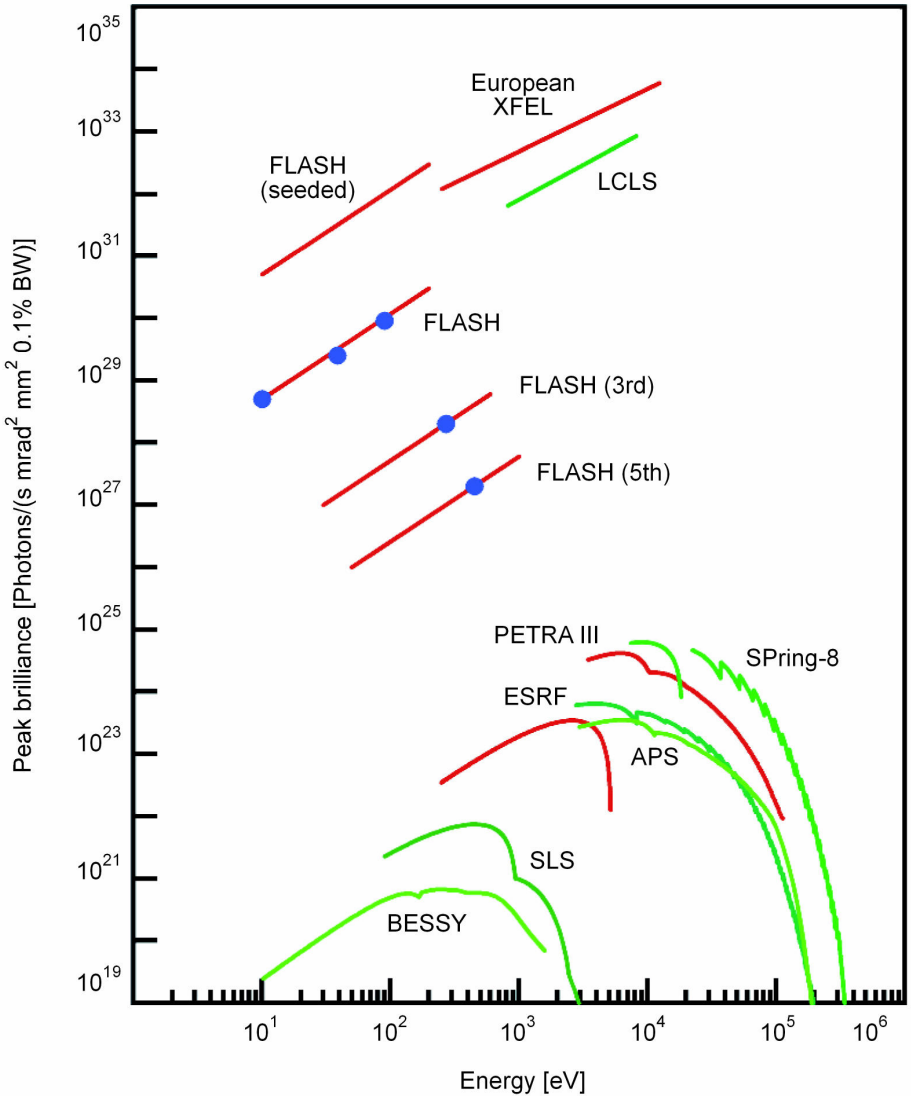
Motivation

- We look for X-ray diagnostics
  - fast
  - accurate
  - durable in extreme XFEL conditions
- CVD diamond detectors might work for
  - XFEL x-ray intensity, position, timing
- What is the *European XFEL* ? What is *FLASH* ?
- How can we collaborate ? Tests for XFEL of
  - diamond detectors
  - fast DAQ
- open positions (see www.xfel.eu)

content

- European XFEL
  - the project
  - the international context
  - beamlines and facility parameters
- Pulse structure and energy
  → special requirements
- Diagnostics Concept
- Some devices: XGMD, XBPM, PES
- Diamond detectors

Peak brilliance of X-ray Sources



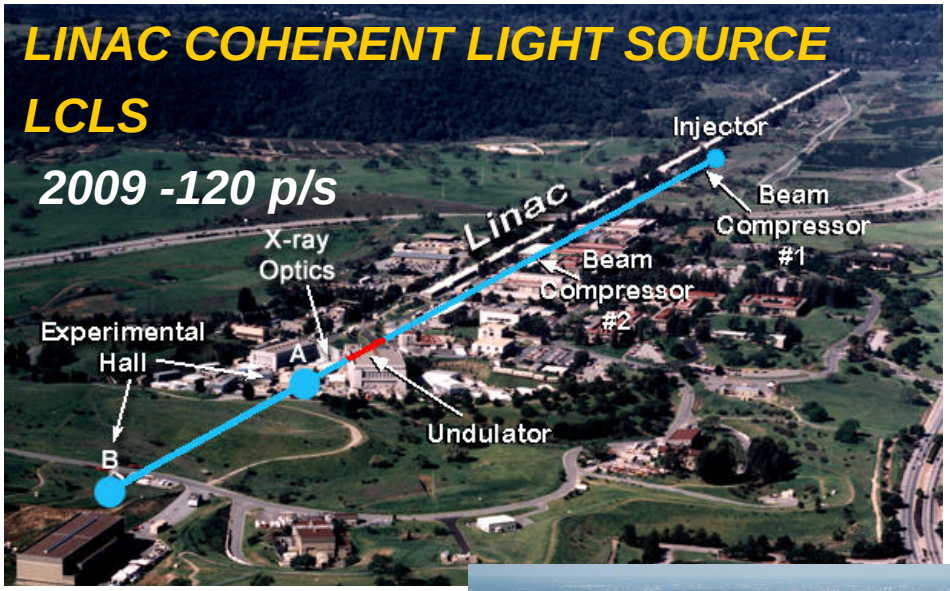
Free Electron Lasers:

- 4th generation light sources
- based on Linear Accelerators
- deliver ultrashort pulses: 100 fs = 10^{-13} s or less
- (Transversely) spatially coherent (laser-like) radiation

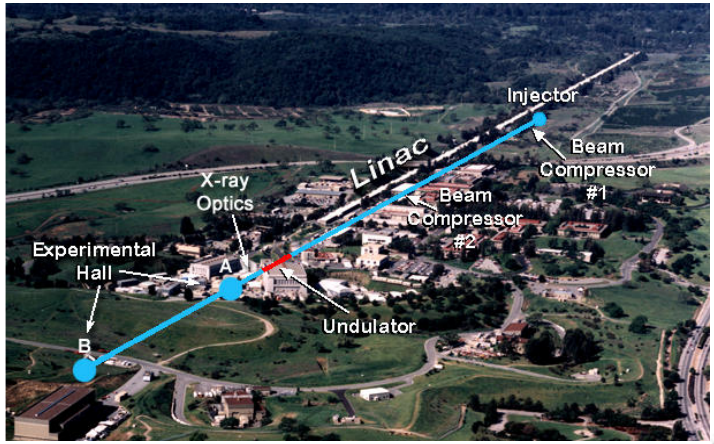
FLASH at DESY

- The first SASE FEL
- 1 GeV Superconducting Linear Accelerator
- Delivers VUV / soft X-rays
  - down to 6.5 nm
  - (+3rd, 5th harmonic!)
- Testbed for XFEL

Hard x-ray FEL's in construction/commissioning



April 10, 2009: the big news from LCLS!



First coherent hard X-rays

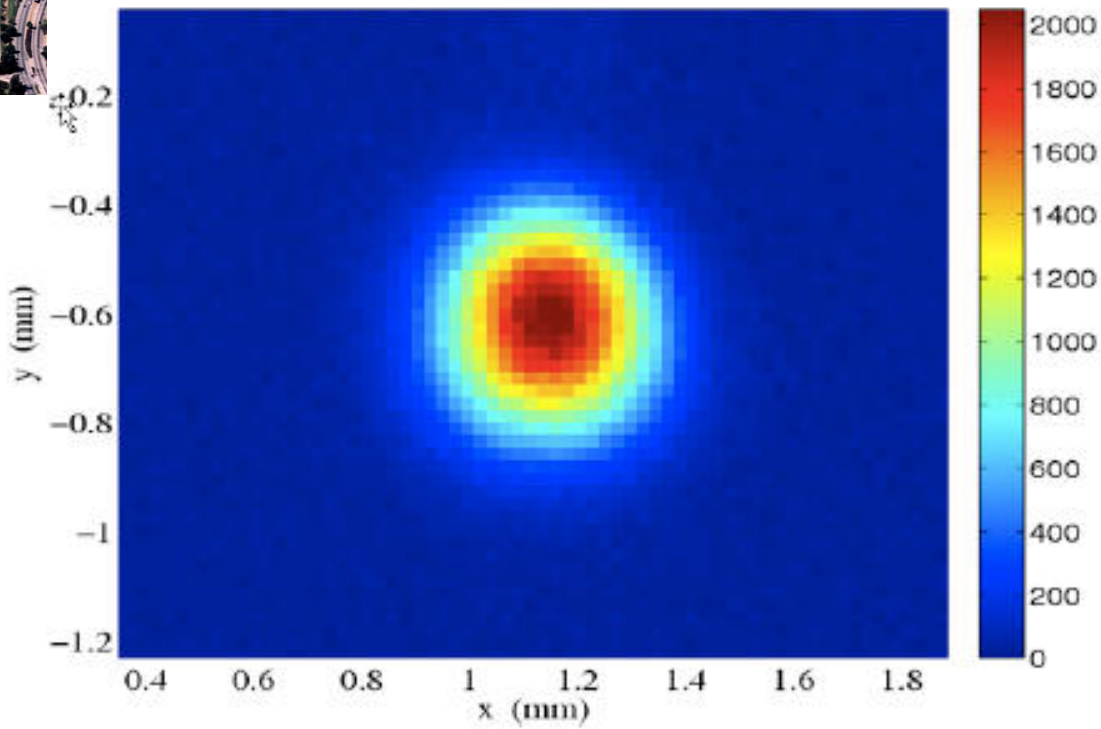


Figure 10: FEL x-rays at 1.5 Å on a YAG screen 50 m after the last inserted undulator (see Table 1 for measured parameters).

The European XFEL Project

- 5 beamlines (3 × SASE)
- 10-15 experiments
- 30,000 pulses/sec
- 10^{12} - 3.7×10^{14} phts/pulse @ 1Å – 49 Å
- flux: 1.5×10^{16} phts/(0.1% sec) @ 12.3 keV

Timeline:

June 5, 2007: Official funding of project by Germany and 12 international partners

Sept 2008: construction contracts

Jan 2009: start of construction

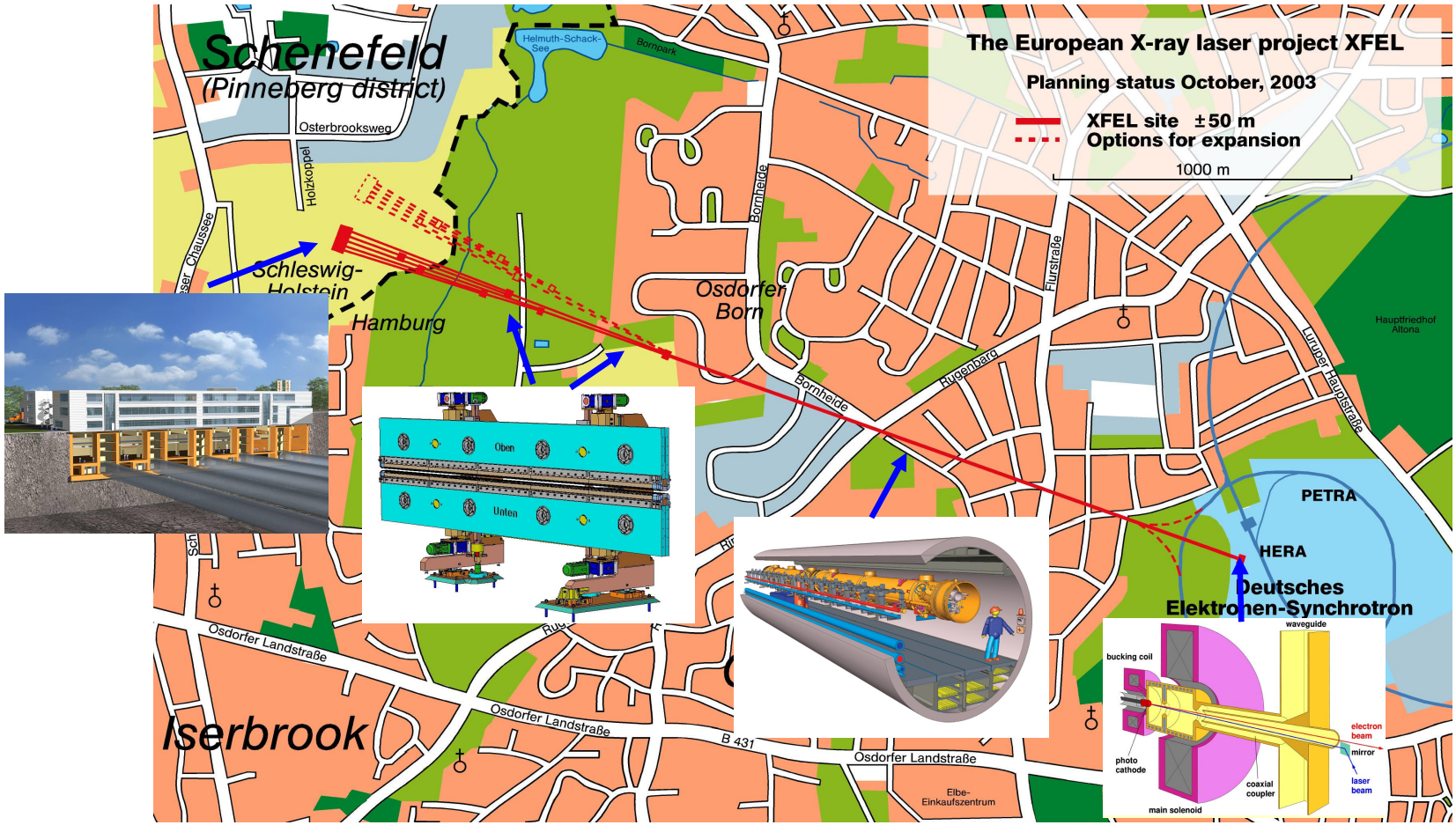
Nov 2009: foundation of the company (European XFEL GmbH)

June 2013: All buildings finished, start commissioning (2014)

June 2014: SASE 2 Å

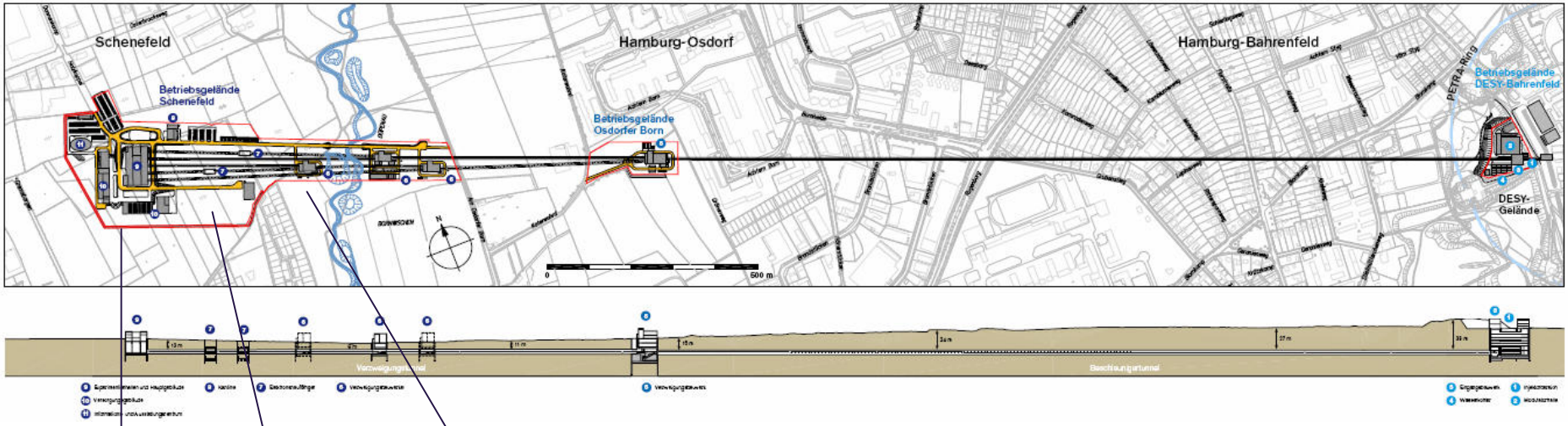
June 2015: User operation, SASE 1 Å

Overall layout of the European XFEL



The European XFEL

3.4km



5 Undulators (3 SASE)

17.5 GeV LINAC

Injector

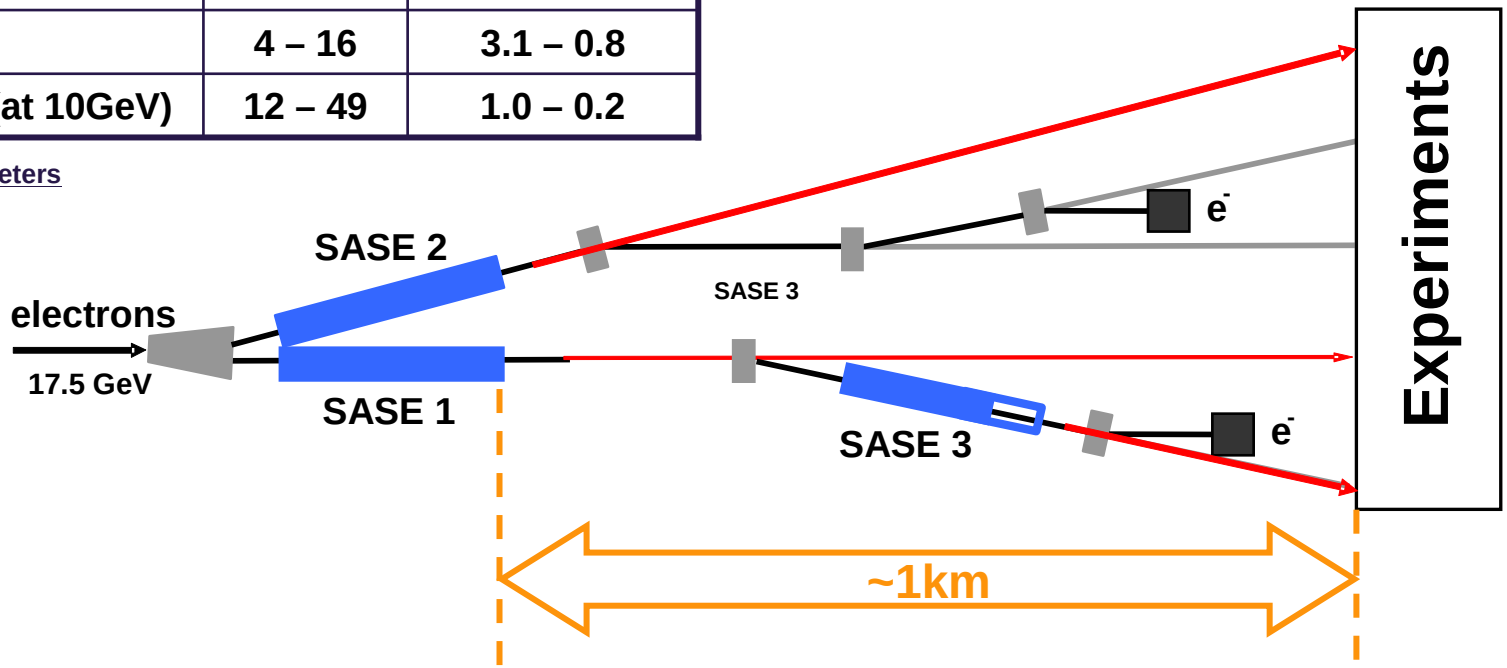
5 Photon Beamlines

10-15 Experiments

Photon beamlines

	λ [Å]	E [keV]
SASE 1	1	12.4
SASE 2	1 – 4	12.4 – 3.1
SASE 3	4 – 16	3.1 – 0.8
SASE 3 (at 10GeV)	12 – 49	1.0 – 0.2

more parameters

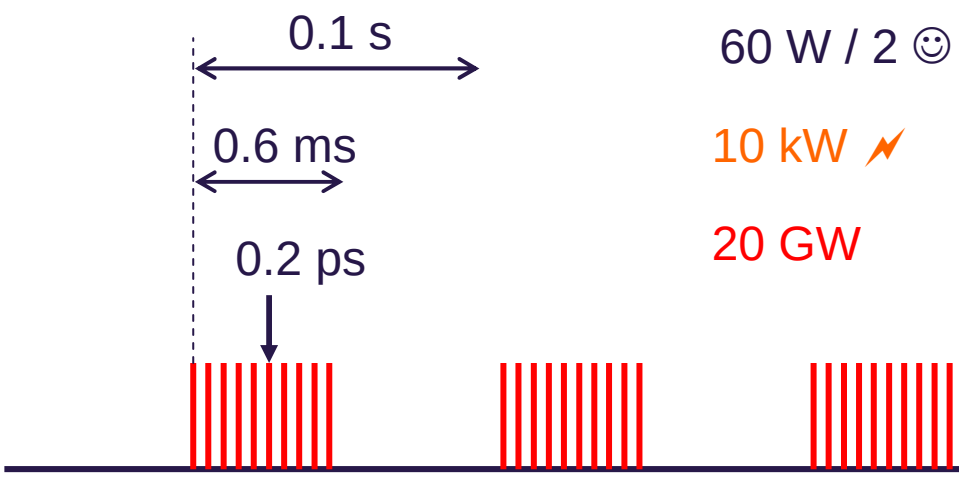


Initial configuration:

SASE1, SASE2, SASE3 (planar) plus six instruments

Special requirements for E-XFEL diagnostics

XFEL pulse pattern: 99.4 % empty



60 W / 2 ☺

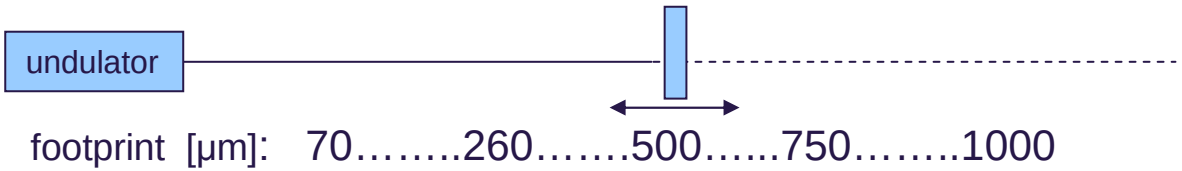
10 kW

20 GW

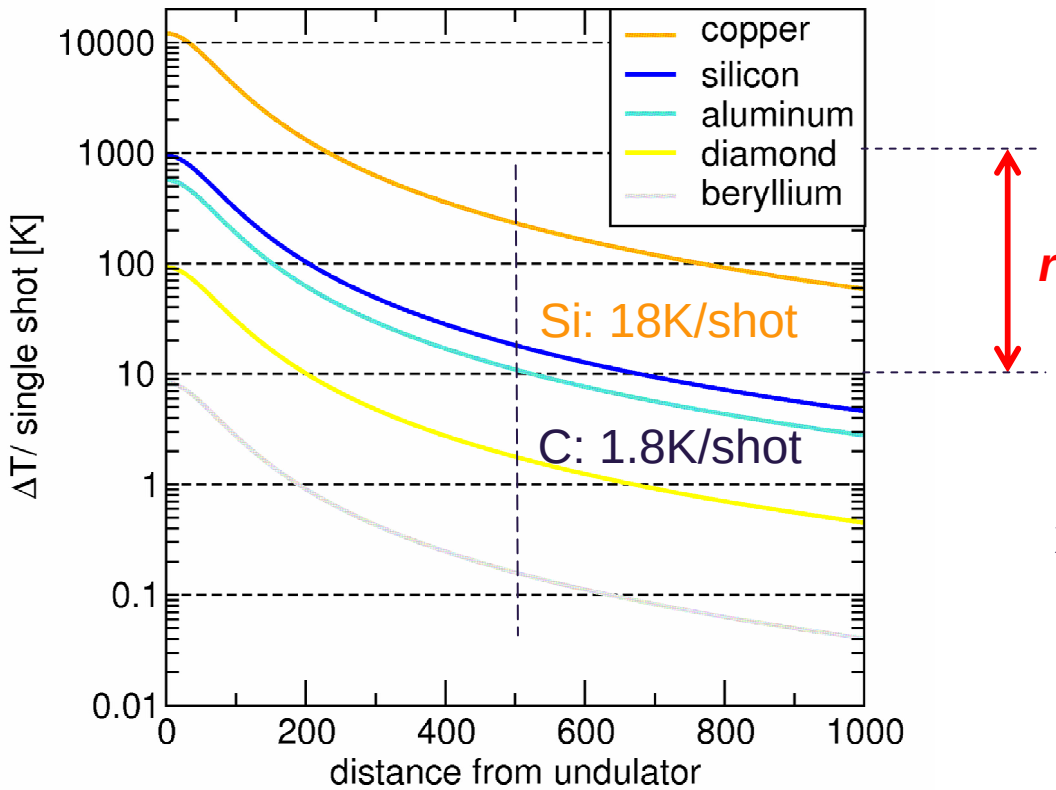
40,000 W/mm²

slide by H.Sinn

Damage potential at SASE 1 beamline (12.3 keV)



footprint [µm]: 70……..260…….500…...750……..1000



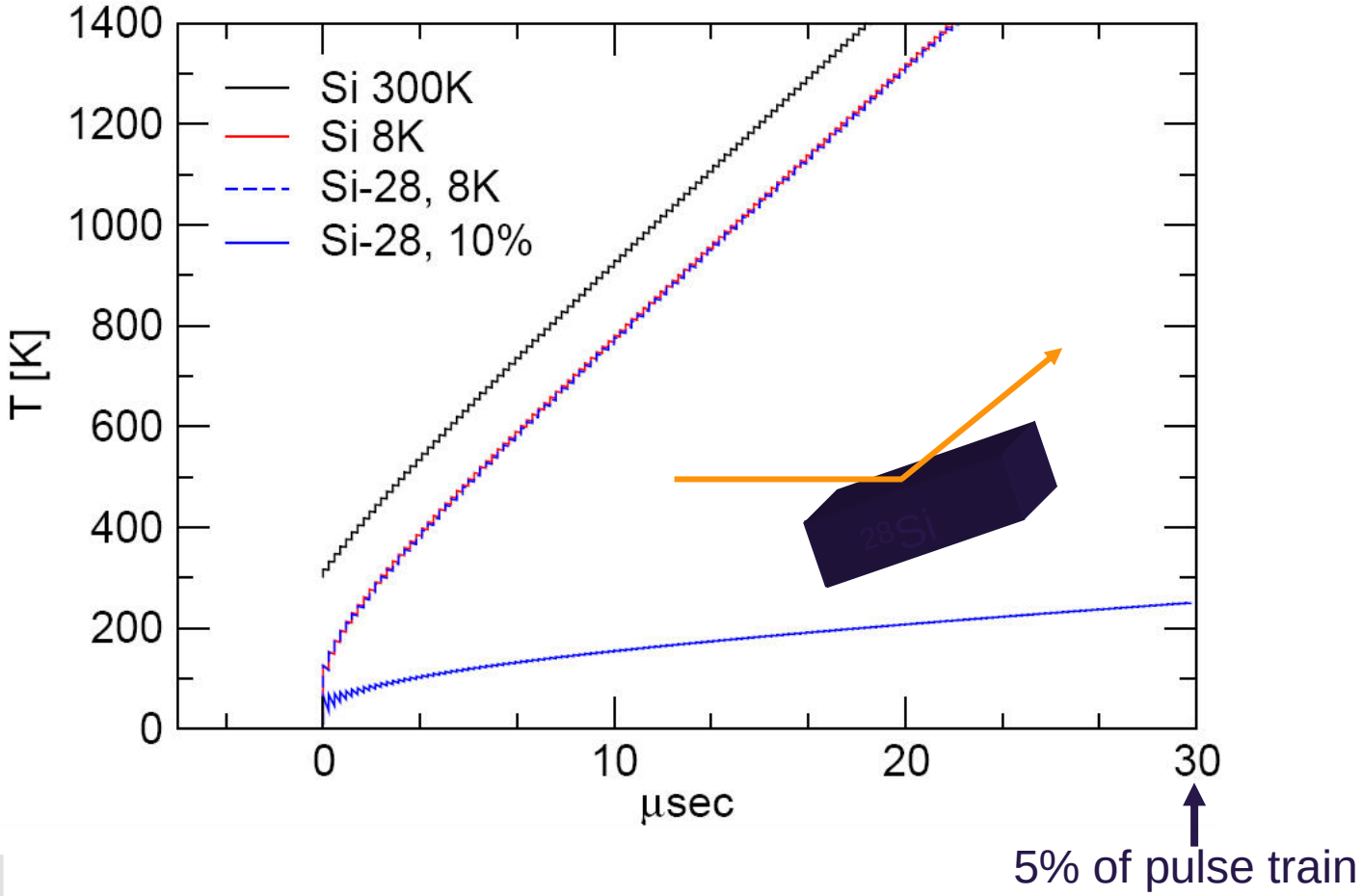
factor 100 reduction at 600 m!

x 3000 during 0.6 ms pulsetrain!

(later more ..)

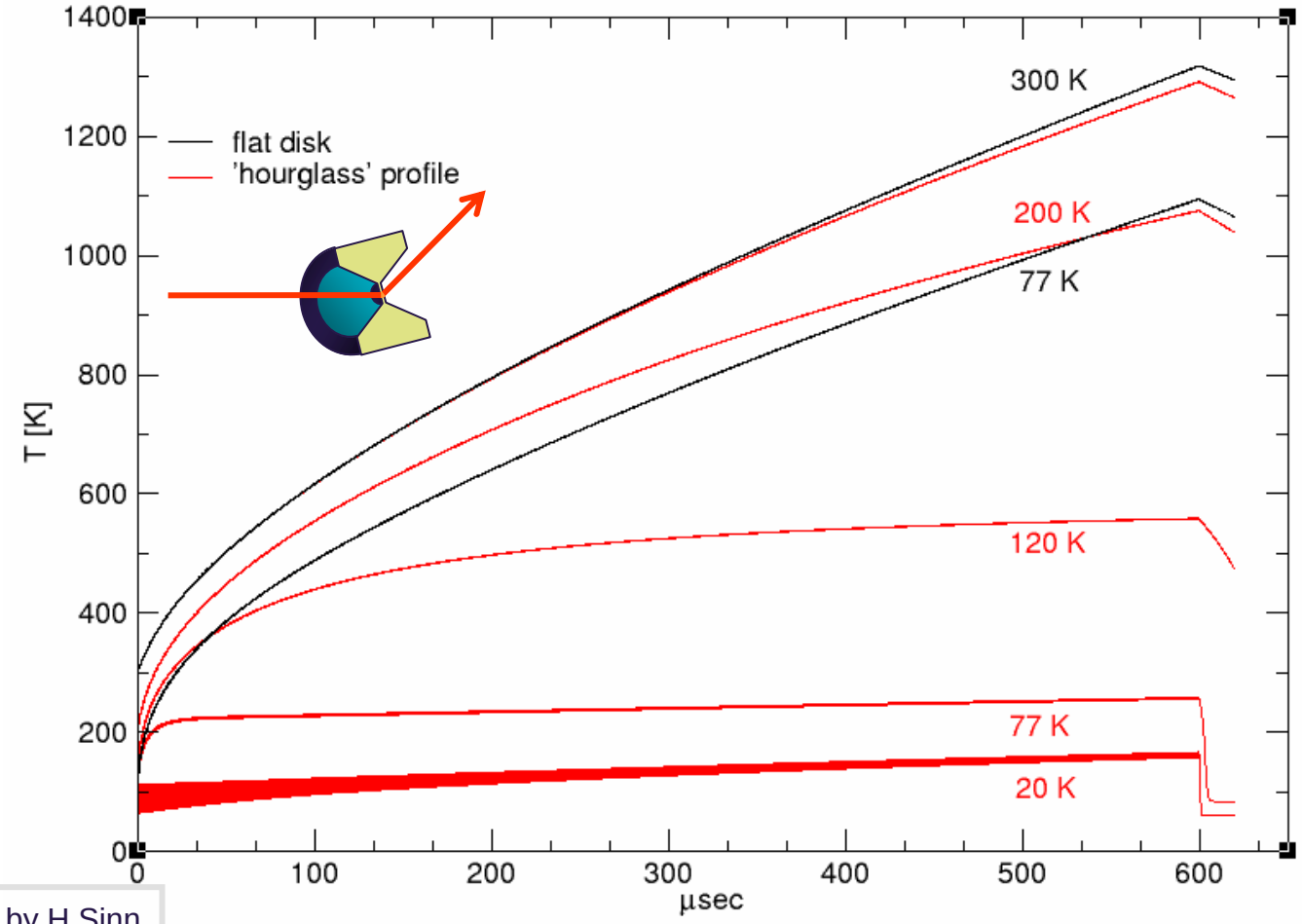
slide by H.Sinn

Results Silicon during 600 µsec pulse train



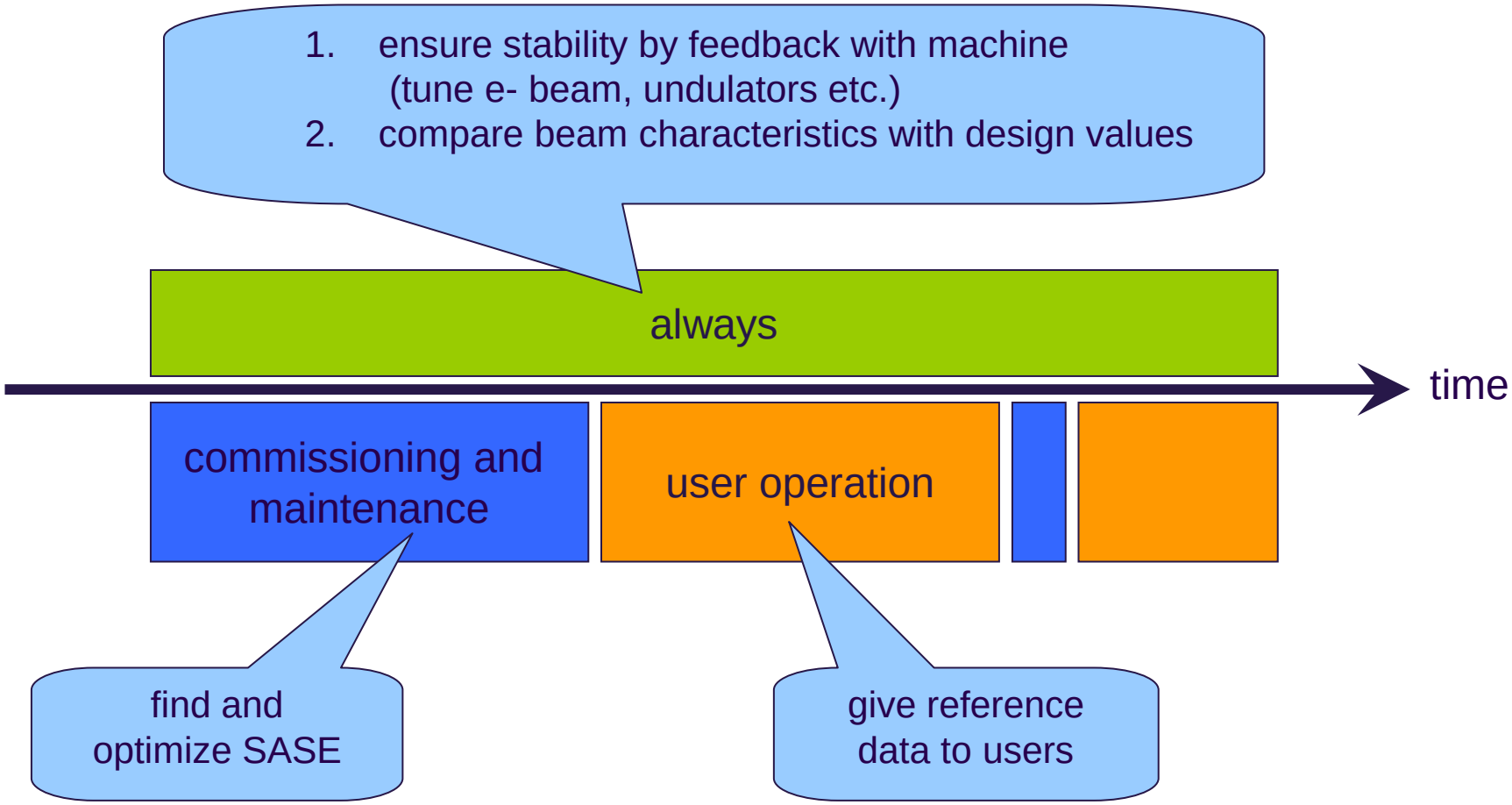
slide by H.Sinn

Results diamond



slide by H.Sinn

When monitoring photons and why ?



Beam properties

divergence
(far field)

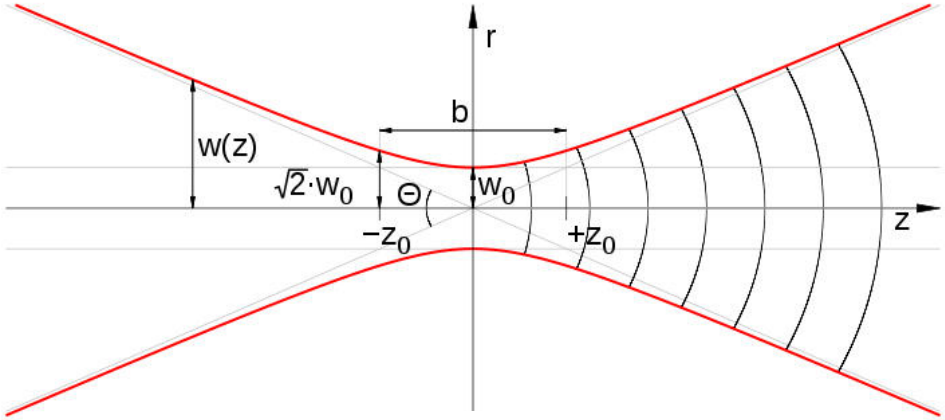
$$\theta = \frac{\lambda}{\pi w_0}$$

time structure
temporal coherence
pulse length

wavelength / spectrum

transverse size

$$w(z) = w_0 \sqrt{1 + (z / z_R)^2}$$



position of centroid

transverse intensity distribution

spatial coherence

laser modes (M^2)

Rayleigh length

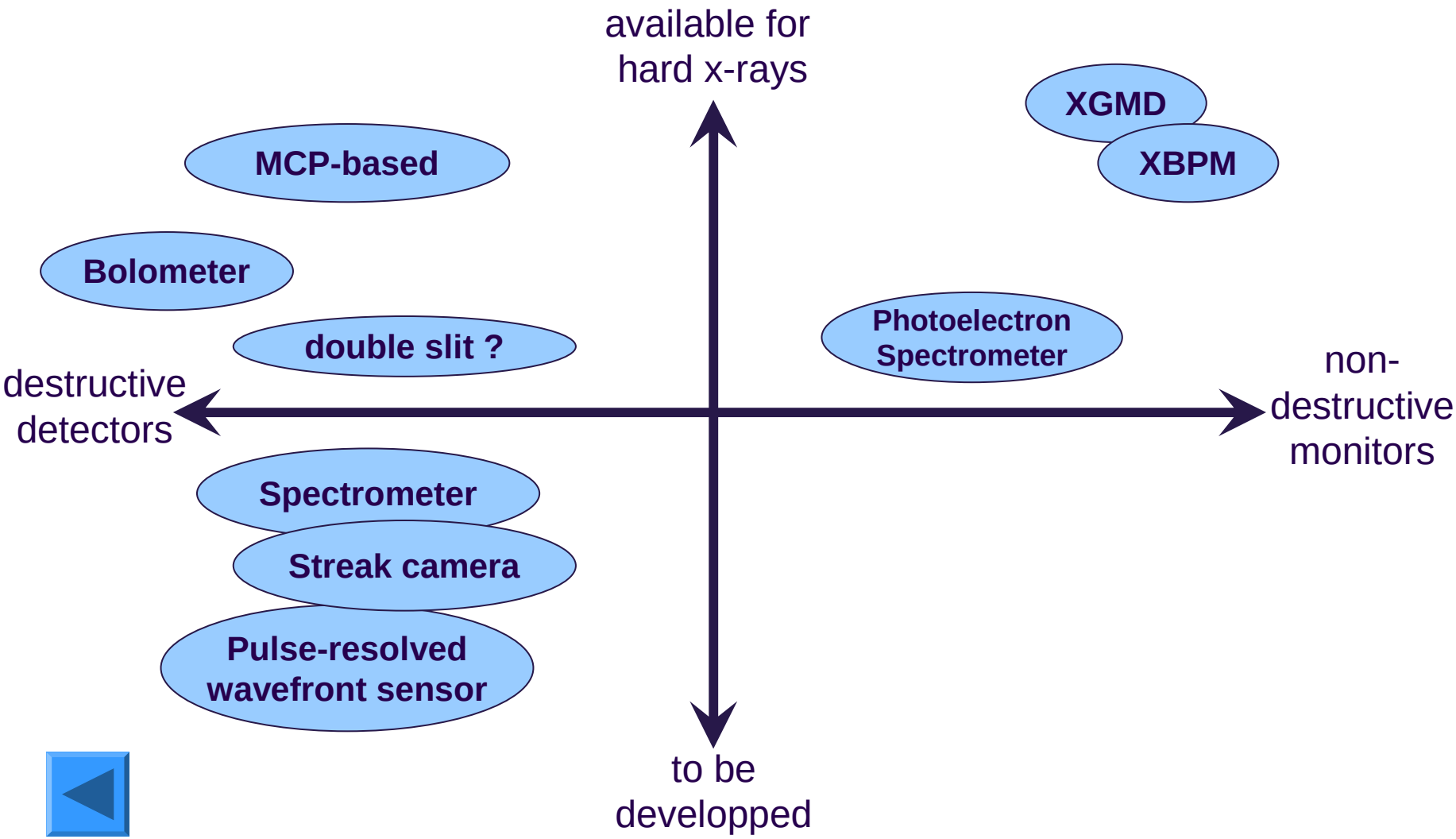
$$z_R = \frac{\pi w_0^2}{\lambda}$$

(local) curvature of wavefront

$$R(z) = z\left[1 + (z_R / z)^2\right]$$

sketch: wikimedia.org

Photon diagnostics systems



Concept Overview Diagnostics

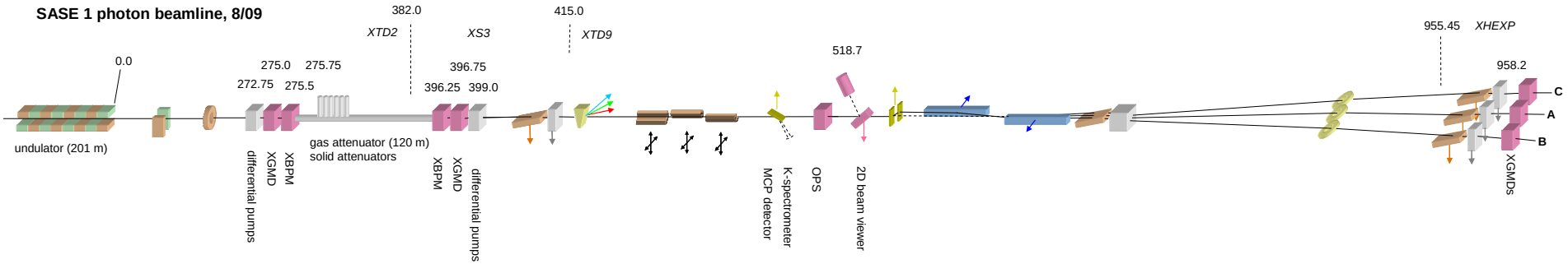
- baseline devices

commissioning !

	property	per pulse	pulses per train	online device	absolute value
XGMD	intensity	X	full	X	X
MCP-based detector	intensity 2D image	X –	< 30 pulses	–	–
K-Monochromator	spectrum	–	few	–	–
XBPM	position profile	X –	full	X	–
Imager	2D image	–	full	–	–
Photoionization Spectrometer	spectrum polarization	X X	full	X	X

[1] J.Grünert, *Concept - Photon Diagnostics for the European XFEL*, 09/2009

SASE1 schematic



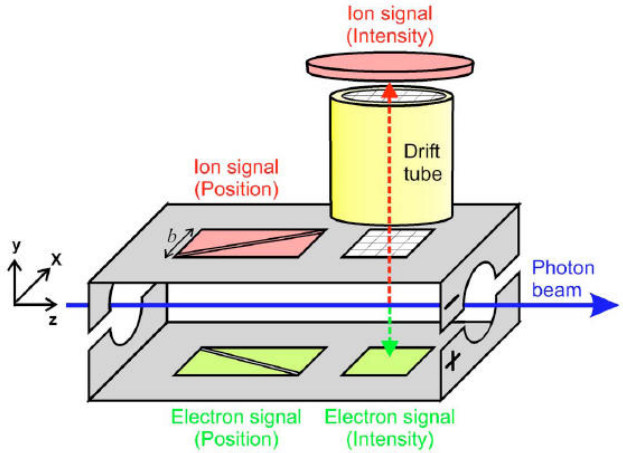
Concept Overview Diagnostics

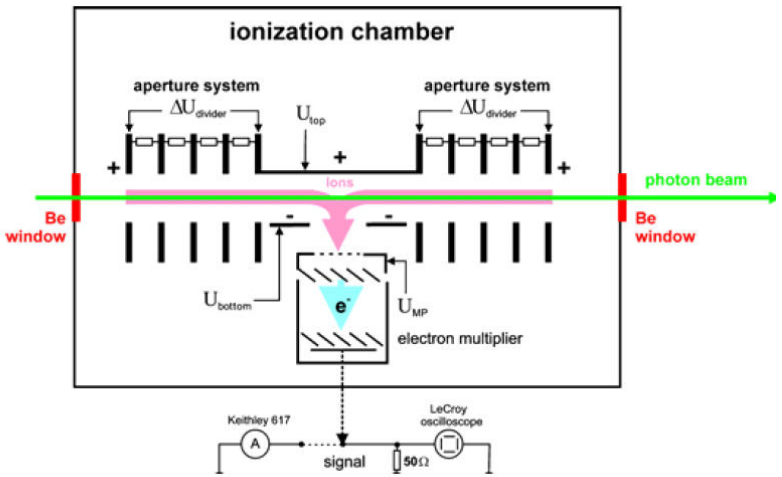
- advanced devices (R&D)
  - pulse-resolved wavefront sensor
  - (online) measurement of transverse coherence
  - photon beam arrival monitor
  - temporal pulse shape and pulse overlap monitor

- other devices
  - Intensity detector at the beam stop (e.g. “intelligent beamstop”)
  - Retractable intensity monitors behind every x-ray optical element
  - Retractable filters, crosshairs, and slits

XGMD

- Online intensity measurement
  - abs. uncertainty <10%
  - rel. accuracy <1%
    (photoion signal statistics:
    for 10^{10} x-ray photons ≈ 10^4 ions)
  - pulse-resolved
  - range: 10^7 to 10^{15} photons/pulse
  - gas pressure 10^{-4} to 10^{-6} mbar





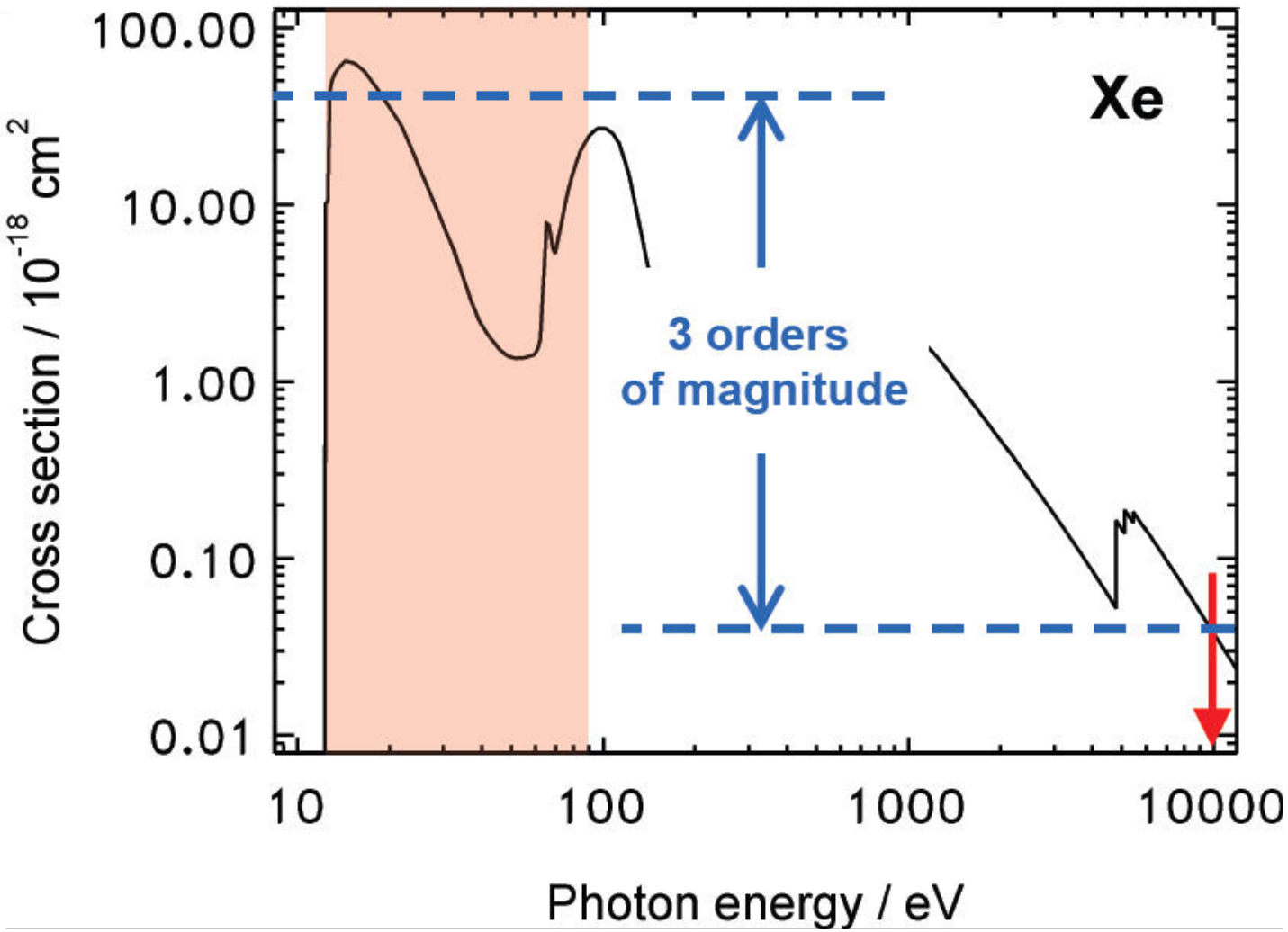
Single photoionisation:

$$N = N_{ph} \times n \times \sigma \times l$$

N = number of electrons or ions
N_{ph} = number of photons
n = target density
σ = photoionisation cross section
l = length of interaction volume

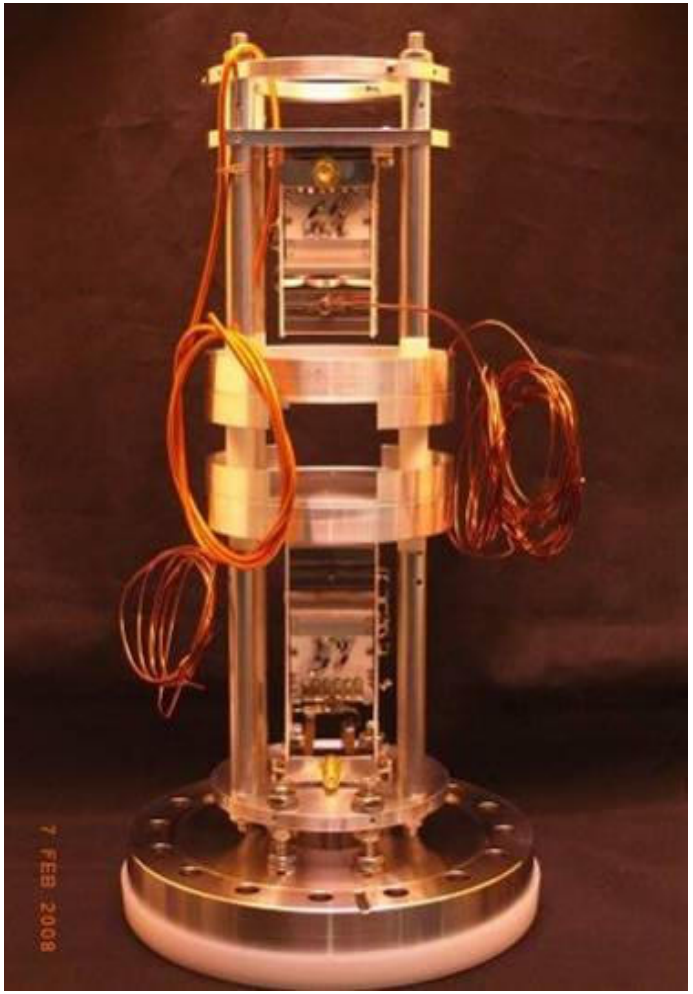
[1] K. Tiedtke et al, *Gas-detectors for X-ray lasers*, J. Appl. Phys. **103**, 094511 (2008)

Cross sections



B.L. Henke et al., Atomic Data and Nuclear Data Tables **54**, 181-342 (1993)

the “new” GMD (2009)



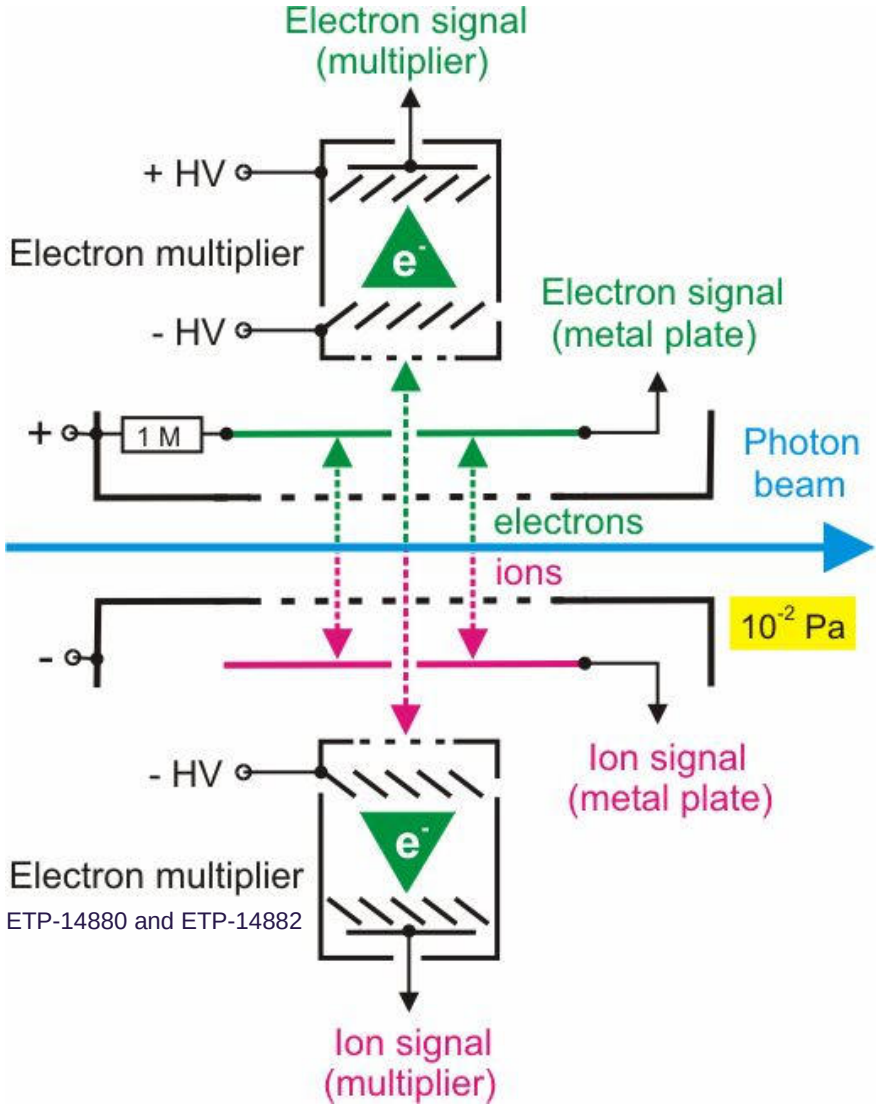
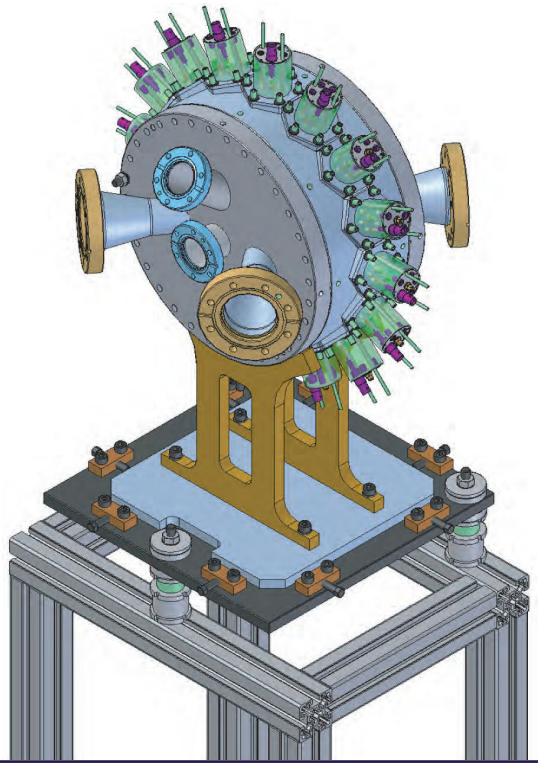
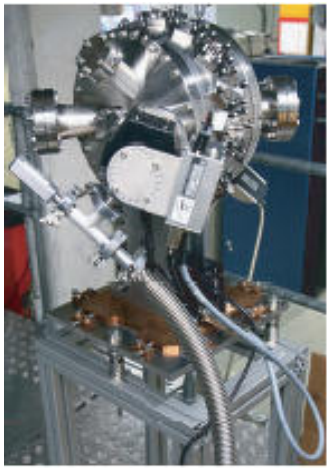


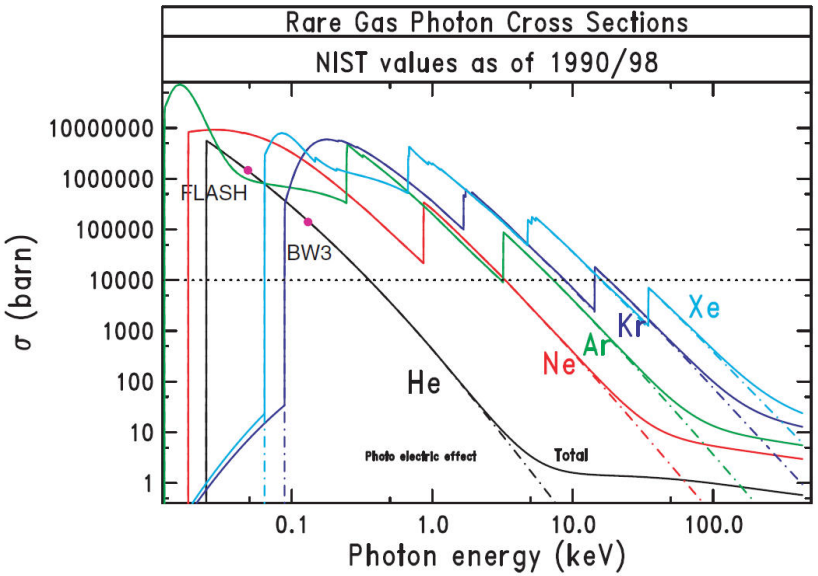
Photo-electron spectroscopy (PES)

- pulse energy + polarization
- transportable setup at DESY
- proof-of-principle exp. at PETRA3 for hard x-rays (3 to 15keV)
- technical difficulties: retardation voltages, kapton windows, ...

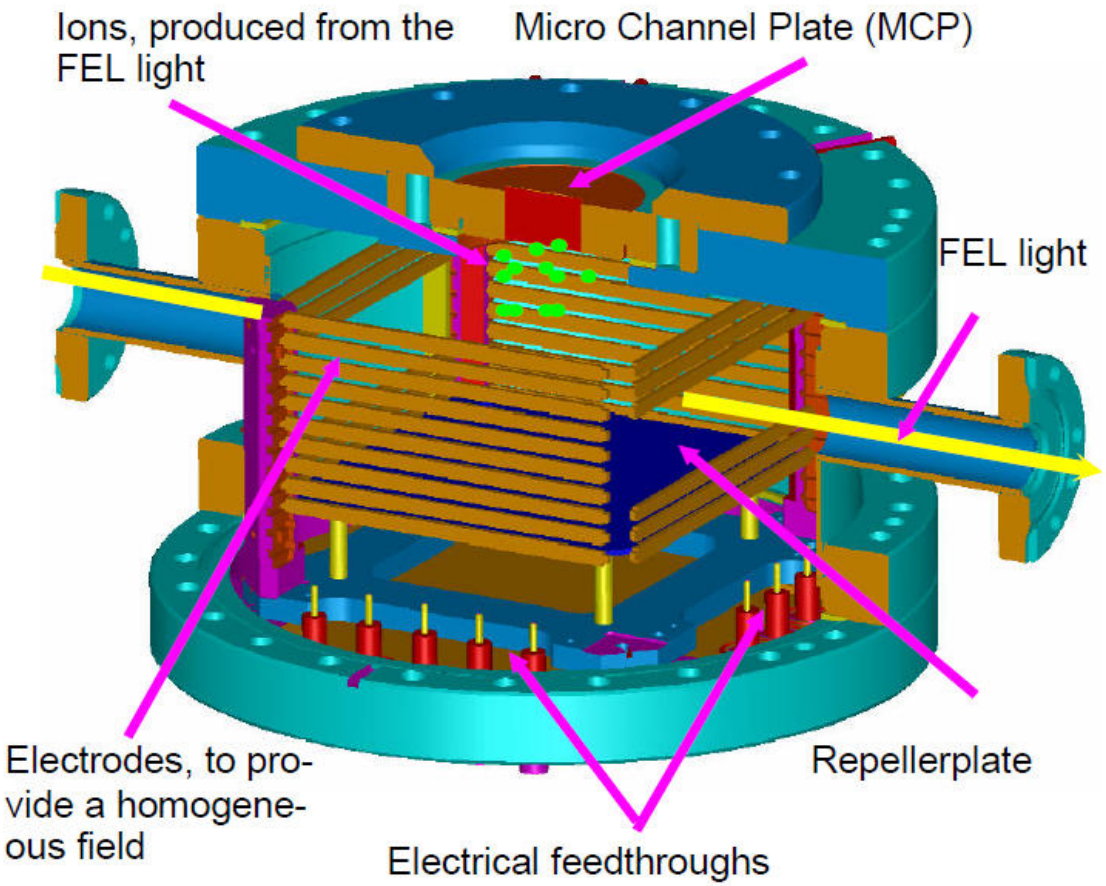




PETRA3-P04 setup
(courtesy J.Viefhaus)



IPM / visual BPM



- resolution in 2008 [1]

CCD	10µm
LVDT	1µm
position	**50µm**

- next: online operation test in FLASH tunnel

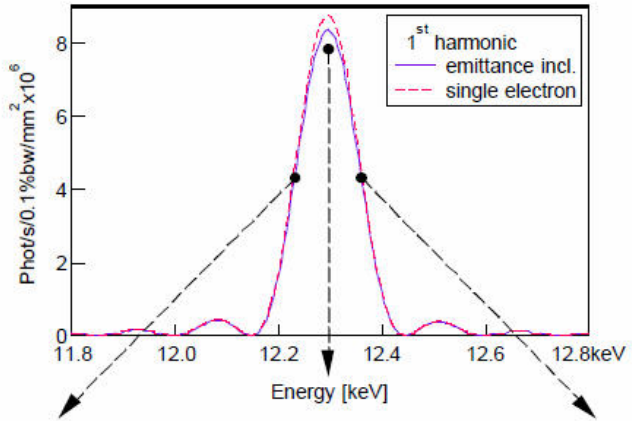
Specs for XBPM:

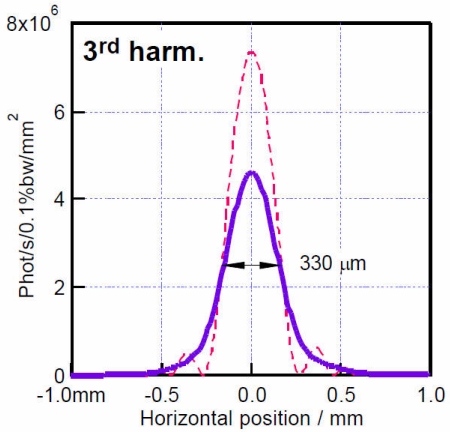
- uncertainty 10µm (in ± 1mm)
- rel. accuracy <1%
- angular resolution: 0.1µrad
- temporal resolution: <180 ns
- range: 10^7 to 10^{15} photons/pulse

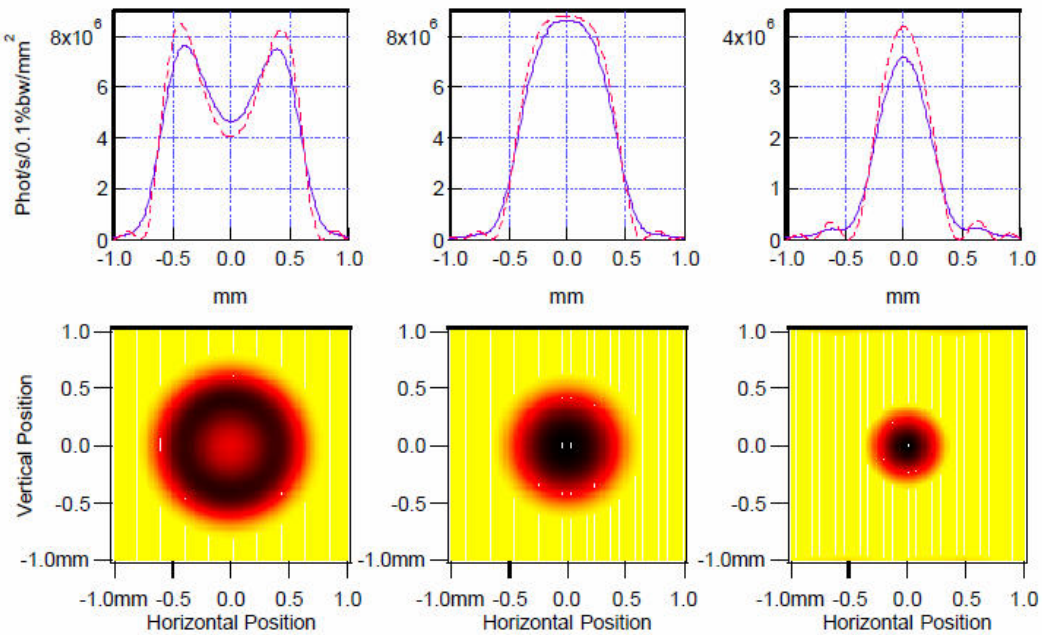
[1] M. Sachwitz, A.Hofmann, S. Pauliuk, K. Tiedtke and H. Wabnitz, Ionization profile monitor to determine spatial and angular stability of FEL radiation of FLASH, TUPC090, Proceedings of EPAC08

Trajectory alignment

- mean linewidth ~330µm
- center of gravity determination with ~7% accuracy
- → 20 µm in 100m distance or 0.2 µrad angular resolution



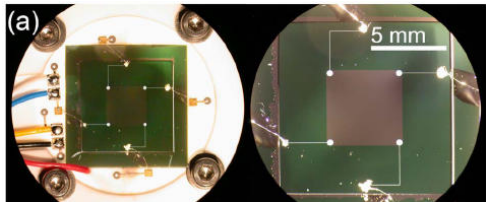




Ref.: Markus Tischer, Poster, ESFRI 2003

Alternative position monitors

- thinned-down (5-10µm) transmissive silicon position sensitive detector
  - submicron position resolution up to 1 kHz (S/N=$6 \cdot 10^4$ @ 10 Hz)
  - at 12.4keV: ~95% transmission
  - lower flux limit: ~10^7 photons/s
  - Scenario: 1 pulse / train



Transmissive x-ray beam position monitors with submicron position- and submillisecond time resolution
Martin R. Fuchs, Karsten Holldack, Mark Bullough, Susanne Walsh, Colin Wilburn, Alexei Erko, Franz Schäfers, and Uwe Mueller,
Rev. Sci. Instrum. **79**, 063103 _2008, [local]

- coded-aperture imaging
  - goals: few µm resolution, at sub-nanosecond response time (shot-to-shot profiles)
  - but: not transmissive

X-ray monitor based on coded-aperture imaging for KEKB upgrade and ILC damping ring
J.W. Flanagan, H. Fukuma, S. Hiramatsu, H. Ikeda, K. Kanazawa, T. Mitsuhashi, J. Urakawa (KEK/Japan),
G.S. Varner, (U.Hawaii / USA), J.P. Alexander, M.A. Palmer, LEPP, Cornell U. / USA, Proceedings of EPAC08, Genoa, Italy, [web], [local]

- CVD diamond photocurrent pixel detectors

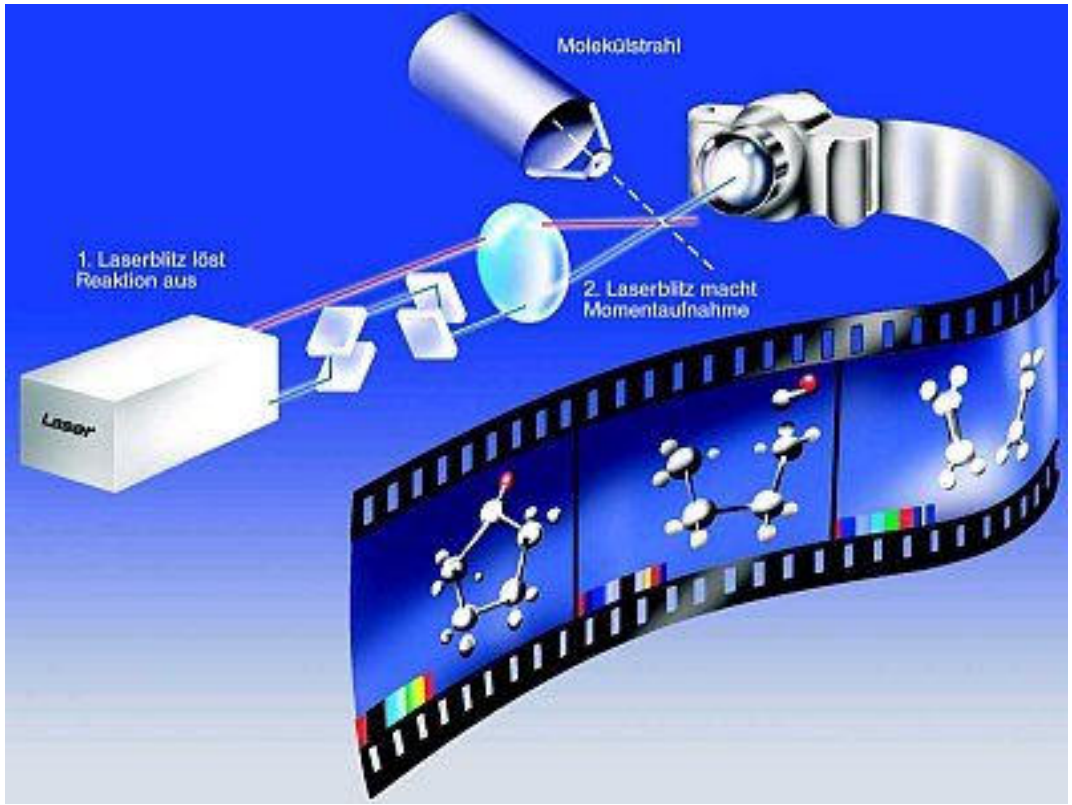
A CVD-diamond based beam profile monitor for undulator radiation
C. Schulze-Briese, B. Ketterer, C. Pradervand, Ch. Brönnimann, C. David, R. Horisberger, A. Puig-Molina, H. Graafsma,
NIM A 467–468 (2001) 230–234 [web], [local]

commissioning: two transparent XBPMs with µm accuracy

Timing

- application
  - Pump probe experiments
  - X-ray-induced dynamics

- What to measure ?
  - pulse arrival and duration
  - pulse shape
  - temporal coherence



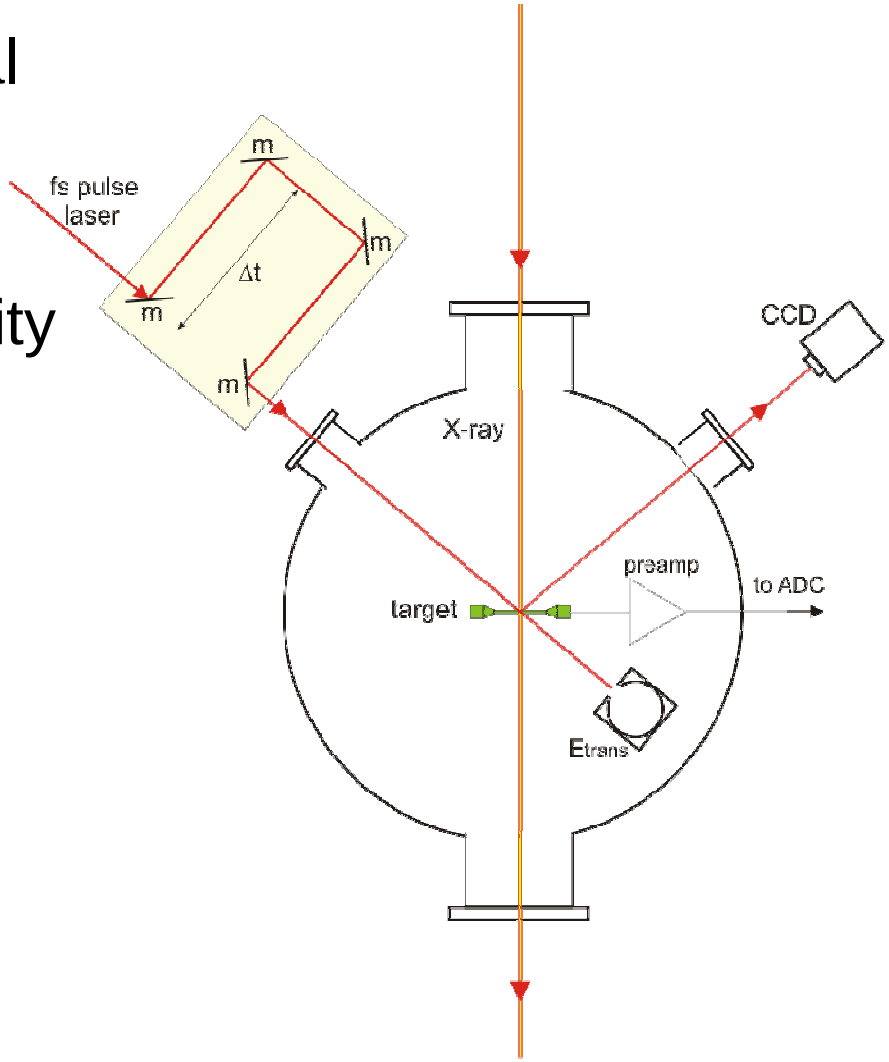
Timing

- application
  - Pump probe experiments
  - X-ray-induced dynamics
- What to measure ?
  - pulse arrival and duration
  - pulse shape
  - temporal coherence
- How to measure ?
  - based on electrons (EO mod. effect)
  - single-pulse wavelength spectra
  - streak cameras
  - autocorrelator (beam splitter) [1]
  - laser-induced side-band generation [2]
  - THz-field-driven x-ray streak camera [3]
  - X-ray induced optical reflectivity change [4,5]

[1] R. Mitzner, B. Siemer, M. Neeb, T. Noll, F. Siewert, S. Roling, M. Rutkowski, A.A. Sorokin, M. Richter, P. Juranic, K. Tiedtke, J. Feldhaus, W. Eberhardt and H. Zacharias, *Spatio - temporal coherence of free electron laser pulses in the soft x-ray regime,* Optics Express 16, 19909-19919 (2008); http://dx.doi.org/10.1364/OE.16.019909
[2] P. Radcliffe, S. Düsterer, A. Azima, H. Redlin, J. Feldhaus, J. Dardis, K. Kavanagh, H. Luna, J. Pedregosa Gutierrez, P. Yeates, E. T. Kennedy, J. T. Costello, A. Delserieys, C. L. S. Lewis, R. Taïeb, A. Maquet, D. Cubaynes, and M. Meyer, *Single-shot characterization of independent femtosecond extreme ultraviolet free electron and infrared laser pulses*, APL 90 131108 (2007), http://dx.doi.org/10.1063/1.2716360
[3] U. Frühling, M. Wieland, M. Gensch, T. Gebert, B. Schütte, M. Krikunova, R. Kalms, F. Budzyn, O. Grimm, J. Rossbach, E. Plönjes and M. Drescher, *Single-shot terahertz-field-driven X-ray streak camera*, Nature Photonics 3, 523 - 528 (2009) http://dx.doi.org/10.1038/NPHOTON.2009.160
[4] C.Gahl, A.Azima, M. Beye, M. Deppe, K. Döbrich, U. Hasslinger, F. Hennies, A. Melnikov, M. Nagasono, A. Pietzsch, M. Wolf, W. Wurth, and A. Föhlisch, *A femtosecond X-ray/optical cross-correlator nature photonics*, VOL 2, p.165 (MARCH 2008), http://dx.doi.org/10.1038/nphoton.2007.298
[5] M. Gabrysch, E. Marklund, J. Hajdu, D. J. Twitchen, J. Rudati, A. M. Lindenberg, C. Caleman, R. W. Falcone, T. Tschentscher, K. Moffat, P. H. Bucksbaum, J. Als-Nielsen, A. J. Nelson, D. P. Siddons, P. J. Emma, P. Krejcik, H. Schlarb, J. Arthur, S. Brennan, J. Hastings, and J. Isberg, *Formation of secondary electron cascades in single-crystalline plasma-deposited diamond upon exposure to femtosecond x-ray pulses*, Journal of Applied Physics 103, 064909 (2008)

Timing

- pump-probe with CVD crystal
  - transient charge cloud
  - time-delay dependent changes in optical reflectivity



Reference: Markus Gabrysch, Jan Isberg (Uppsala University)

Summary

- *European XFEL*
  - project, status, challenges, diagnostics
- Collaboration with this community on diamond detectors for
  - x-ray intensity
  - x-ray position
  - timing
- Concrete wishes
  - tests of detectors at FLASH, PETRA3 ?
  - open positions

Acknowledgements

- European XFEL GmbH
- DESY
- European Union – Pre-XFEL Project
- my collegues at the European XFEL (especially Altarelli and Sinn for some material used in this presentation)

additional material

6 Instruments (start-up version)

Hard X-rays

Soft X-rays

Instrument	Brief description of the instrument
SPB	Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules – **Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.**
MID	Materials Imaging & Dynamics **–Structure determination of nano- devices and dynamics at the nanoscale.**
FDE	Femtosecond Diffraction Experiments – **Time-resolved investigations of the dynamics of solids, liquids, gases**
HED	High Energy Density Matter – **Investigation of matter under extreme conditions using hard x-ray FEL radiation, e.g. probing dense plasmas.**
SQS	Small Quantum Systems – **Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.**
SCS	Soft x-ray Coherent Scattering **–Structure and dynamics of nano-systems and of non-reproducible biological objects using soft X-rays.**

European XFEL

Photon Beam Parameters

Parameter	Unit	SASE 1	SASE 2		SASE 3		
Electron energy	GeV	17.5	17.5	17.5	17.5	17.5	10.0**
Wavelength	nm	0.1	0.1	0.4	0.4	1.6	6.4
Photon energy	keV	12.4	12.4	3.1	3.1	0.8	0.2
Peak power	GW	20	20	80	80	130	135
Average power*	W	65	65	260	260	420	580
Photon beam size (FWHM)	µm	70	85	55	60	70	95
Photon beam divergence (FWHM)	µrad	1	0.84	3.4	3.4	11.4	27
Coherence time	fs	0.2	0.22	0.38	0.34	0.88	1.9
Spectral bandwidth	%	0.08	0.08	0.18	0.2	0.3	0.73
Pulse duration	fs	100	100	100	100	100	100
Photons per pulse	#	10^{12}	10^{12}	1.6×10^{13}	1.6×10^{13}	1.0×10^{14}	4.3×10^{14}
Average flux	#/s	3.3×10^{16}	3.3×10^{16}	5.2×10^{17}	5.2×10^{17}	3.4×10^{18}	1.4×10^{19}
Peak brilliance	B	5.0×10^{33}	5.0×10^{33}	2.2×10^{33}	2.0×10^{33}	5.0×10^{32}	0.6×10^{32}
Average brilliance*	B	1.6×10^{25}	1.6×10^{25}	7.1×10^{24}	6.4×10^{24}	1.6×10^{24}	2.0×10^{23}

Today's state of the art

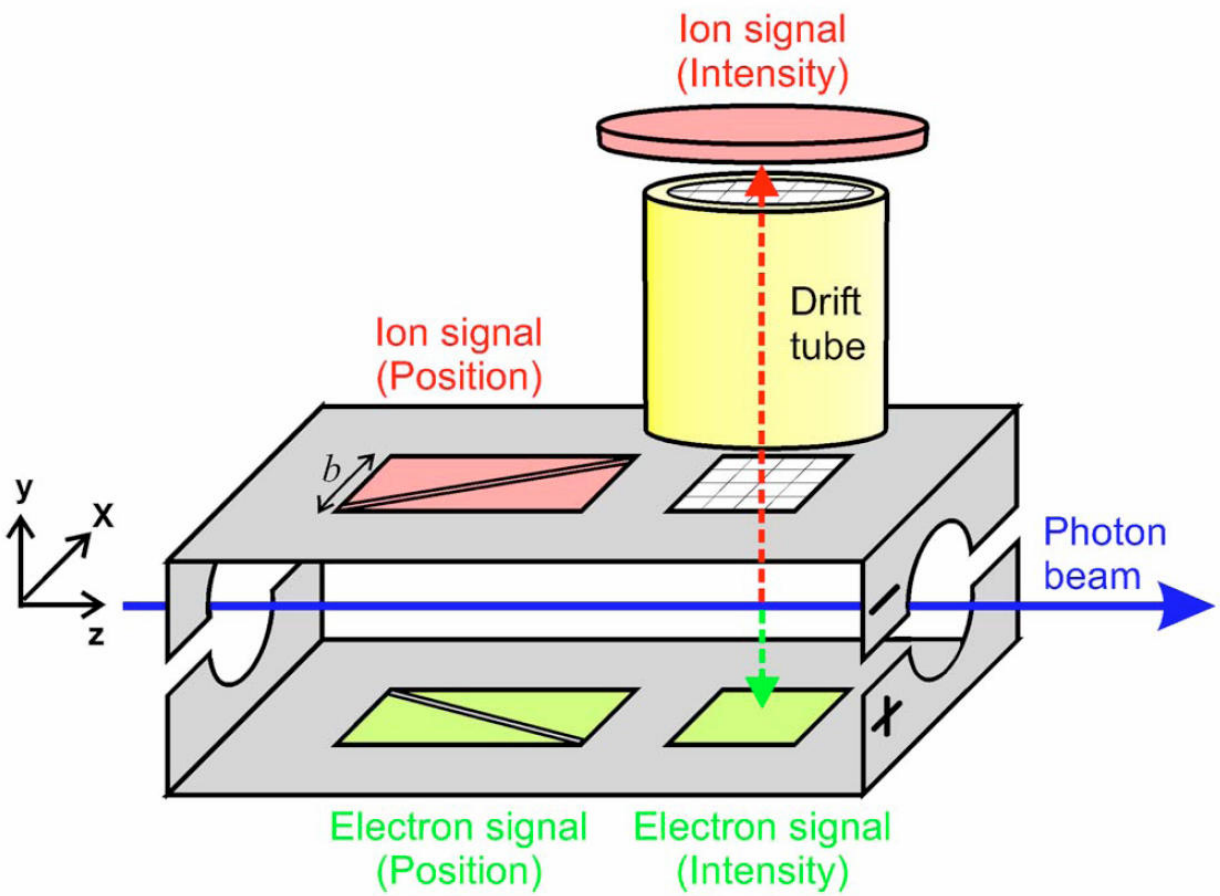
- **FLASH** – Ultraviolet and soft x-ray FEL user facility in Hamburg (down to $\lambda \sim 6.5$ nm) *10^{12} Ph/pulse*

- **SCSS Test Accelerator** – Ultraviolet and soft x-ray FEL user facility at Spring 8 ($\lambda \sim 30 – 60$ nm)

- **SPPS** – (Sub-ps Pulse Source) Stanford, operating 2003-2006, spontaneous emission from conventional x-ray undulator of ultrashort (<100 fs) electron bunches from SLAC Linac *10^{6} Ph/pulse*

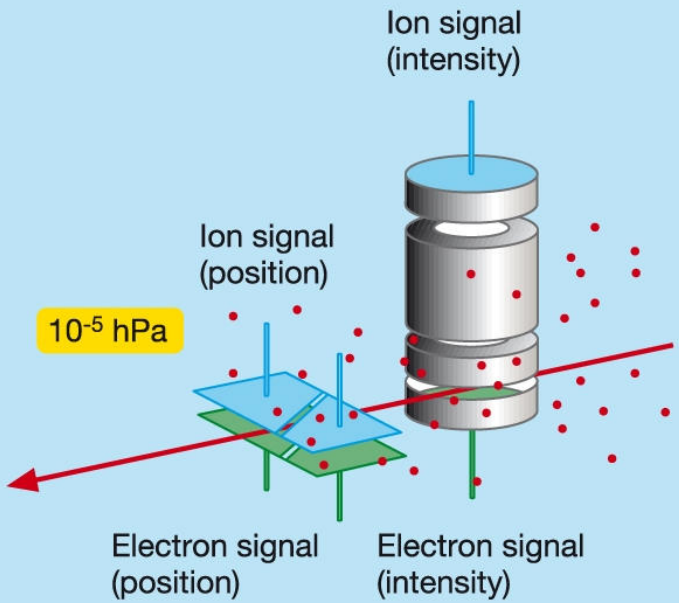
- First beam at 0.15 nm from **LCLS** (Linac Coherent Light Source at SLAC) on April 10, 2009; first experiments since October 1st *10^{12} Ph/pulse*

GMD @ FLASH



from: Tiedtke et al., Journal of Applied Physics 103, 094511 (2008)

GMD @ FLASH



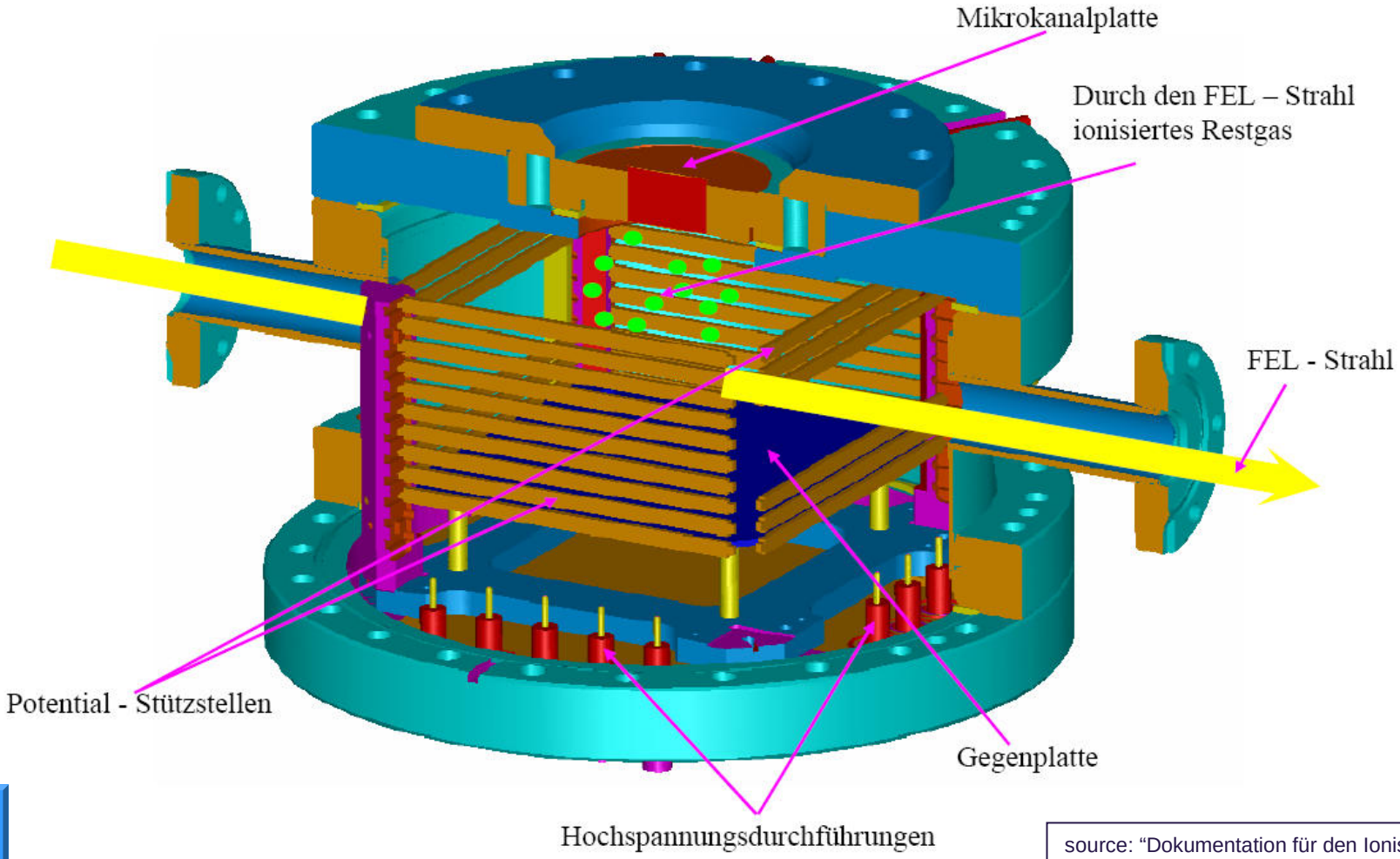
Single photoionisation:

$$N = N_{ph} \times n \times \sigma \times l$$

N	Number of electrons or ions
N_{ph}	Number of photons
n	Target density
σ	Photoionisation cross section
l	Length of interaction volume

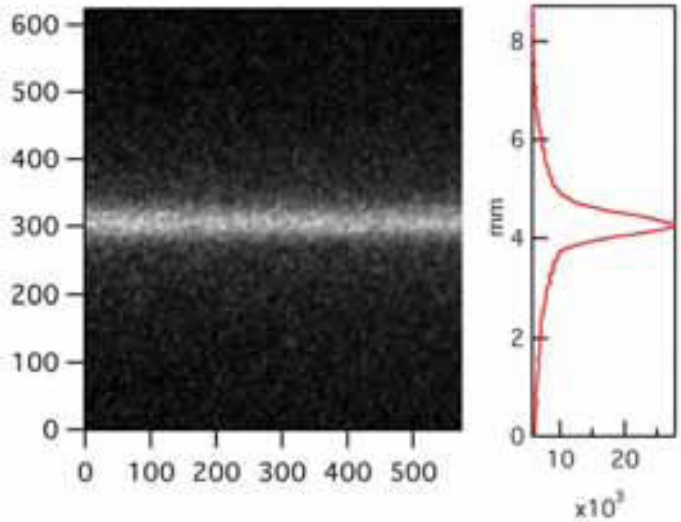
[6-51] R. Klein et al., Synchrotron Radiation News 15 (2002) 23.
[6-52] K. Tiedtke et al., Gas detectors for x-ray lasers, J. Appl. Phys. 103, 094511 (2008)

XBPM



source: “Dokumentation für den Ionisations Profil Monitor bei FLASH“, Sep.2007

RGXBPM



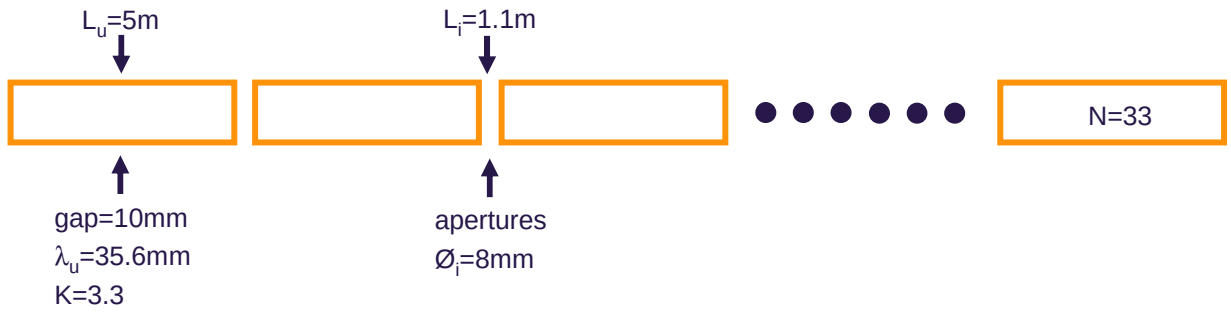
see TDR 07/2006

Photon beam properties

- Geometry
  - Center Position
  - Transverse Dimension
  - Divergence
  - longitudinal focus position
  - pointing vector
- Photon energy
  - Pulse energy
  - energy spread / bandwidth
- Intensity (# of photons per pulse)
  - max. pulse intensity
  - pulse shape
- Timing
  - Pulse duration
  - Pulse arrival time
- Polarization
  - lin. / horiz.
  - right / left circ.
- Coherence
  - transverse
  - longitudinal ?
- Wavefront

Divergence

SASE1



L_{tot}=201.3m

E_e=17.5GeV
E_{ph}=12.4keV (0.1nm)

spont.rad. (1 segment, N=140,i=1):
Θ = 6.3 µrad (σ)
Θ = 14.7 µrad (FWHM)

$$\Theta_{cen} = \frac{1}{\gamma^* \sqrt{iN}} = \frac{\sqrt{1+\frac{K^2}{2}}}{\gamma\sqrt{iN}}$$

spont.rad. (33 segments, N=4620, i=1):
Θ = 1.1 µrad (σ)
Θ = 2.57 µrad (FWHM)

FEL beam (FWHM):
size: w_0 = 70 µm
divergence: Θ = 1 µrad

contains spectral bandwidth:

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{iN}$$

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-x_0)^2}{2\sigma^2}\right]$$

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.35482\,\sigma.$$