CERN Accelerator School on

Free Electron Lasers and Energy Recovery Linacs

Photon Beam Transport

Makina YABASHI

RIKEN SPring-8 Center

yabashi@spring8.or.jp

June 8, 2016 @Hamburg

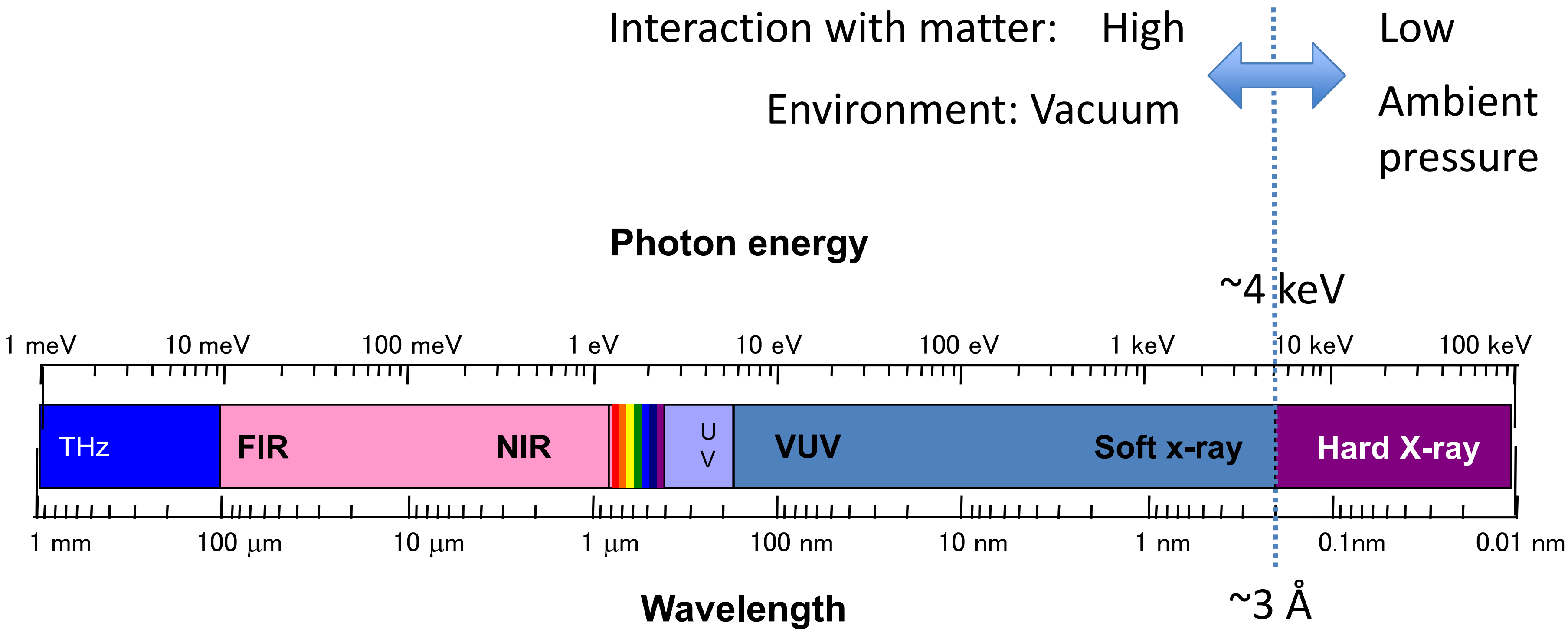
Initial Remarks

- Photon beam transport = Photon beamline or X-ray beamline
- Not just “transport”
- Control & characterization of photon beam properties in 6-dimensional phase space (+ polarization)
- Key bridge & interface between accelerator and experiments

Goal

- To provide key concepts on design and working principles of x-ray beamlines & optics
- To promote comprehensive understanding of both XFEL machine and x-ray beamline as a *light source complex*

Hard or Soft ?


Interaction with matter: High
Low
Environment: Vacuum
Ambient pressure
Photon energy
~4 keV
1 meV
10 meV
100 meV
1 eV
10 eV
100 eV
1 keV
10 keV
100 keV
THz
FIR
NIR
U V
VUV
Soft x-ray
Hard X-ray
1 mm
100 µm
10 µm
1 µm
100 nm
10 nm
1 nm
0.1nm
0.01 nm
Wavelength
~3 Å

Contents

Prototypical photon beamline at 1st gen. synchrotron sources ('70~)

Synchrotron Radiation as a Source for X-ray Diffraction

G. ROSENBAUM & K. C. HOLMES
Max-Planck-Institut für Medizinische Forschung, Heidelberg
J. WITZ
Laboratoire des Virus des Plantes, Institut de Botanique de la Faculté des Sciences de Strasbourg, Strasbourg

Nature 1971

NATURE VOL. 230 APRIL 16 1971

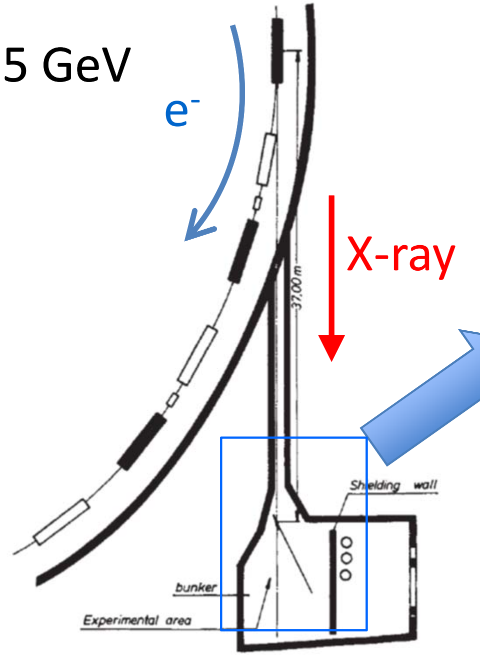


Fig. 1 The F41 bunker at DESY and its position with respect to the synchrotron.

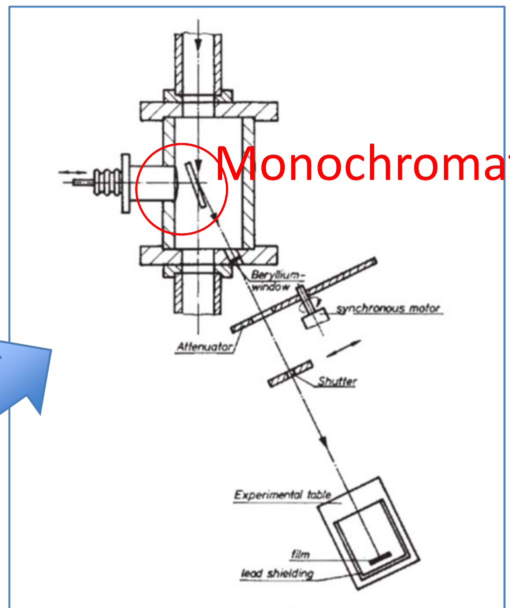
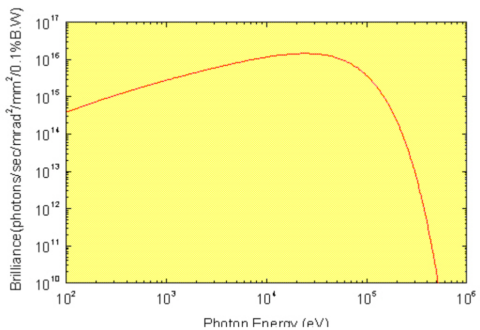


Fig. 2 Monochromator housing and the experimental set-up.

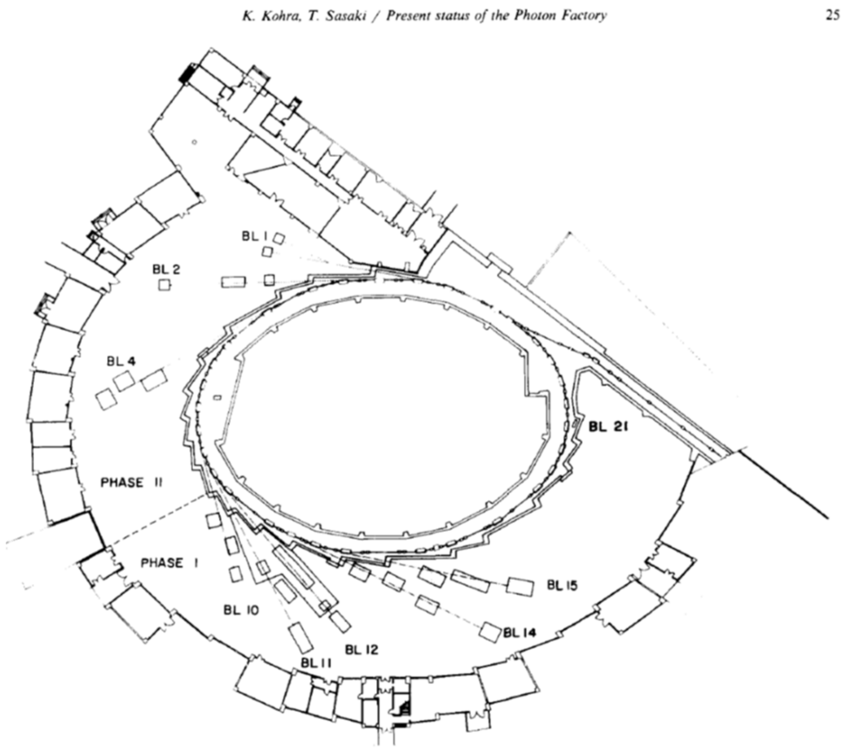
- Parasite to synchrotrons for high-energy physics
- Separation of experimental area from accelerator
- Key optics: monochromator (white spectrum of bending magnet source)

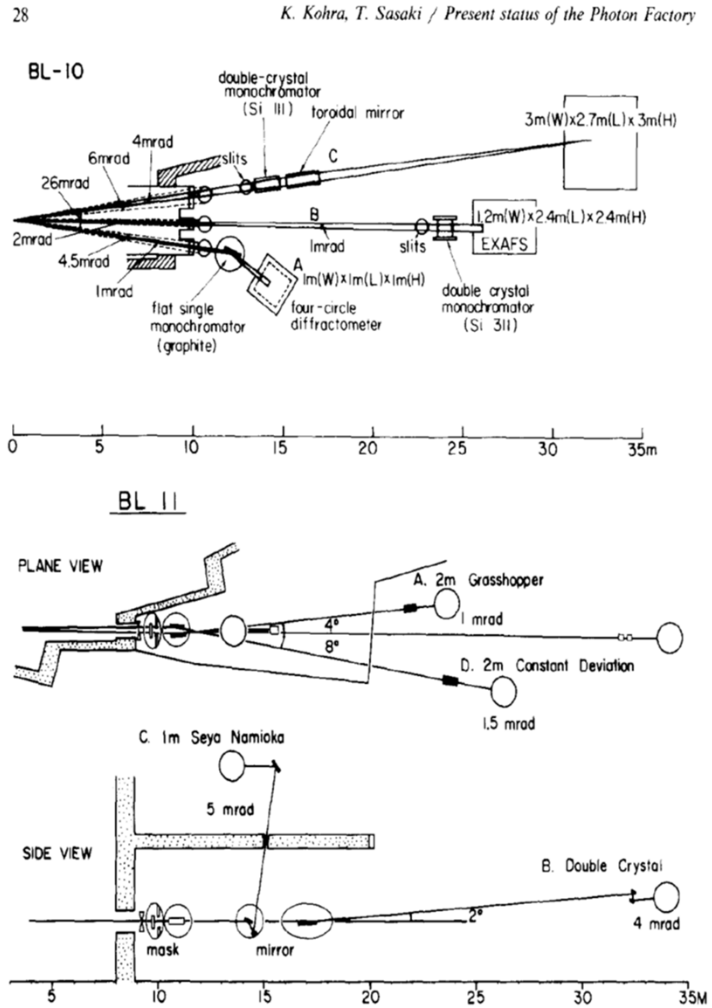


Beamline at 2nd gen. SR (‘80~)

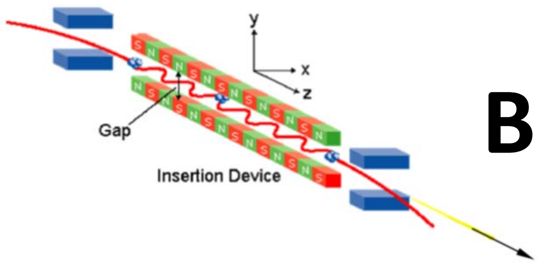
Photon Factory (KEK, Japan)

Kohra & Sasaki, NIM **208** (1983) 23

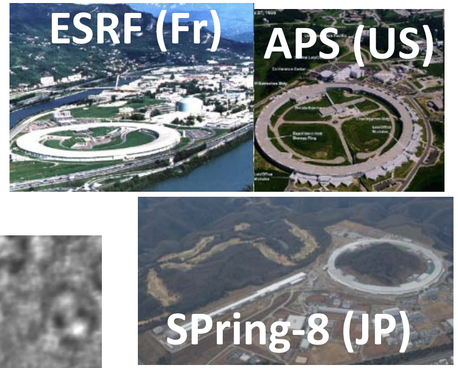




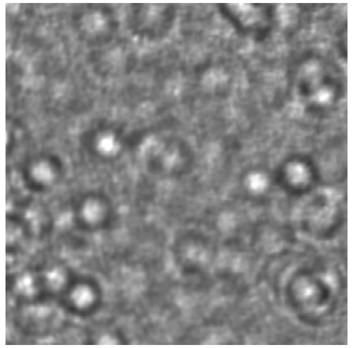
- Facility dedicated for utilizing X-rays
- Establishment of basic scheme of beamline
- Development of various X-ray optics (e.g., monochromator, focusing mirrors)
- Common optics installed into “optics hutch”



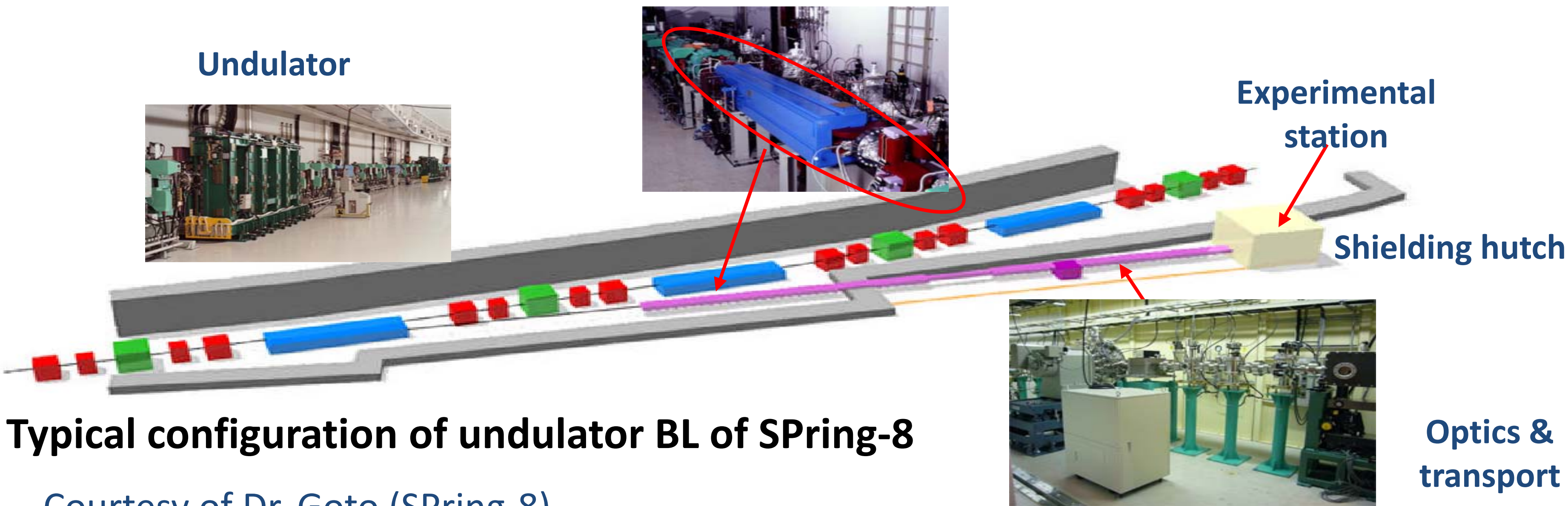
Beamline at 3rd gen. SR



- Facility dedicated for utilizing undulator radiation at low-emittance storage ring
- Matured technologies
- “Coherence” much pronounced
- Higher quality required for x-ray optics to preserve coherent wavefront and to avoid speckles



Speckle patterns from conventional Be window (1-km BL @Spring-8)

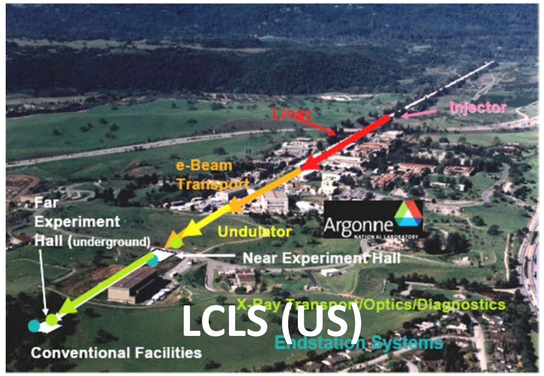


Typical configuration of undulator BL of SPring-8

Courtesy of Dr. Goto (SPring-8)

Beamline at XFEL

- XFEL: Pulsed x-ray source with excellent transverse coherence
- Shot-to-shot changes in x-ray properties: photon diagnostics needed for conducting good experiments
- X-ray properties sensitive to machine parameters: BL provides useful information for achieving stable machine operation
- Enhanced connection between accelerator and BL



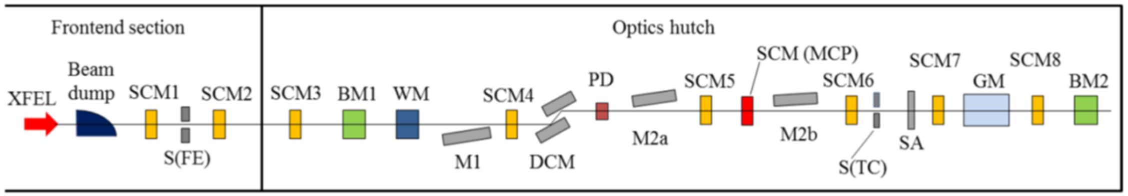


Figure 3. Photon diagnostic system on BL3. SCM1–8: screen monitor module; BM1,2: thin-foil beam monitor; WM: thin-foil wavelength monitor; GM: scattering-based gas monitor; SCM (MCP): screen monitor with a micro-channel-plate image intensifier.

Beamline configuration of SACLA XFEL
Tono et al, New J Phys **15** (2013) 083035

Summary: Development on x-ray beamline

‘70~ 1st gen. SR

- Prototypical BL for parasitic use
- Separation from accelerator

’80~ 2nd gen. SR

- Establishment of basic scheme for dedicated use

’90~ 3rd gen. SR

- High-quality optics for coherent x-ray applications

‘00~ XFEL

- Photon diagnostics for both users & machine
- Closer connection to accelerator

Contents

1. Introduction: Brief history of photon beamlines for SR/XFEL
2. Preparatory: Phase space
    1. Transverse phase space & coherence
    2. Longitudinal phase space
3. X-ray optics
4. X-ray diagnostics
5. Design of beamline
6. Summary

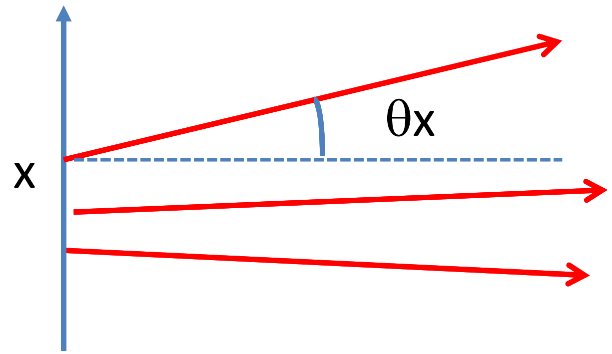
Phase space

Role of photon beamline: "*Control & characterization of photon beam properties in 6-dimensional phase space (+ polarization)*"

Transverse x 4

Position: (x,y)

Angle: (θx, θy)



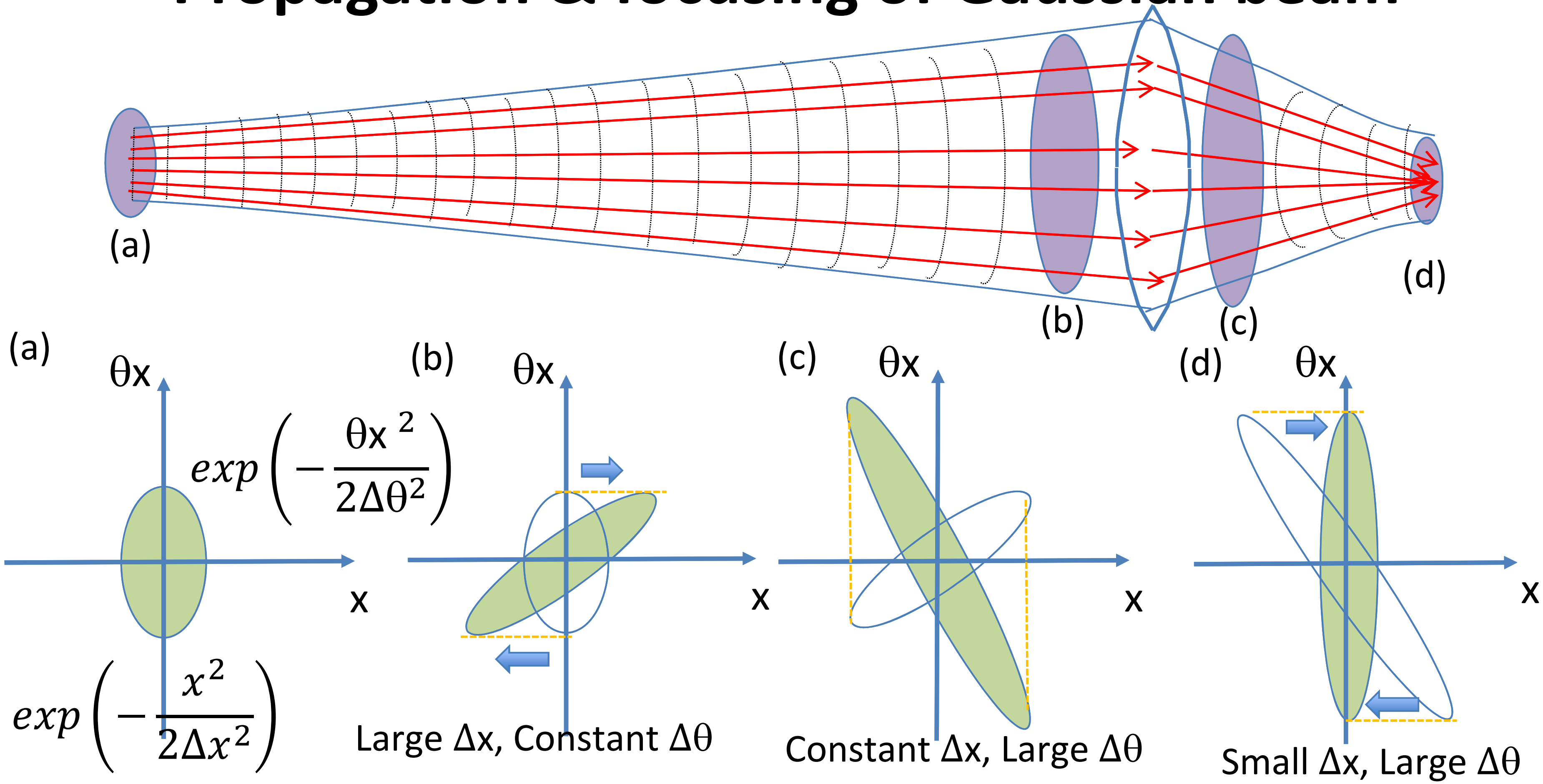
Longitudinal x 2

Frequency (=photon energy or wavelength) hν (=hc/λ)

Time: t

Brilliance: photon density in 6-D phase space

Transverse phase space:
Propagation & focusing of Gaussian beam

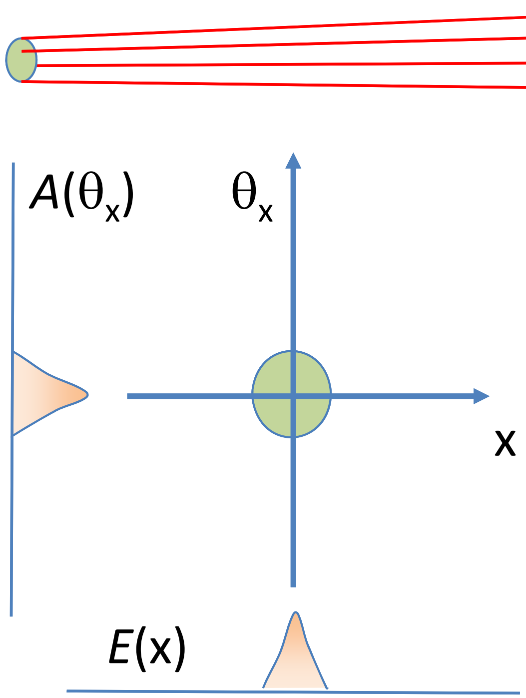


- Area of ellipse is called emittance
- Emittance is conserved with optical transformation
- Minimum emittance: $\Delta x \cdot \Delta\theta \sim C \cdot \lambda$ Diffraction-limited condition

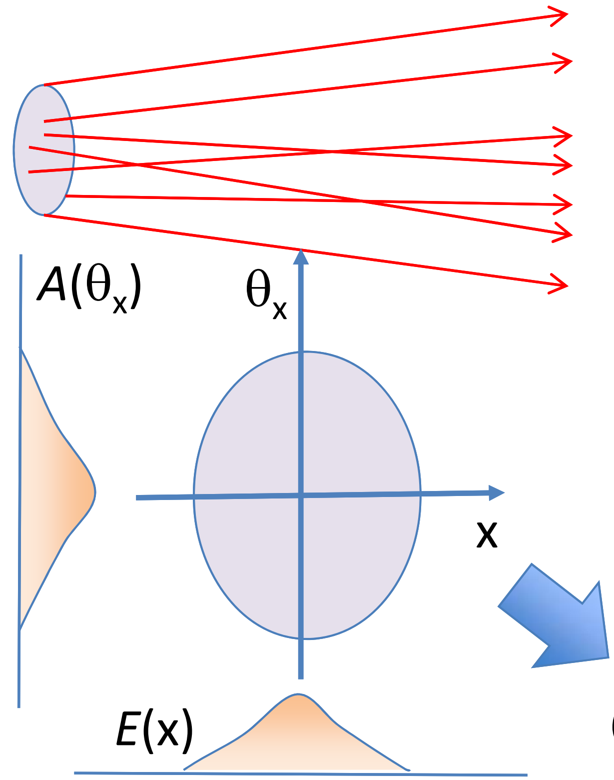
  e.g., XFEL: $\Delta x \cdot \Delta\theta \sim$10 um. 1 urad~ 1e-11 um ~ 1 Å/4π

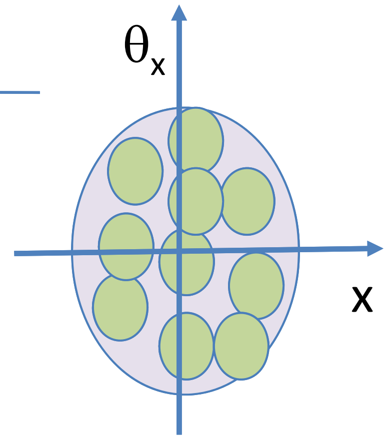
Distribution in transverse phase space (x-θ)

Small size/small divergence



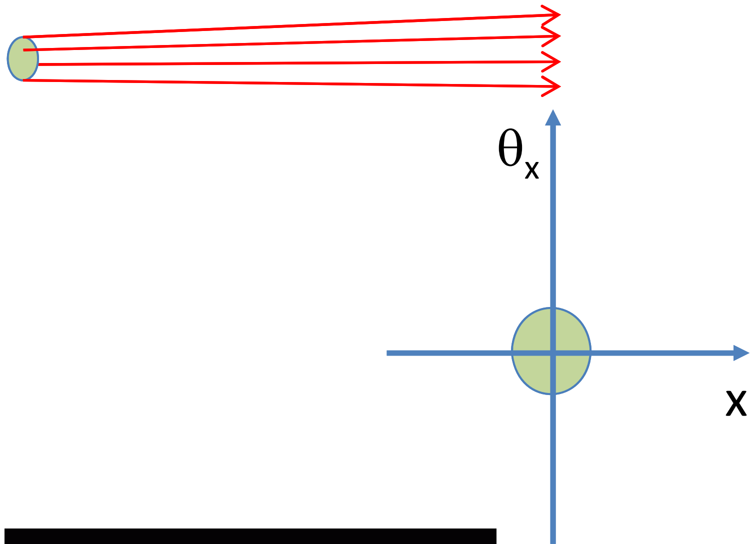
Large size/large divergence



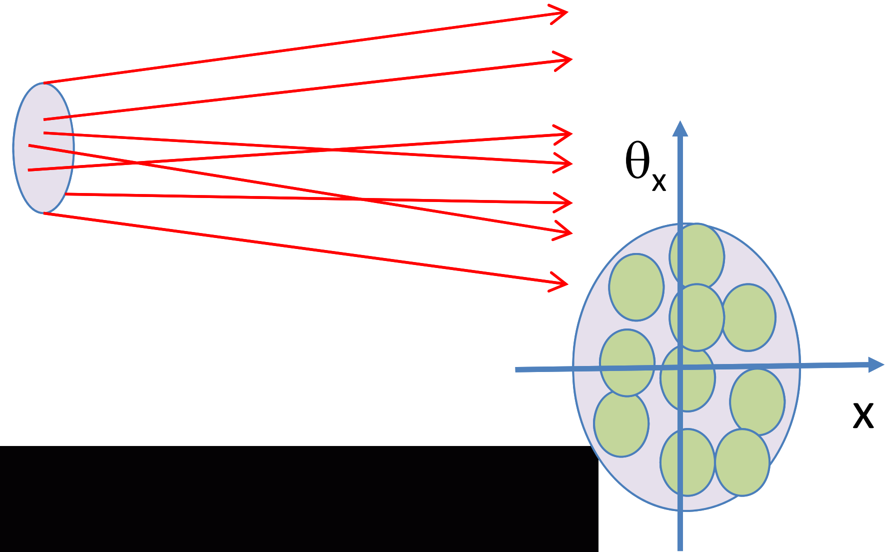


Composed of many coherent elements (wave packets) with random amplitudes and phases

Transverse coherence



[redacted]



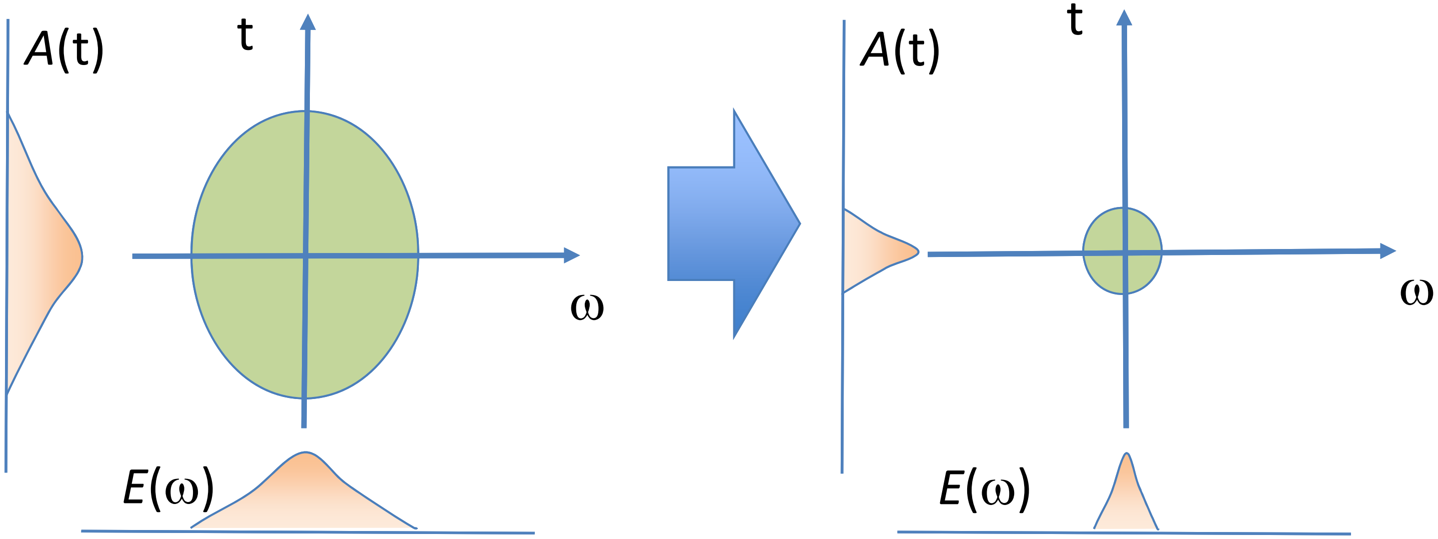
[redacted]

Full transverse coherence

XFEL generates transversely coherent x-rays

Partially transverse coherence

Distribution in longitudinal phase space



Large bandwidth/long pulse

Small bandwidth/short pulse

- Minimum area: $\Delta\omega \cdot \Delta t \sim \lambda/2\pi$ Fourier-limited condition
- X-ray pulse can be compressed into very short duration (λ/c~1e-18 s = 1 as)

Short summary

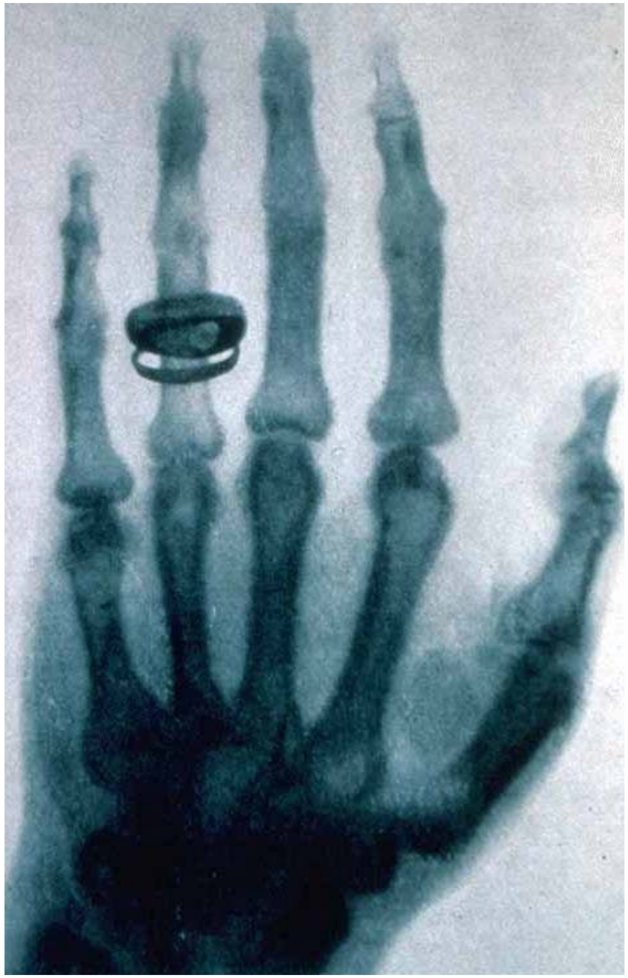
- Phase space is a useful concept for intuitive understanding of photon beam properties and optics design

References:

- K. J. Kim, "Characteristics of synchrotron radiation" AIP Conf. Proc. 184 (1989) 565: Excellent introduction of synchrotron light sources with usage of phase space
- M. Born & E. Wolf, "Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light," 7th ed. Cambridge University (1999); standard textbook on general optics and interference
- J.W. Goodman, "Statistical optics" A Wiley-Interscience Publication, New York, (2000); facilitate essential understanding of coherence and statistical optics
- A. Yariv & P. Yeh, "Photonics: Optical Electronics in Modern Communication (The Oxford Series in Electrical and Computer Engineering)", Oxford Univ. Press, (2006): One of the most standard textbooks on optics and beam physics

Contents

X-ray optics



X-rays:

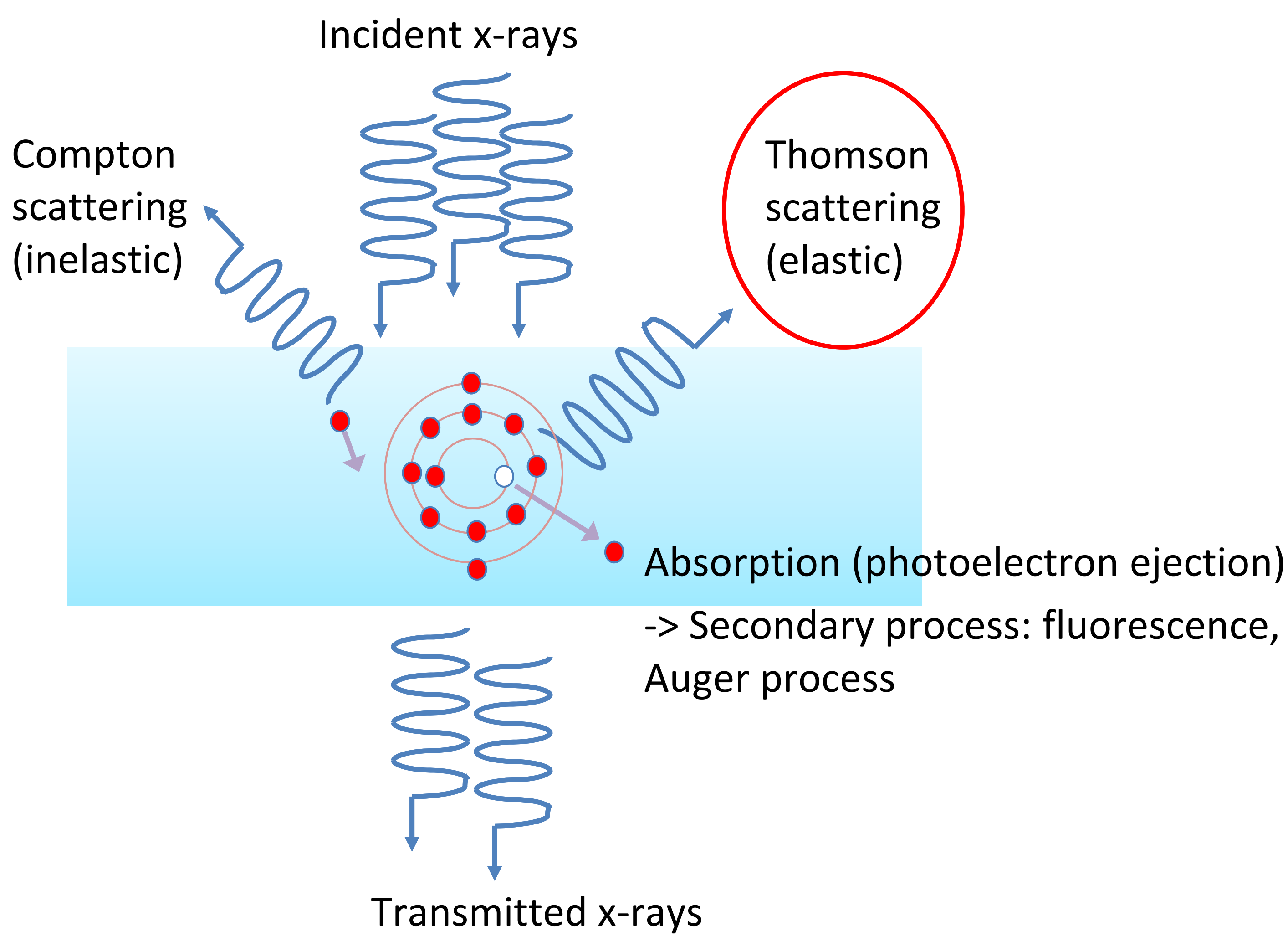
High penetration to materials

Small (but non-zero) interactions with matters

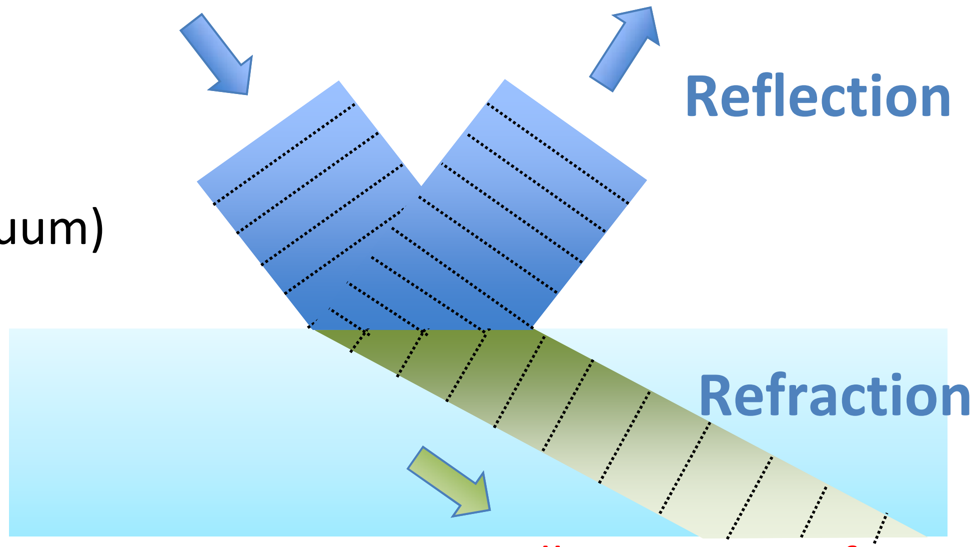
Design of x-ray optics is feasible, but not straightforward

We could not use magnetic forces

Major interactions of x-ray with matter



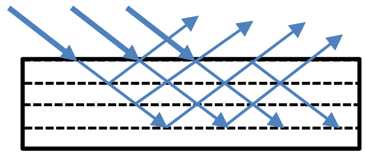
Key optical property: Refractive index



$n = 1$ (Vacuum)

$n = 1 - \delta + i\beta$

Diffraction (with periodic media)



Classical e-radius

Wavelength

Density of electrons

Small correction of anomalous effect

$$\delta = \frac{\lambda^2 r_e (Z + f')N}{2\pi} \qquad \beta = -\frac{\lambda^2 r_e f'' N}{2\pi}$$

$$\delta \sim \frac{(10^{-10}\ \mathrm{m})^2 10^{-15}\mathrm{m}^{-1} \cdot 10 \cdot 10^{30}\mathrm{m}^{-3}}{10} \sim 10^{-5}$$

δ, β ~ 1e-5 to 1e-7 at λ~1 Å

n<1

Derivation: harmonic oscillations of electrons in atoms generate secondary wave

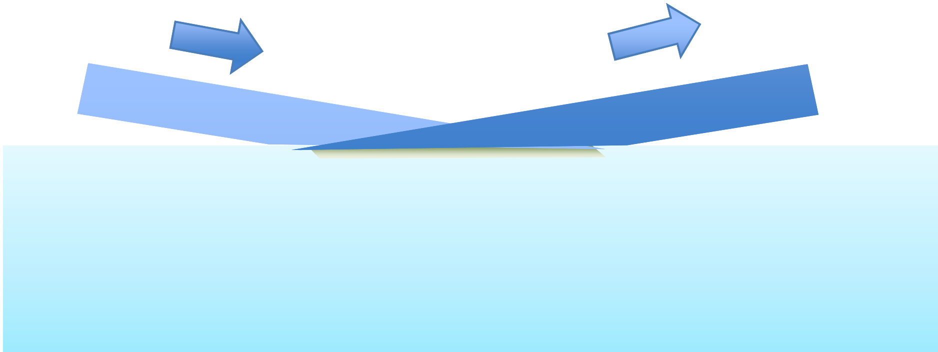
Integration of many secondary waves

Contents

1. Introduction: Brief history of photon beamlines for SR/XFEL
2. Preparatory: Phase space
3. X-ray optics
    1. Interaction of x-ray to matter
    2. Optical elements
        Reflective/Refractive/Diffractive
    3. Function
4. X-ray diagnostics
5. Design of beamline
6. Summary

Reflective optics: Total reflection at surface with grazing angle incidence

$n = 1$



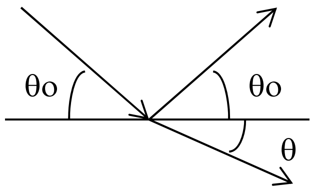
$n = 1 - \delta + i\beta$

Refraction angle: Snell's law $n = \frac{cos\theta_O}{cos\theta}$

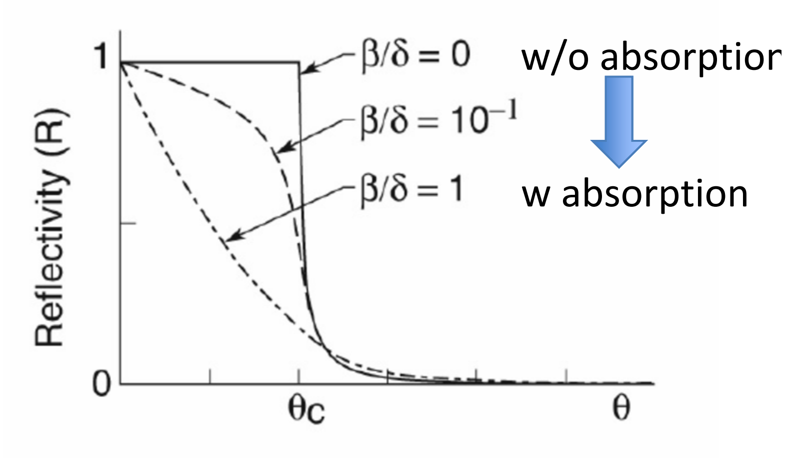
Total reflection ($\theta = 0$) with incident angle smaller than θ_C

$1 - \delta = cos\theta_c = 1 - \frac{{\theta_C}^2}{2}$

-> $\theta_C = \sqrt{2\delta}$ ~ 1e-3 (rad)



Reflectivity/transmissivity at interface: Fresnel's formula



Reflective optics: X-ray mirror

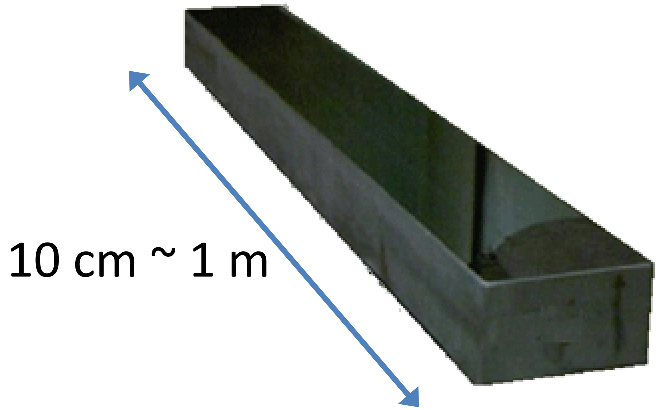
θ_C~ mrad

-> give small deflection angle to incident x-rays

(beam steering)

-> focusing with specific surface shape

-> long length required along the meridional direction (1 mrad x 1 m length = 1 mm acceptance)

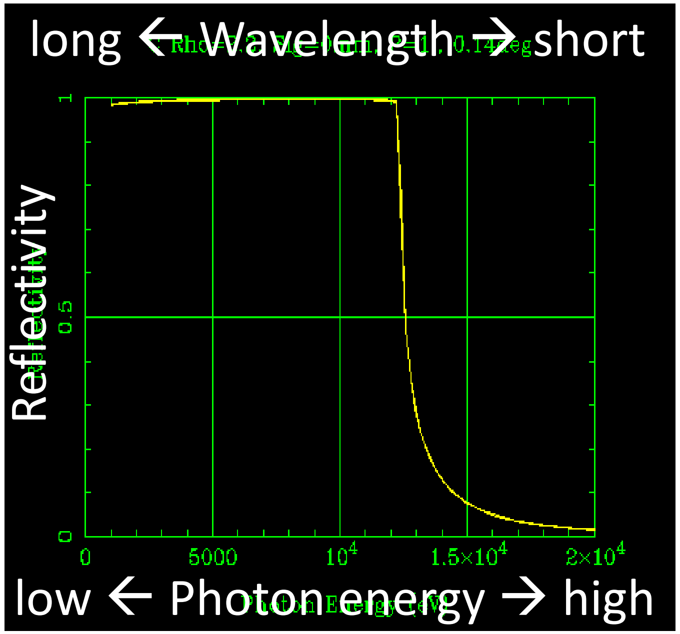


$$\theta_C = \sqrt{2\delta} \sim \sqrt{\frac{2\lambda^2 r_e (Z + f')N}{2\pi}} = A \cdot \lambda c \sqrt{\rho}$$

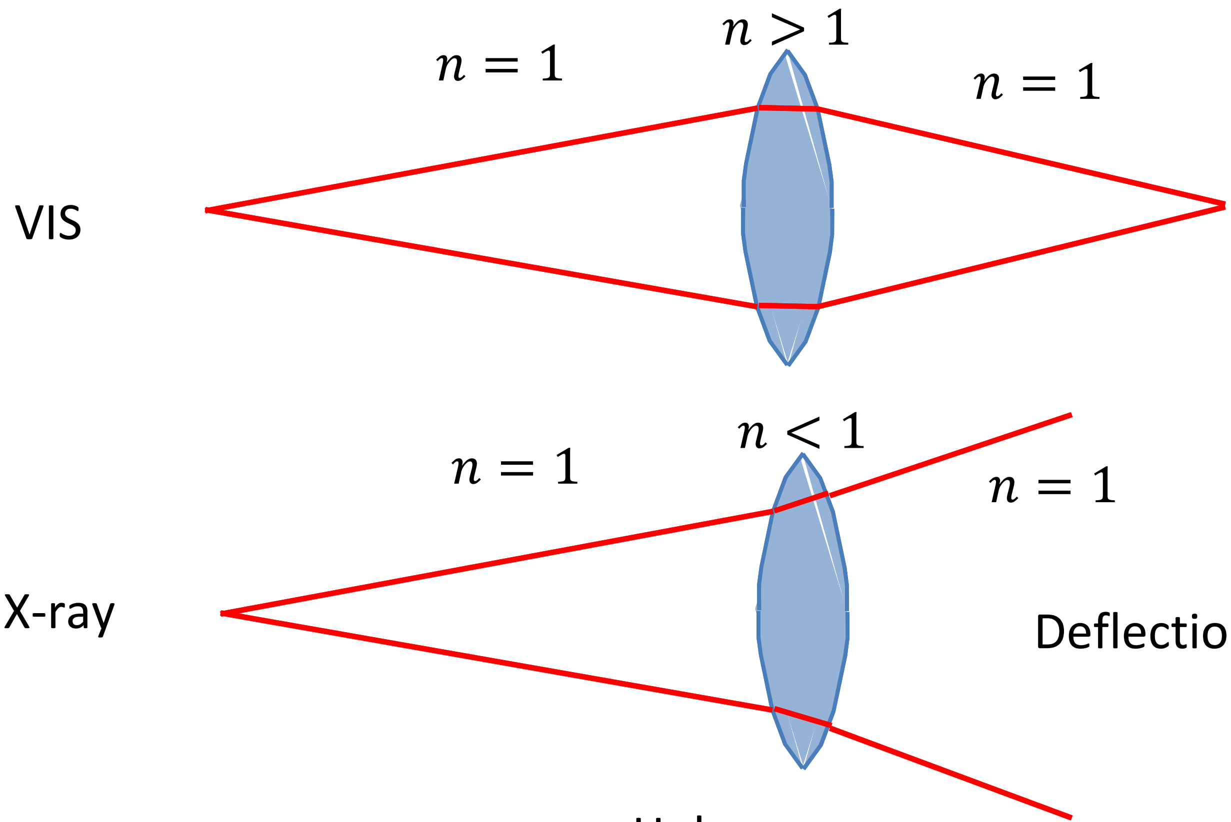
-> Total reflection only for $\lambda > \lambda_C$ for fixed θ_C

(low-pass filter in frequency domain)

-> reject higher harmonics or gamma-rays from source



Refractive optics: lens

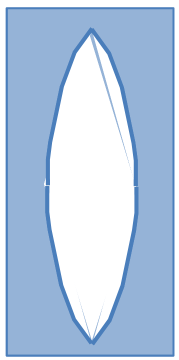


Deflection angle (~ δ) < 10 urad

Compound Refractive Lenses (CRL)

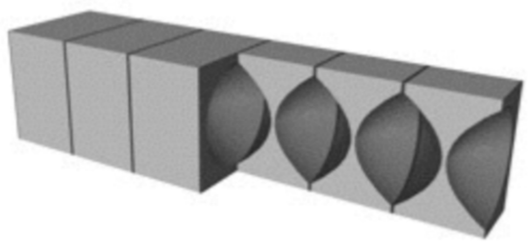
A. Snigirev et al., Nature 384 (1996) 49

Hole



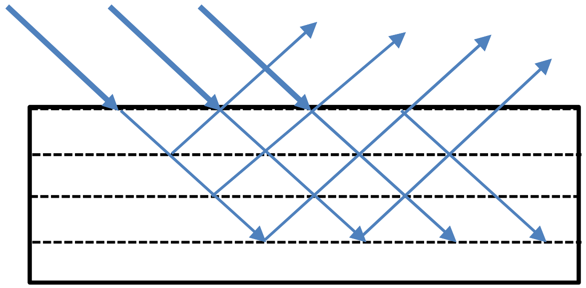
+

Stacking in array

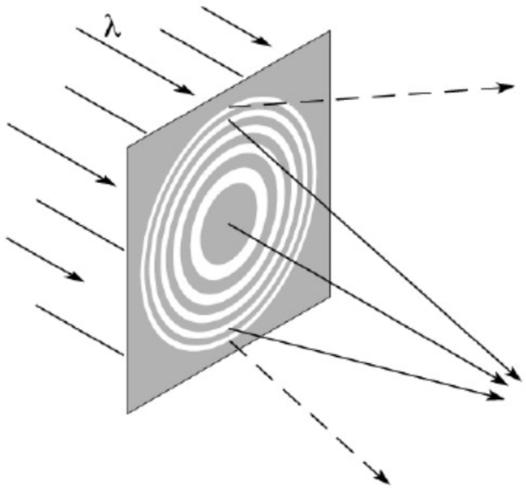


Diffractive optics

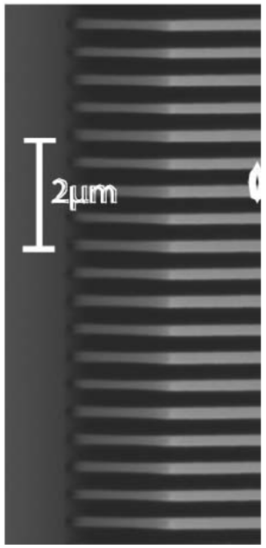
Perfect crystal
Silicon, diamond



Fresnel Zone Plate (FZP)



Grating



Contents

1. Introduction: Brief history of photon beamlines for SR/XFEL
2. Preparatory: Phase space
3. X-ray optics
    1. Interaction of x-ray to matter
    2. Optical elements
    3. Function

       Focusing/monochromator/speckle-free
4. X-ray diagnostics — *e.g., Q-magnet nor chicane …*
5. Design of beamline
6. Summary

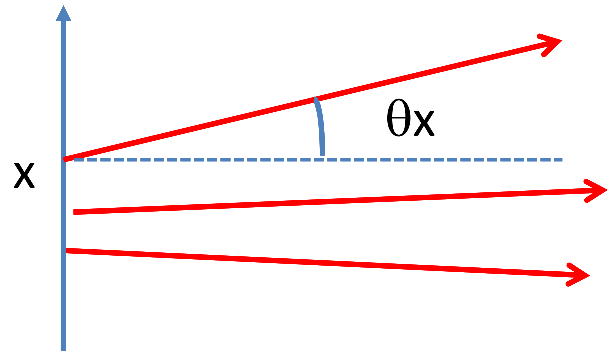
Function of x-ray optics

Tailor of photon beam properties in 6-dimensional phase space (+ polarization)

Transverse x 4

Position: (x,y) ← focusing

Angle: (θx, θy)



Longitudinal x 2

Frequency (=photon energy or wavelength) hν (=hc/λ)

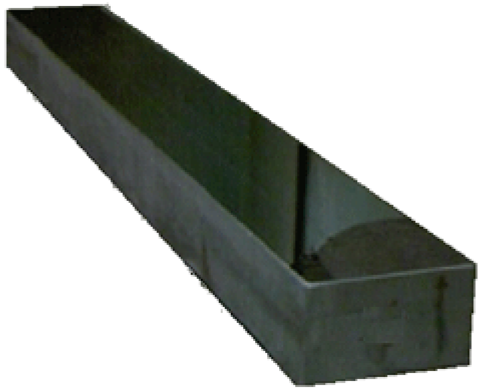
← monochromator

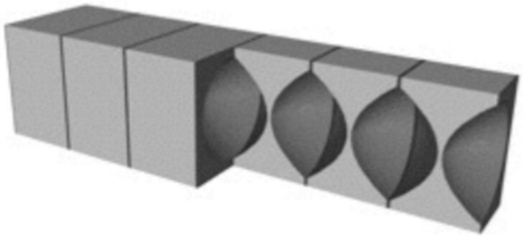
Time: t

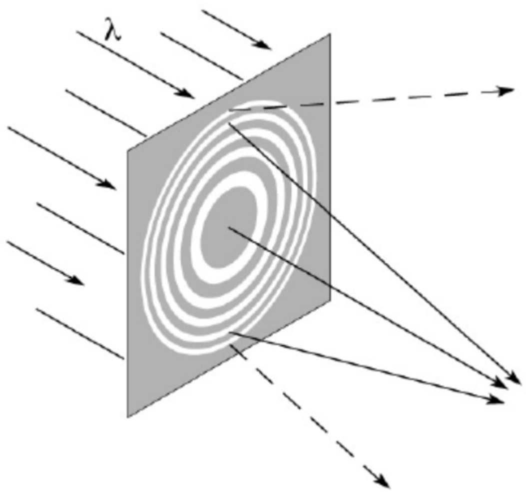
Brilliance: photon density in 6-D phase space

Function (I): Focusing

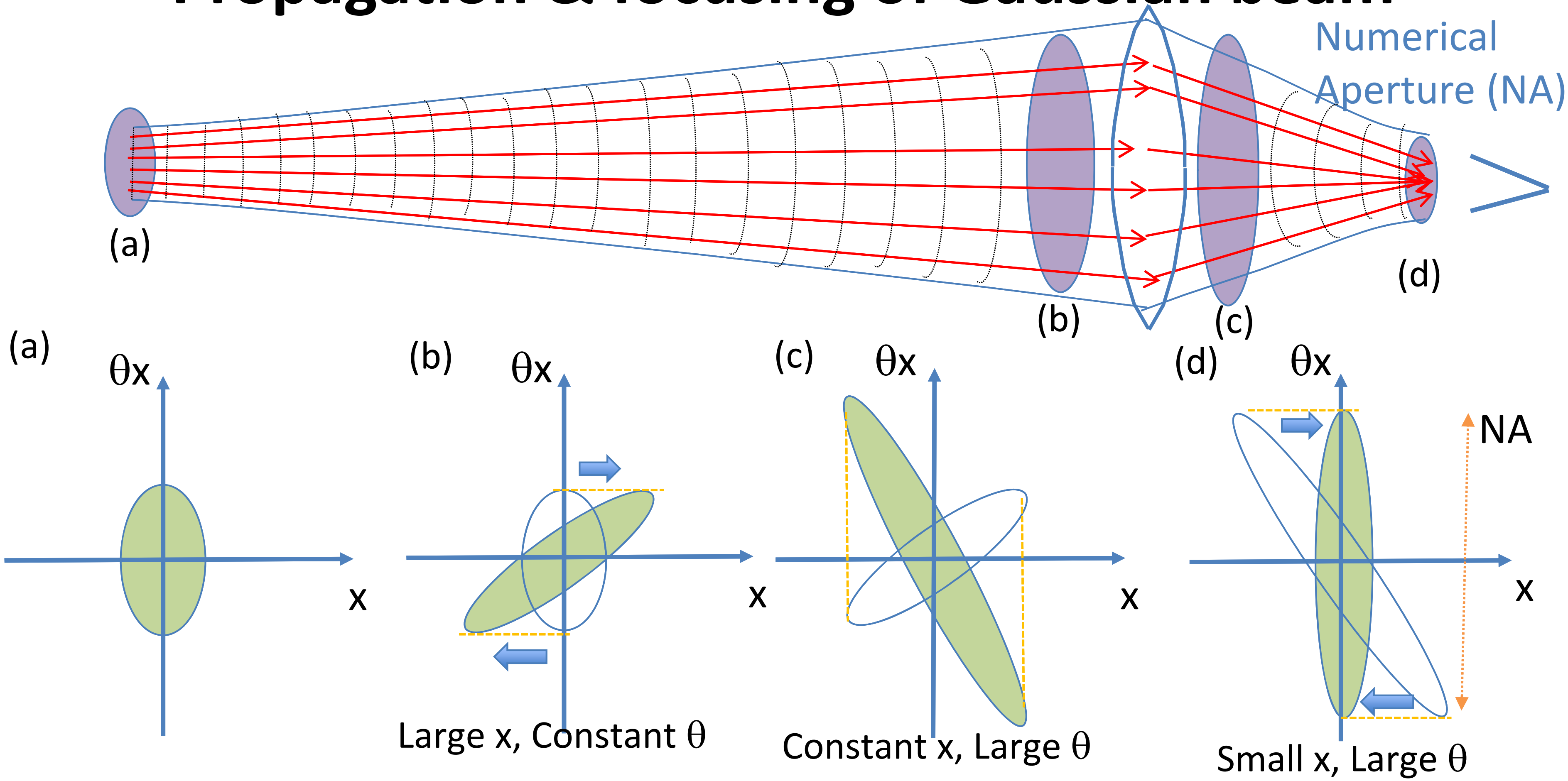
- Focusing capability is one of the most essential functions in x-ray microscopy and analysis
- Reflective, refractive, diffractive optics are used for focusing







Transverse phase space:
Propagation & focusing of Gaussian beam



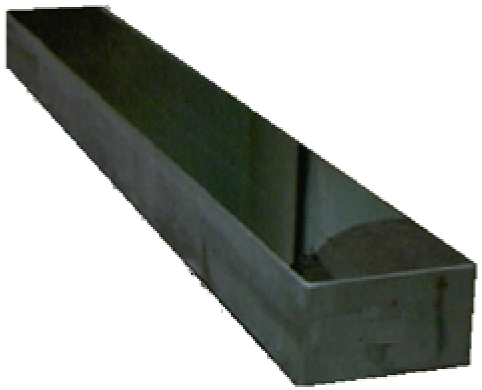
- Smaller beam size, larger divergence (NA) $\Delta x \cdot NA \sim \lambda$

→ Large NA is required for generating small spot

X-ray beam can be focused into small spot (~nm)

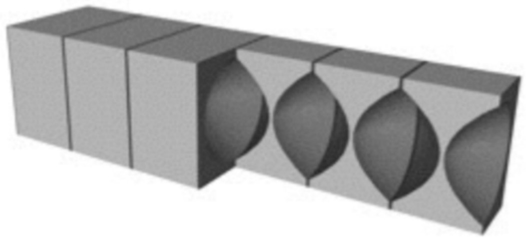
Comparison

Reflective



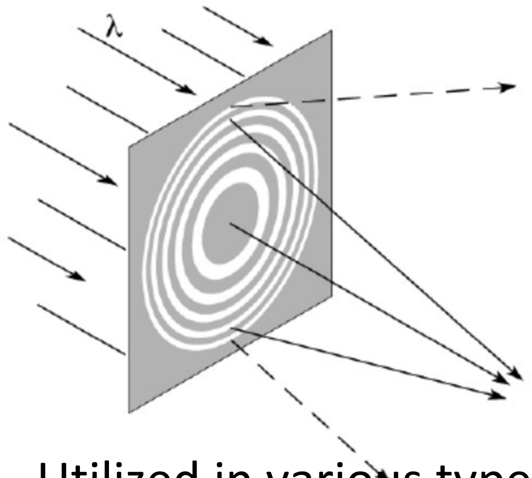
- High efficiency (R>70%)
- Achromatic
- Small spot (7 nm)
- Fabrication complexity
- Small deflection of exit beam

Refractive



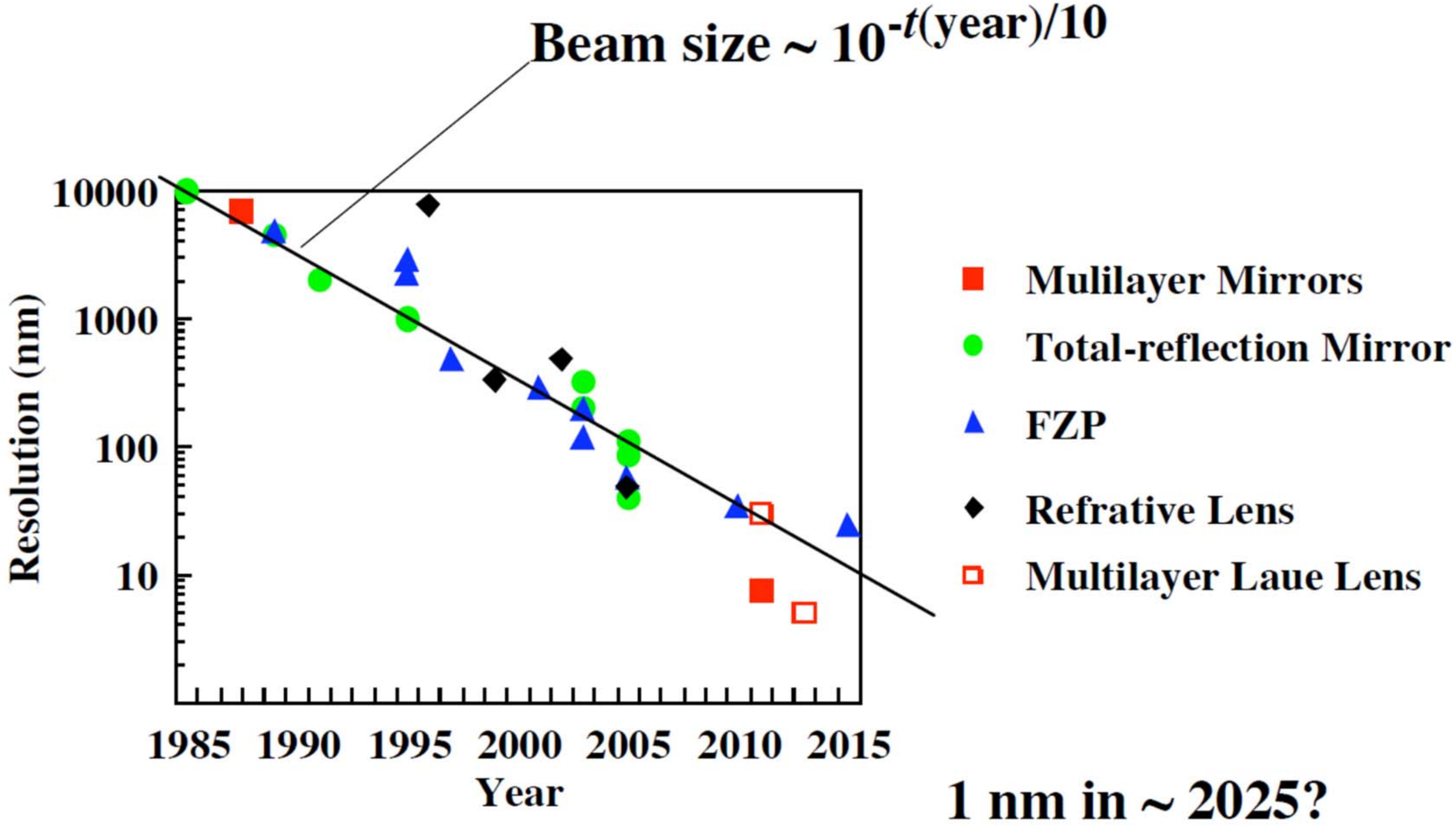
- Operation feasibility
- Tunable focal length with changing # of stack
- Prefer to high energy x-rays (> 10 keV) for reducing absorption

Diffractive



- Utilized in various types of soft x-ray microscopy
- Variation in patterns for phase control
- Compact design
- Fabrication complexity
- Efficiency limited by diffraction
- Bandwidth: $\Delta\lambda/\lambda \sim 1/N$

Trend of spot size

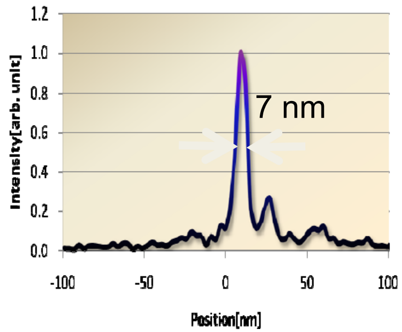


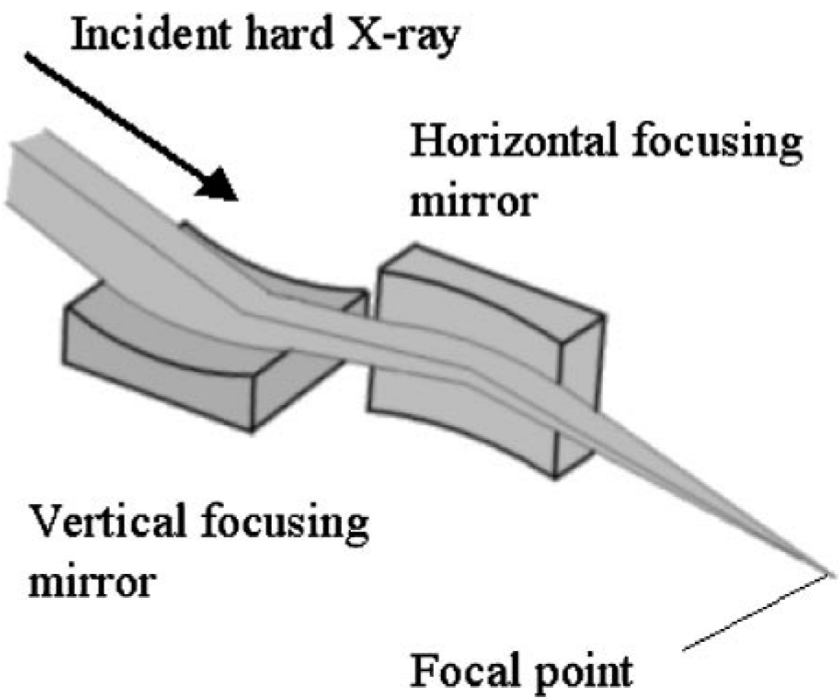
Resolution Trend of X-ray Microbeam

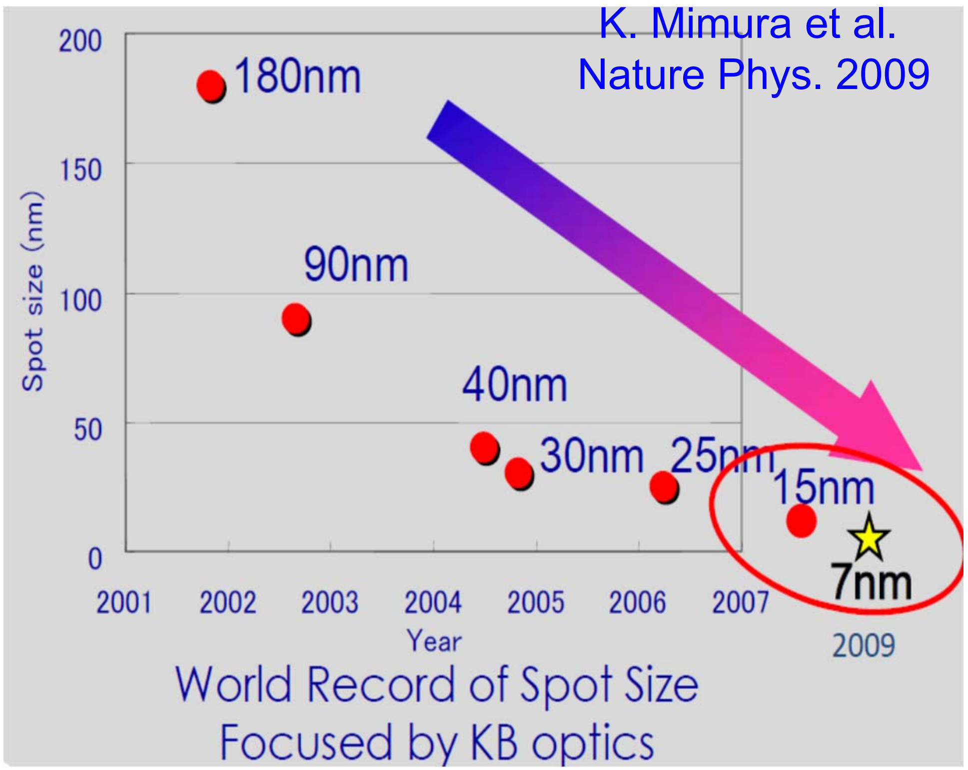
Courtesy of Dr. Yoshio Suzuki

Focusing with mirrors

- Total reflection only working at grazing incidence condition
- Combination of two cylindrical mirror was first proposed by Kirkpatrick and Baez (JOSA, 1948)
- High reflectivities, but challenging in fabrication
- Cylindrical → elliptical shape for generating small spot without aberration
- Technological developments since 2000 for achieving accurate figure shape

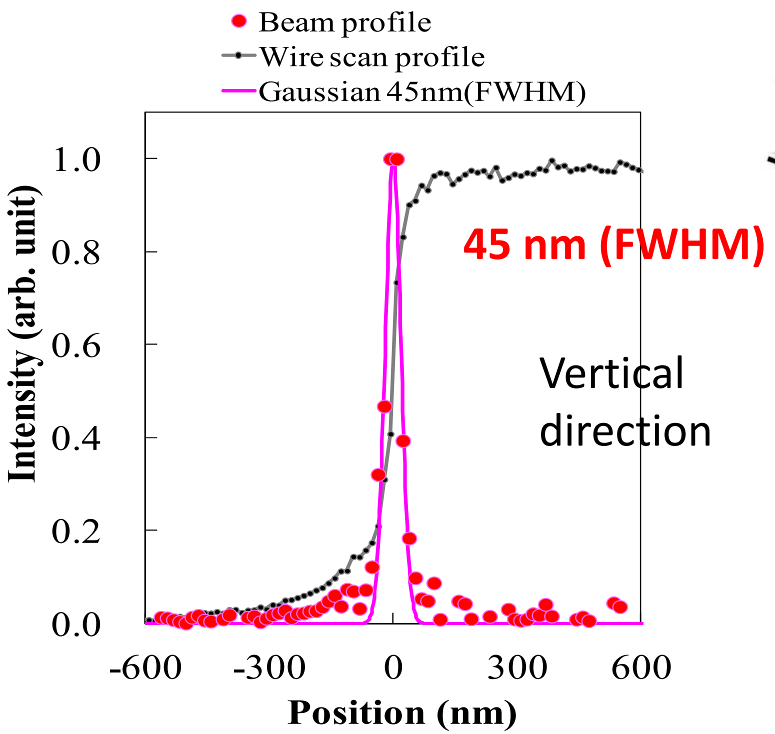


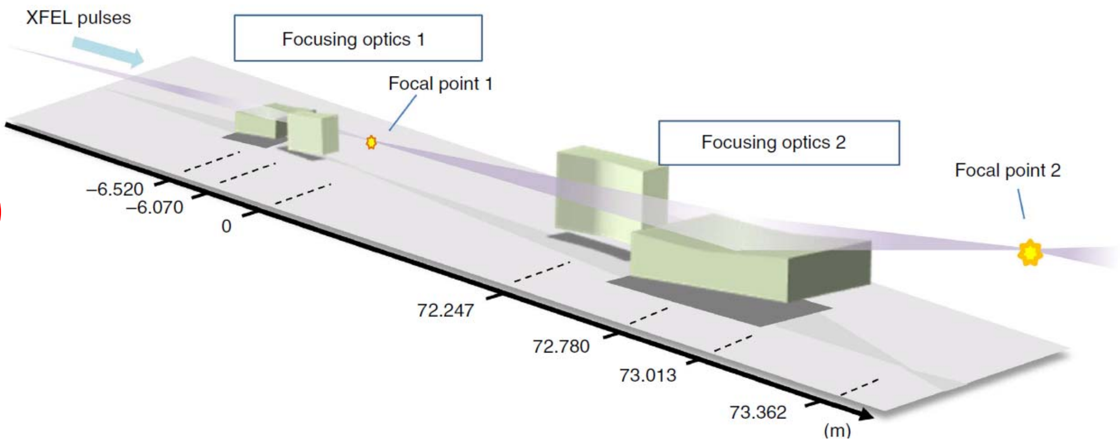




Nano-focusing for XFEL

- Focusing of XFEL → production of extremely high intensity of X-ray pulse
- Low divergent beam (~urad) → small beam size at focusing optics → limitation of NA → difficulty in achieving small focus
- Combination of two focusing system: first one for enlarging divergence and beam size, and second one for small focusing
- 50 nm size achieved with extreme intensity over 10^{20} W/cm^2

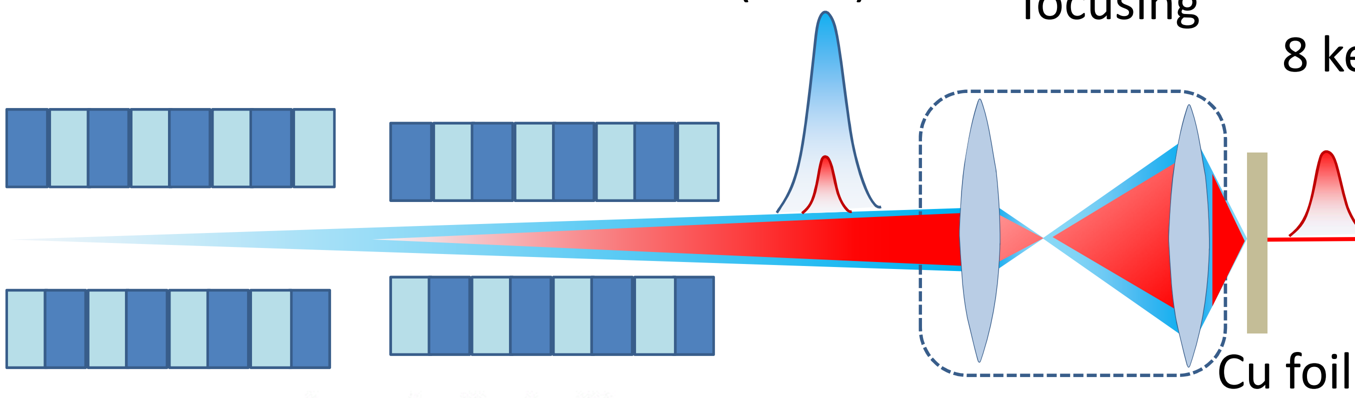




Mimura et al, Nature Commun **5** 3539 (2014)

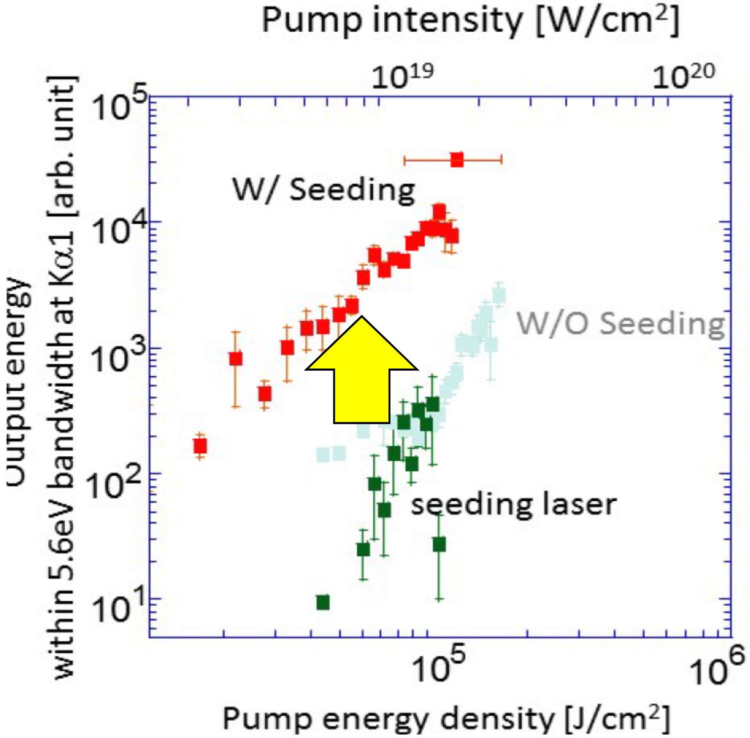
Achievement of Hard X-ray Cu-Ka atomic laser

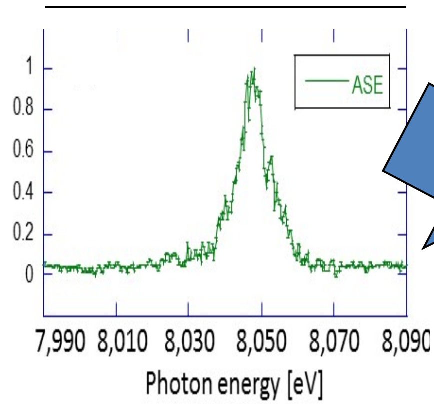
Yoneda *et al.*, Nature **524** 446 (2015)

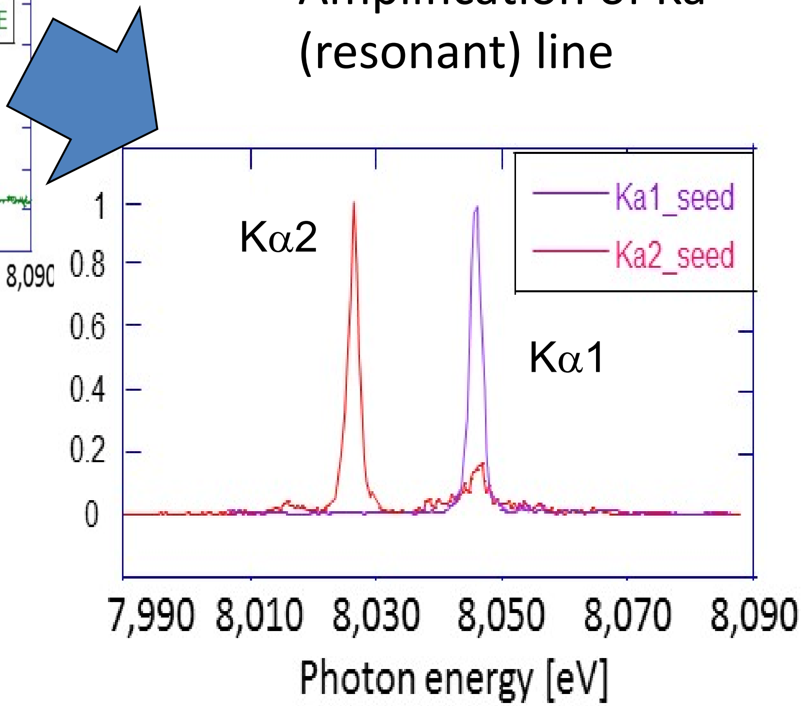


Intense pump x-rays strip K-shell electrons and generate "population inversion:

Amplification of Ka (resonant) line

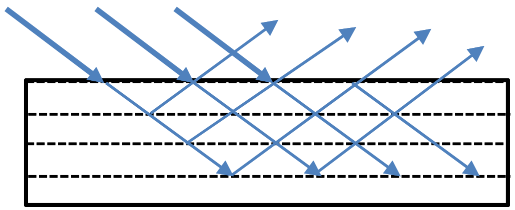


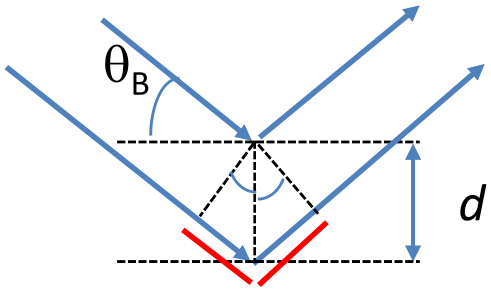




Function (II): Monochromator

- Monochromator is the key optical device in SR beamlines
- Energy resolution (typically several percent for SR) is insufficient for most x-ray applications (crystallography, spectroscopy, etc.)
- Perfect crystals are widely used as monochromator optics





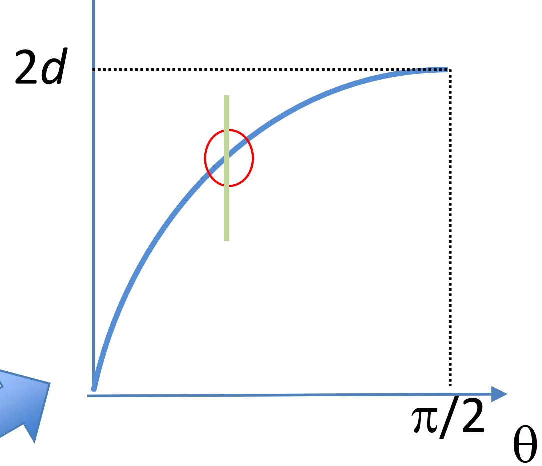
Path difference $\delta = 2d\sin\theta_B$
Diffraction occurred at $\delta = n\lambda$

Bragg's law: $\lambda = 2d\sin\theta_B$

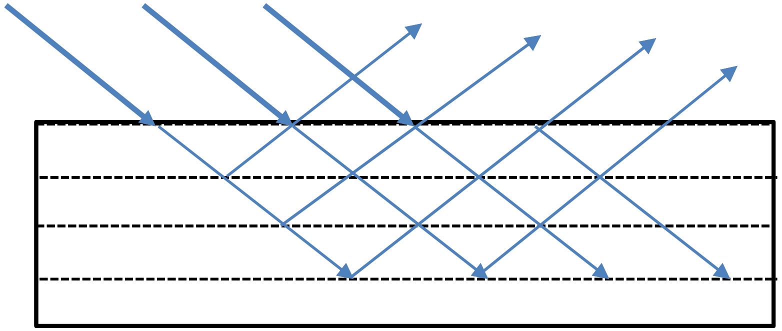
→ Monochromator based on angular-wavelength relationship

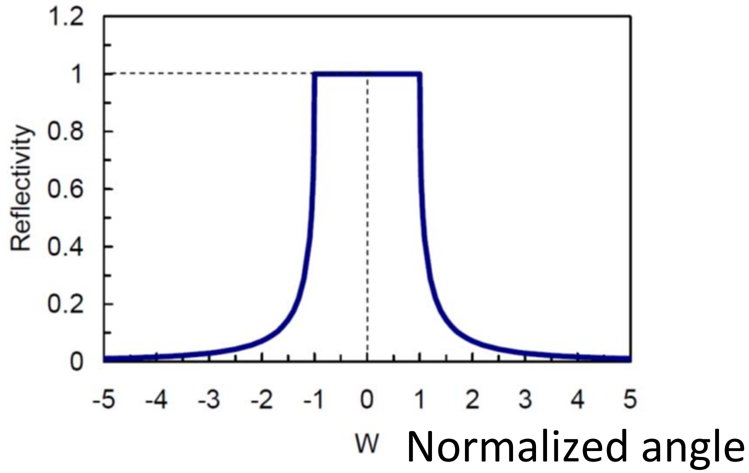
Linewidths are not infinitely small →

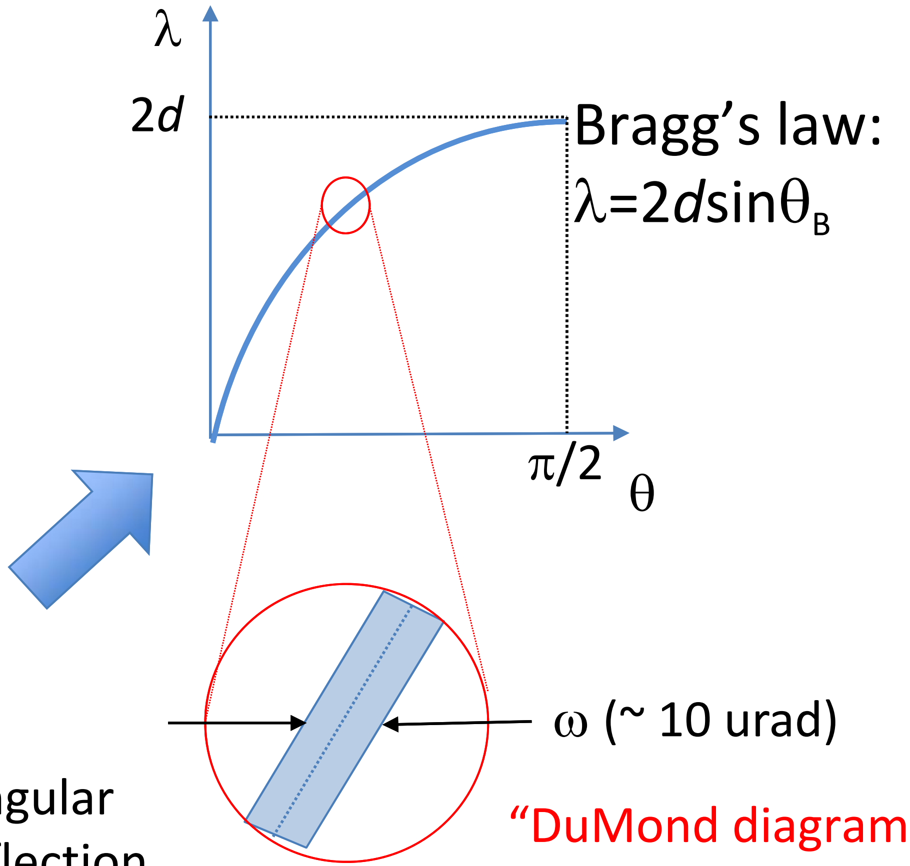
What is the bandwidth ?



Representation of perfect-crystal monochromator in angular-frequency (θ-λ) phase space







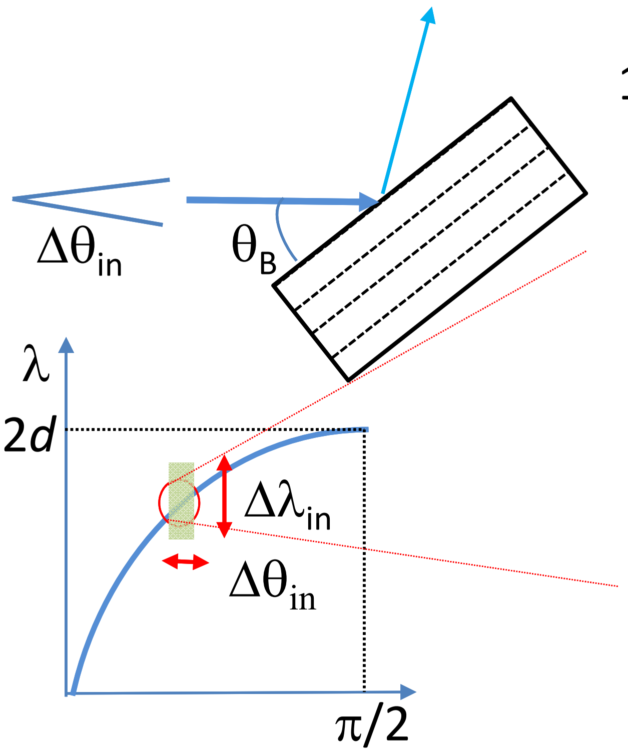
Dynamical theory of diffraction: Multiple reflections in perfect crystal gives finite angular width (Darwin width) for total external reflection

A. Authier, "Dynamical Theory of X-ray Diffraction" Oxford Univ. Press (2001)

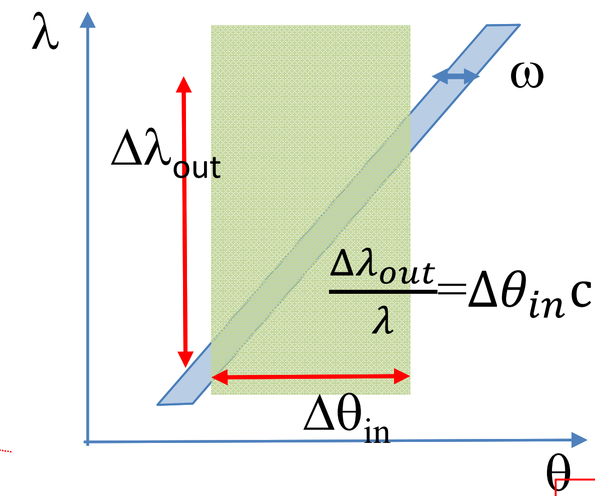
J.W.M. DuMond, Phys. Rev. **32** (1937) 872

Monochromator on DuMond diagram

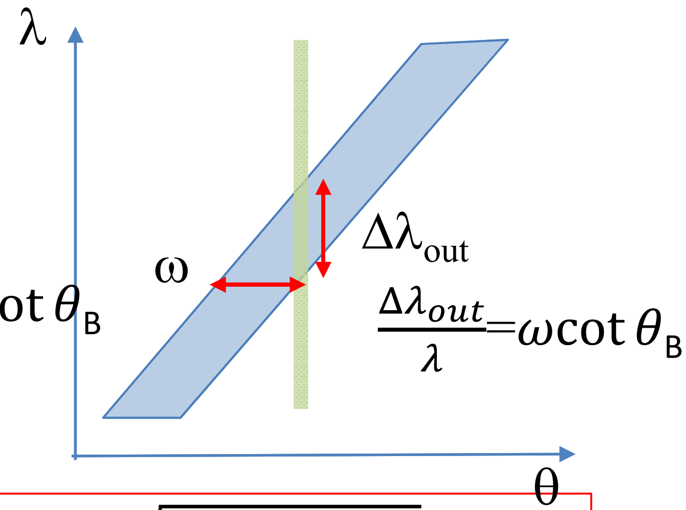
$\lambda = 2d\sin\theta_B \;\rightarrow\; \Delta\lambda = 2d\cdot\Delta\theta\cos\theta_B$



1) $\Delta\theta_{in} >> \omega$



2) $\Delta\theta_{in} << \omega$

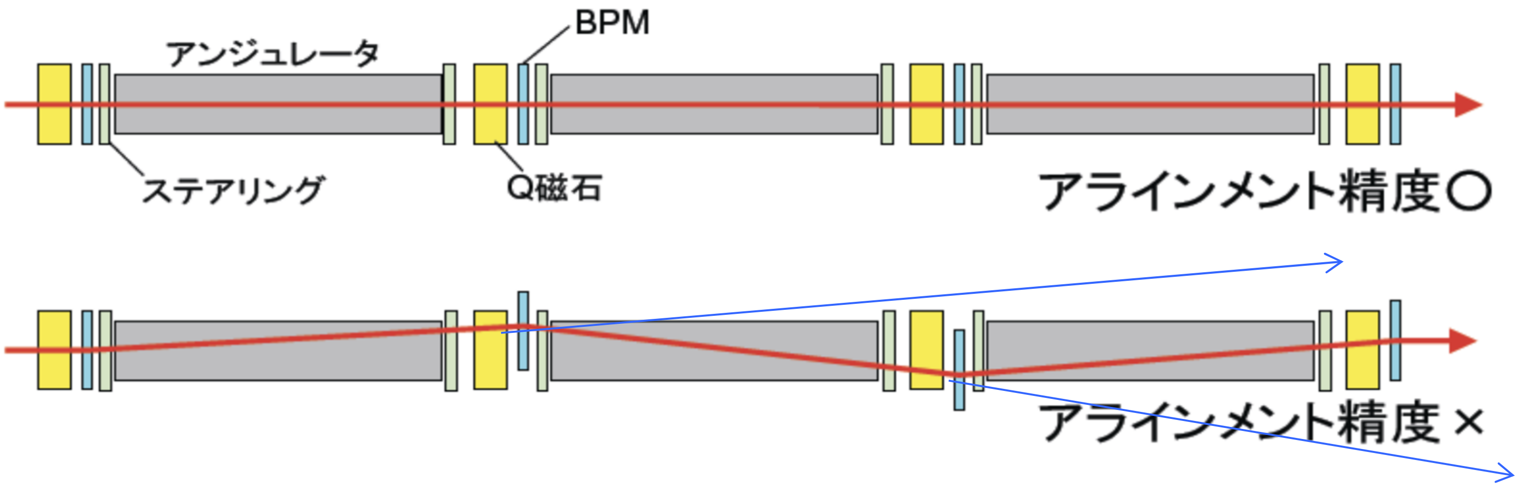


$$\frac{\Delta\lambda_{out}}{\lambda} = \sqrt{\Delta\theta_{in}{}^{2} + \omega^{2}}\,\cot\theta_B$$

Typical parameters with silicon (111) monochromator

	Incident resolution $(\Delta\lambda/\lambda)_{in}$	**Incident divergence $\Delta\theta_{in}$**	**Darwin width ω**	**Output resolution $(\Delta\lambda/\lambda)_{out}$**
Bending magnet	~1	~100 urad	~20 urad w Si (111) @ λ=1 Å (θ_B=9.1°)	~1e-3
Undulator radiation	~1e-2	~10 urad		~1e-4
XFEL	~1e-3	~1 urad		~1e-4

Application of monochromator: Precise ID tuning



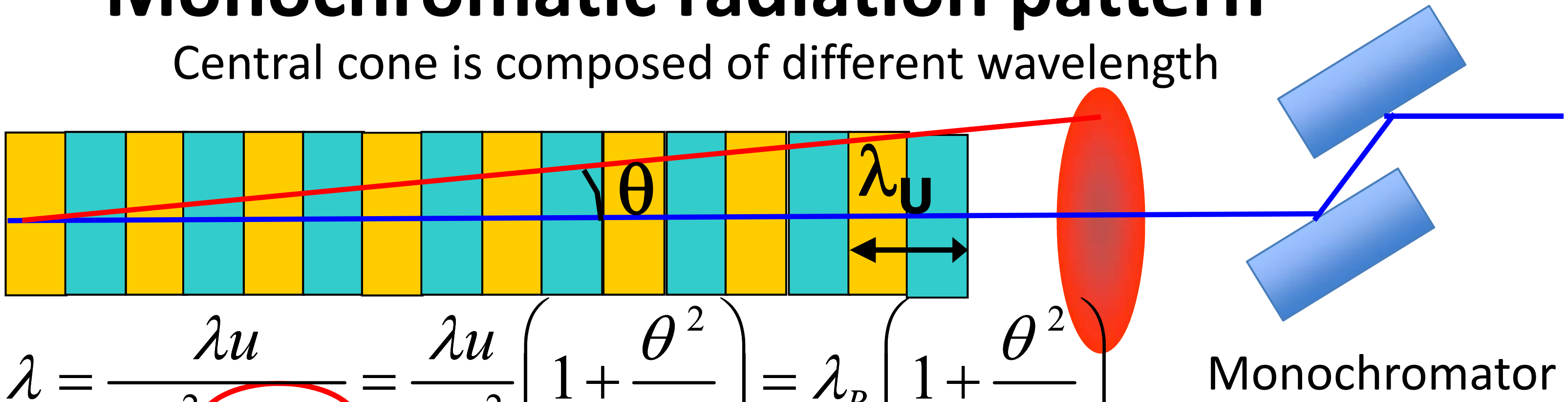
- For efficient lasing, overlap between e-beam and p-beam with an accuracy of ~urad is required
- E-beam trajectory easily bends at the edges of undulator modules
- P-beam goes through along the e-beam in the undulator
- P-beam can be used to monitor the e-beam trajectory in each undulator module

Cf. central cone of the undulator radiation

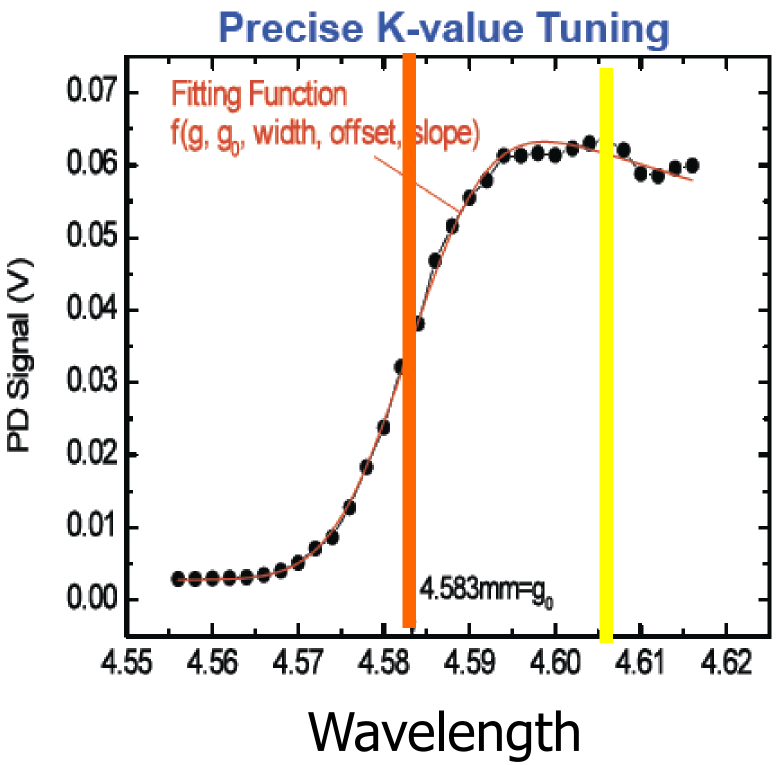
1/g= 1/16000 = 60 urad for 8 GeV → too large

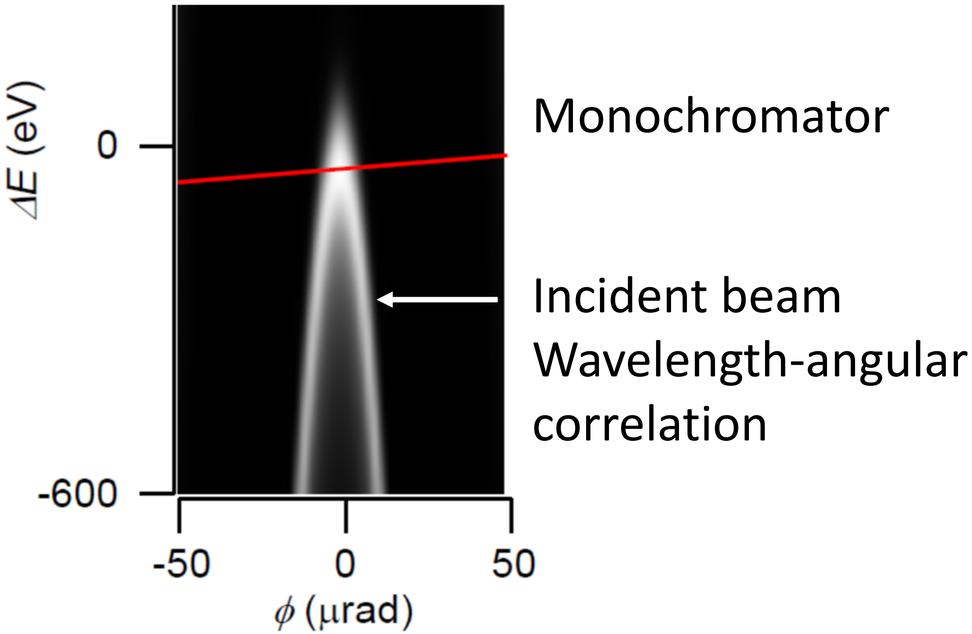
Monochromatic radiation pattern

Central cone is composed of different wavelength



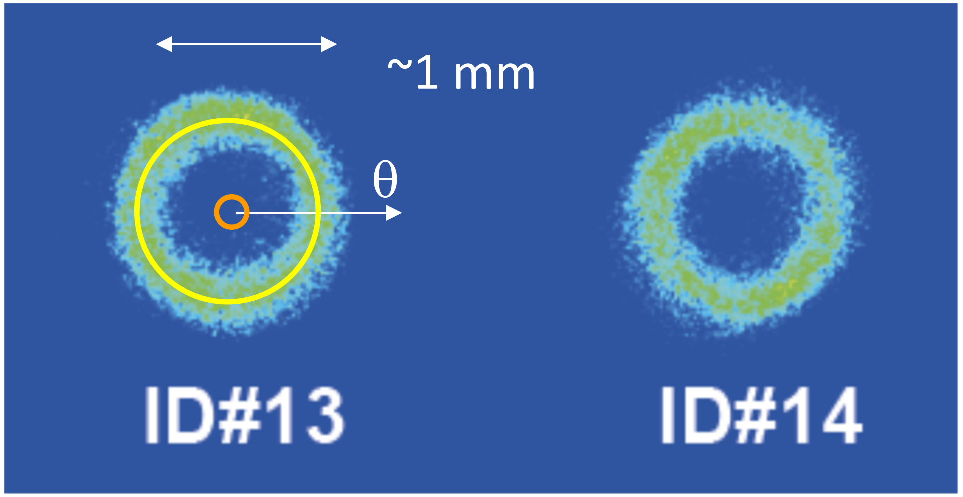
$$\lambda = \frac{\lambda u}{2\gamma^2 \cos\theta} = \frac{\lambda u}{2\gamma^2}\left(1+\frac{\theta^2}{2}\right) = \lambda_R\left(1+\frac{\theta^2}{2}\right)$$





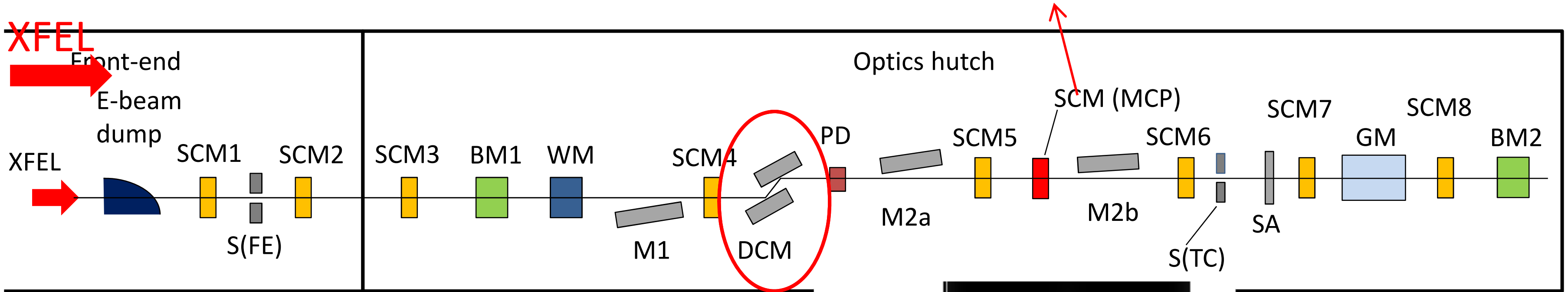
X-ray based undulator alignment

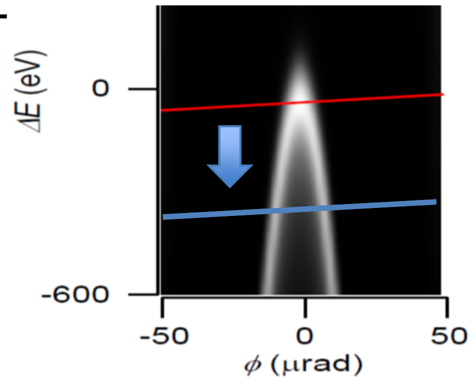
Profile of monochromatized spontaneous radiation



Angular diameter: ~10 urad
Centroid: 1 urad

High-sensitivity screen monitor for spontaneous x-ray detection



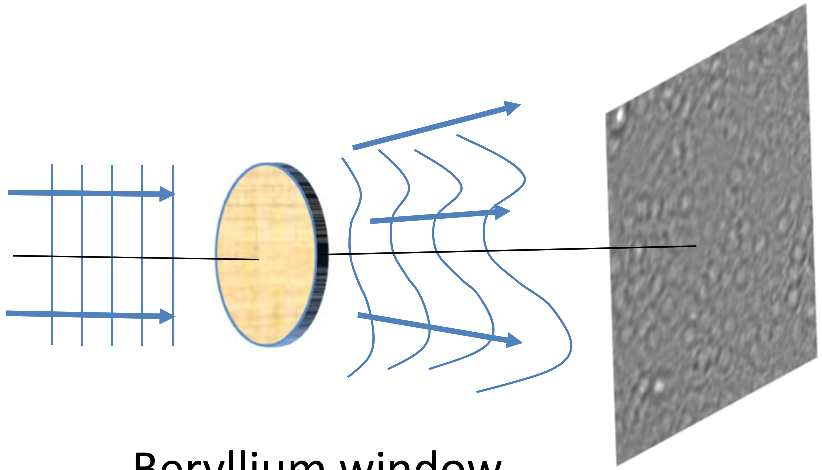


T. Takashi et al., Phys. Rev. ST-AB **15** (2012) 110701

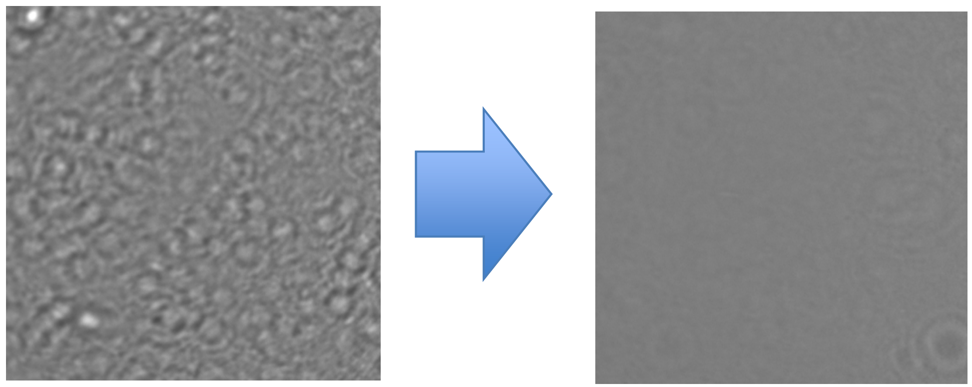
Function (III): Speckle-free X-ray optics for transversely coherent sources

Coherent illumination on imperfect optical elements can easily produce speckles

Measured at 1-km BL of SPring-8



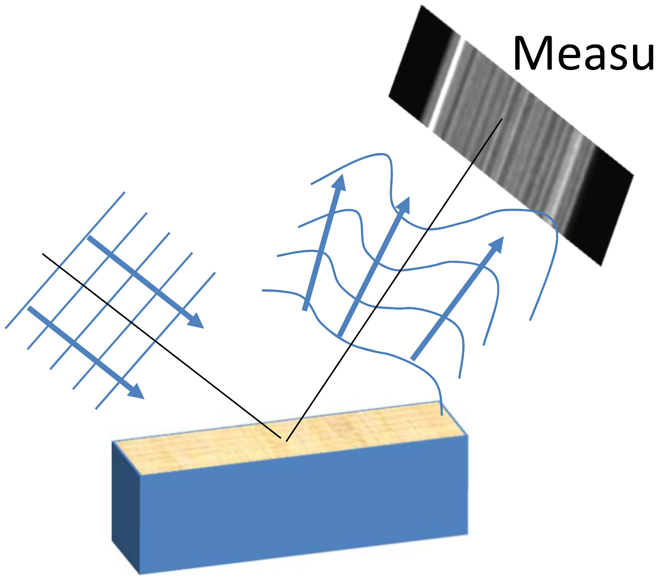
Yabashi et al., J Synchrotron Rad.
21 (2014) 976



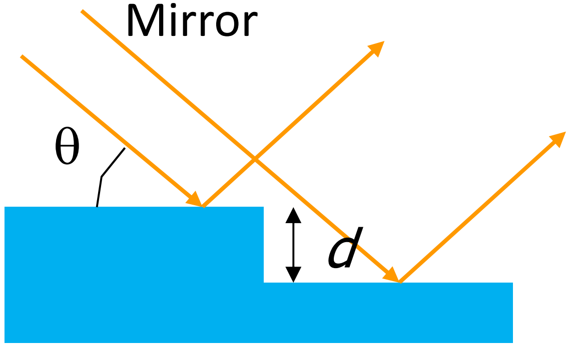
Function (III): Speckle-free X-ray optics for transversely coherent sources

Coherent illumination on imperfect optical elements can easily produce speckles

Measured at 1-km BL of SPring-8



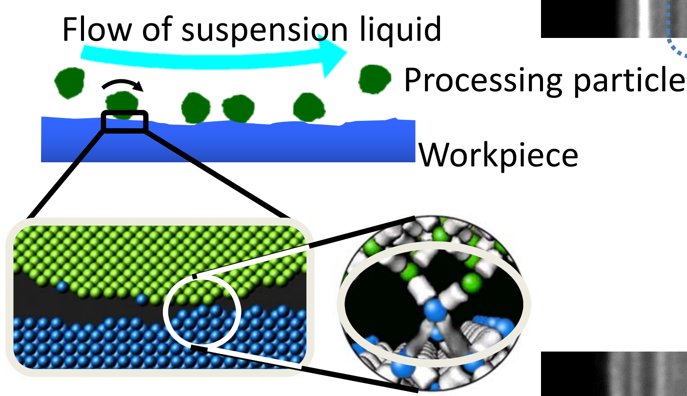
Mirror



Path difference: $\delta=2d\sin\theta$

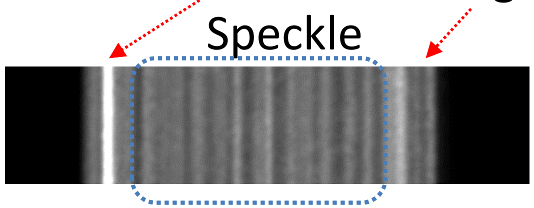
$\delta<\lambda/10 \rightarrow d<\lambda/(20\cdot\sin\theta)=$ 0.1 nm/(20·2.5 mrad) = 2 nm

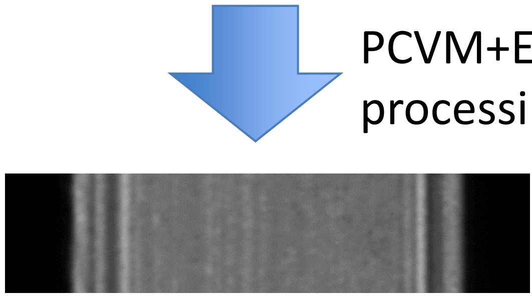
Elastic Emission Machining (EEM)



Fresnel diffraction from edge

Speckle





Sub-nm accuracy in figure shape has been achieved

Short summary

- Reflective/refractive/diffractive optics are used for controlling x-ray properties of beam size (focusing) or bandwidth (monochromator)
- Special high quality is required for x-ray optics under coherent x-ray illumination to avoid speckles

References:

- J. Als-Nielsen & D. McMorrow, "Elements of Modern X-ray Physics" (Wiley, 2001): General introduction of x-ray optics and x-ray applications
- A. Authier, "Dynamical Theory of X-ray Diffraction" Oxford Univ. Press (2001): An authentic textbook on dynamical theory of diffraction
- Yabashi et al., J Synchrotron Rad. **21** (2014) 976; Overview of recent development of x-ray optics for coherent x-ray applications

Contents

1. Introduction: Brief history of photon beamlines for SR/XFEL
2. Preparatory: Phase space
3. X-ray optics
4. X-ray diagnostics
    1. Pulse energy
    2. Pulse duration
    3. Arrival timing
5. Design of beamline
6. Summary

X-ray diagnostics

Characterization of x-ray beam properties in 6-dimensional phase space (+ polarization) + coherence

- Total intensity
- Transverse x 4

  Real space: (x,y) ← fluorescent screens

  Angular direction: (θx, θy)

  ← L × θ: free-space propagation + size measurement
- Longitudinal x 2

  Frequency (=photon energy or wavelength) hν

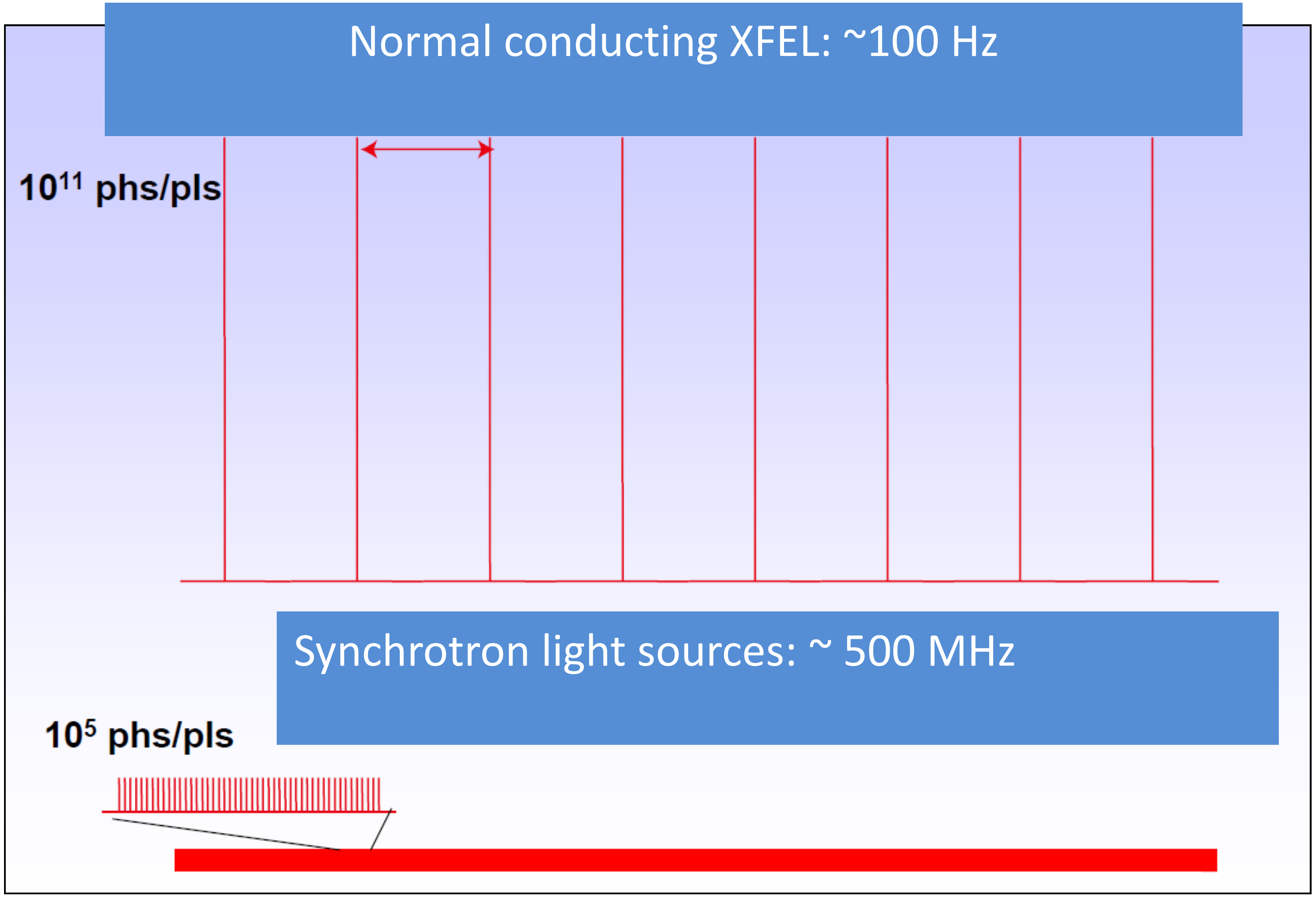
  Time: pulse duration t

  + arrival timing τ for pump-probe experiments with external optical laser
- Coherence

Key words

- Absolute or relative ?
- Resolution and range ?
- How fast ?
  - XFEL: Shot-to-shot fluctuation
  - Shot-to-shot measurements are desirable
- Destructive or nondestructive ?
  - Destructive: full photons are available for diagnostics, more accurate measurements
  - Nondestructive: diagnostics parallel to experiments

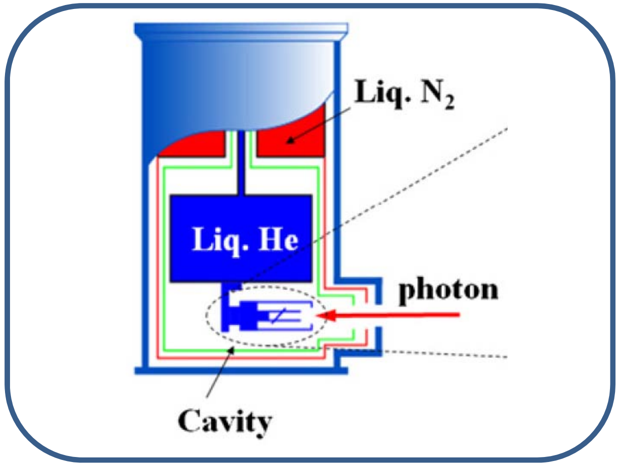
Temporal structure



Pulse energy measurement (I)

- Pulse energy is the most fundamental parameter for both machine and experimental sides
- Pulsed nature → signals easily saturated; reliable measurement is challenging

Cryogenic radiometer

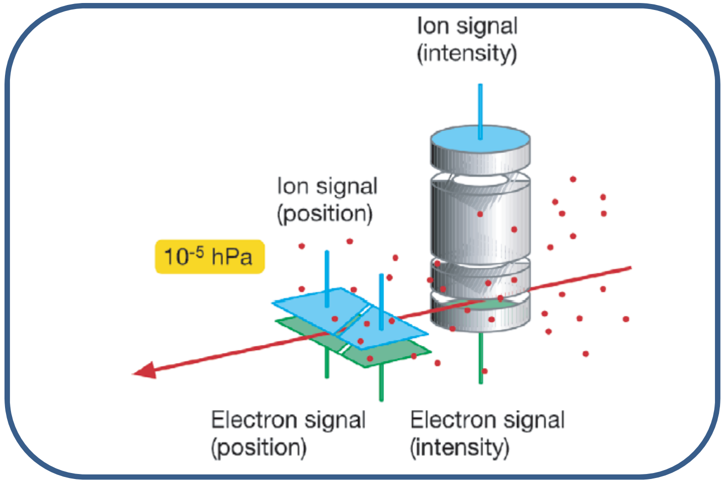


Detection of small temperature increment after x-ray absorption

Destructive
Portable

T. Tanaka et al., *Nucl. Instrum. Methods A* 659, 528 (2011).

XGMD: Gas monitor detector (DESY, PTB)



Detection of electrons/ions ionized with x-ray irradiation

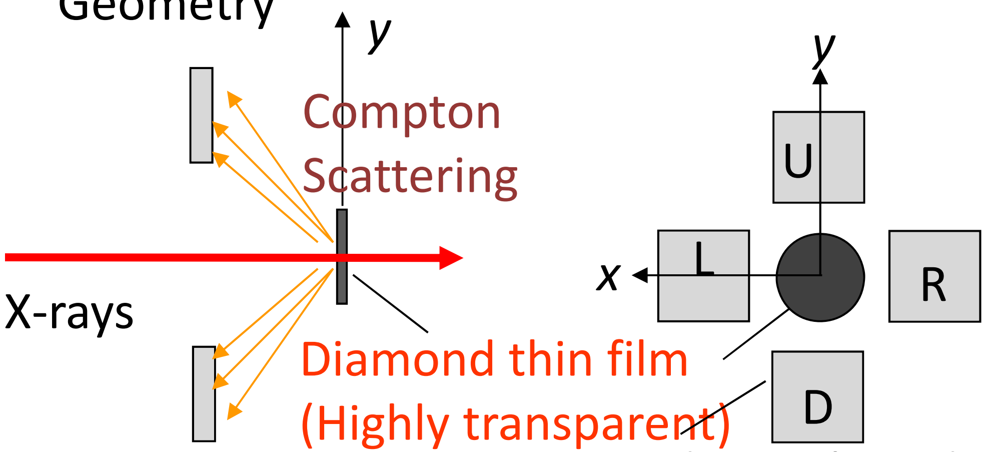
Nondestructive
Vacuum system

M. Richter et al, *Appl. Phys. Lett.* **83** 2970 (2003)
K. Tiedtke et al, *J. Appl. Phys*. **103** 094511 (2008)

Total intensity measurement (II)

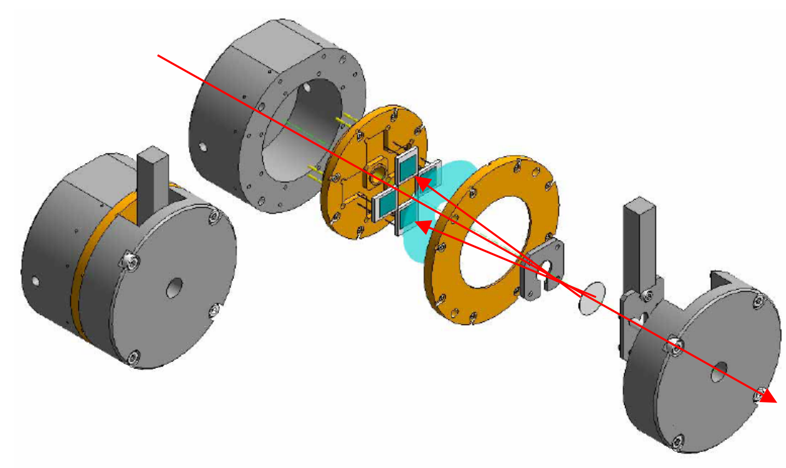
Detection of x-ray scattering (mainly Compton scattering) from thin foil

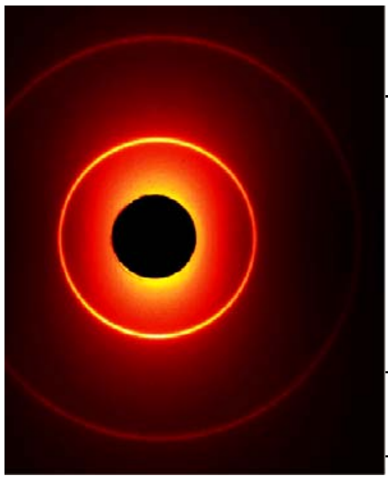
Geometry



Quadrant-photodiodes
Hamamatsu, S3590-09
($10 \times 10\ mm^2$)

K. Tono et al. *RSI* 82, 023108 (2011)





$$\propto \left(I_L + I_R + I_U + I_D\right)$$

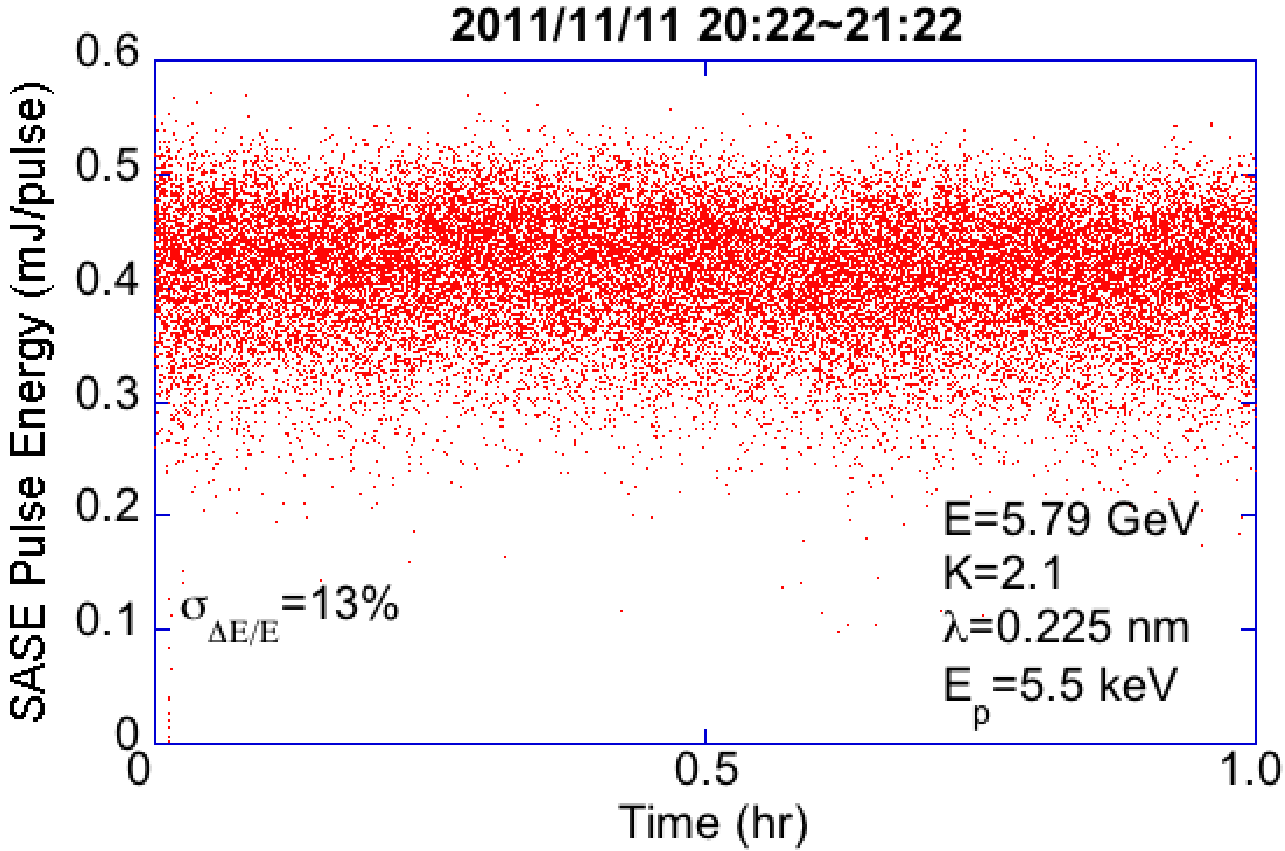
~10μm

Position (center of mass)

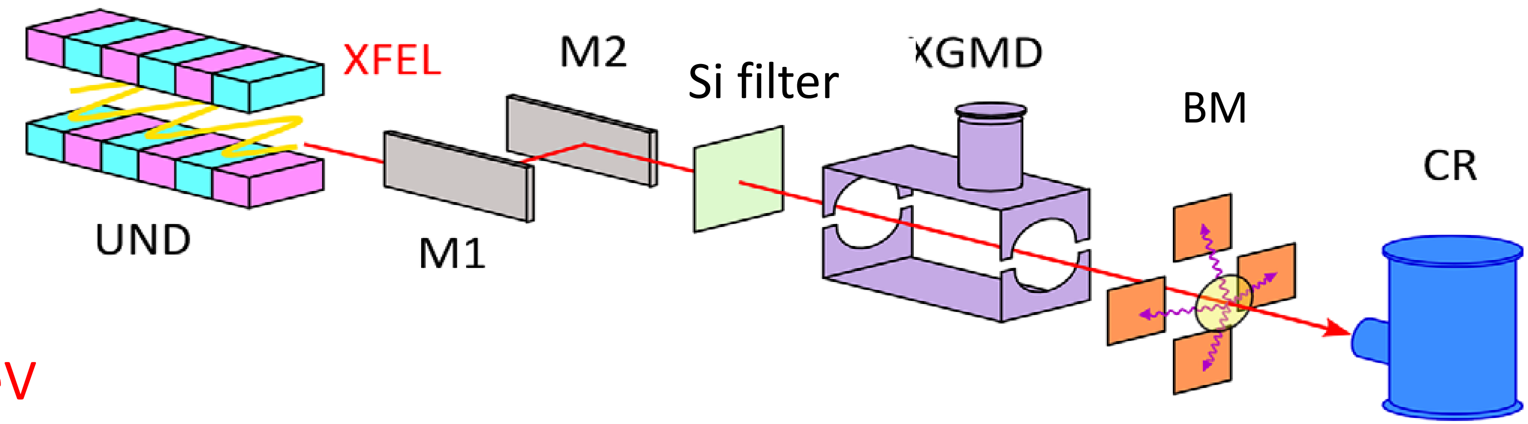
$$x = K_x \frac{I_L - I_R}{I_L + I_R} = K_x \Delta I_x$$

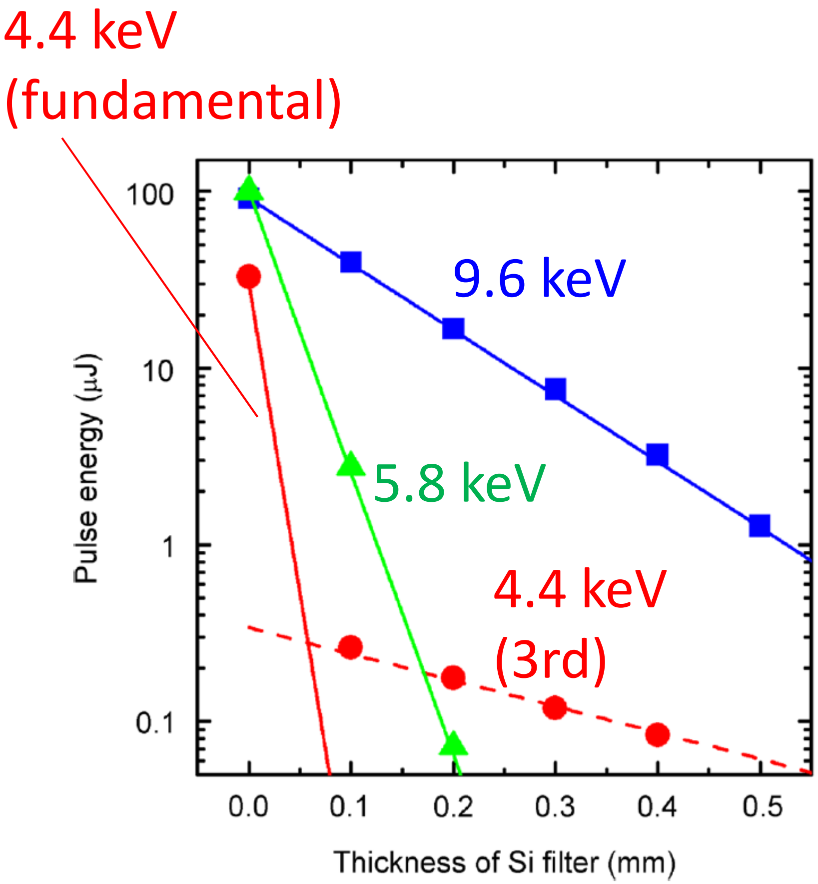
$$y = K_y \frac{I_U - I_D}{I_U + I_D} = K_y \Delta I_y$$

Shot-by-shot measurement



Mutual Calibration





Photon energy /keV	Pulse energy /μJ	
	Radiometer	XGMD
4.4	32.26±0.35	32.9±2.0
5.8	104.2±1.3	106.6±6.1
9.6	95.3±2.3	93.9±6.1
13.6	42.2±1.1	40.8±2.9
16.8	0.96±0.03	---
	AIST (JPN)	PTB

Excellent agreement

Contents

Pulse duration measurement

Deflection cavity after undulator:
Measure time-resolved energy loss/spread after x-ray lasing

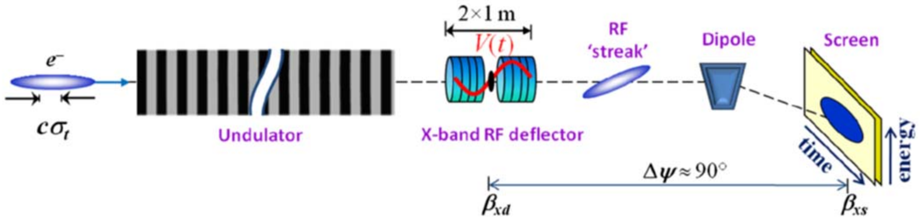


FIG. 1. A layout of the diagnostic system with a transverse rf deflector and an energy spectrometer.

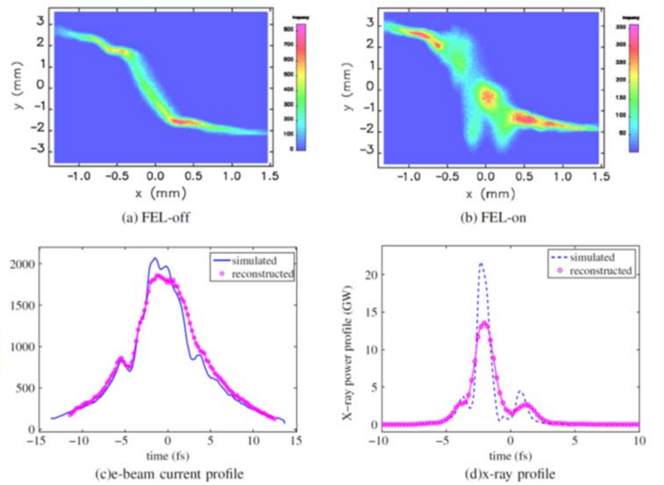
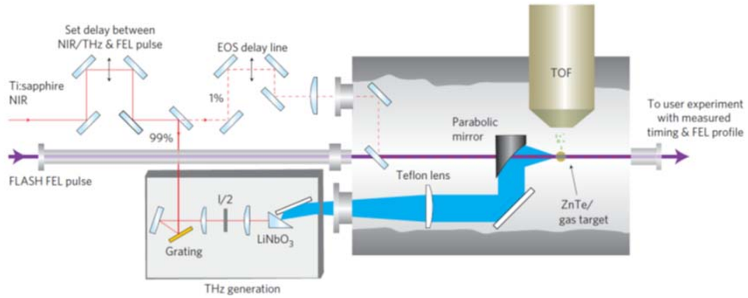
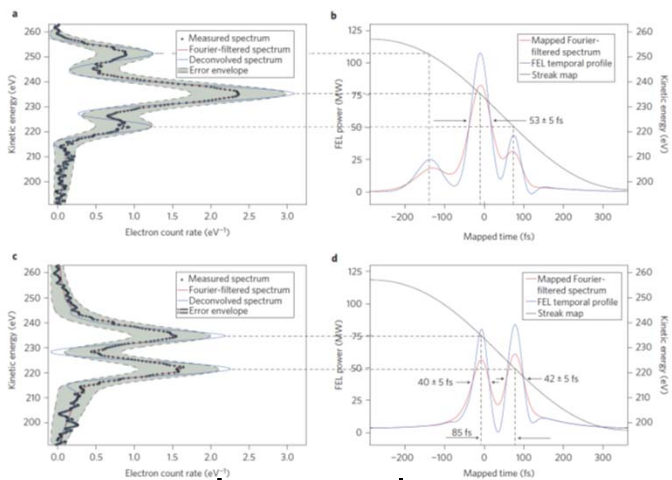


FIG. 4. The simulated images on the screen representing e-beam longitudinal phase space for FEL-off (a) and FEL-on (b). The bunch ... Parts (c) and (d) show the reconstructed e-beam current and FEL x-ray profiles (magenta) ... The bunch head is to the left.

XTCAV @ LCLS
Ding et al., PRST **14**, 120701 (2011)

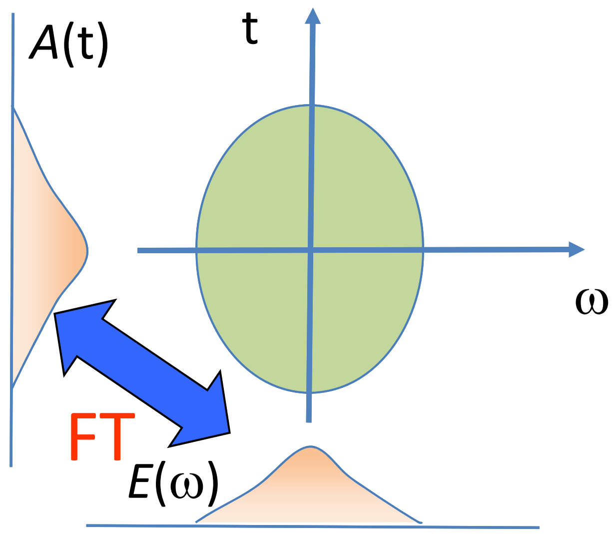
THz streaking method:
photoelectrons -> modulation of energy with external THz field (streaking)





Grguras et al., Nat. Photon **6**, 852 (2012)
Fruhling et al., Nat. Photon **3**, 523 (2009)

Distribution in longitudinal phase space

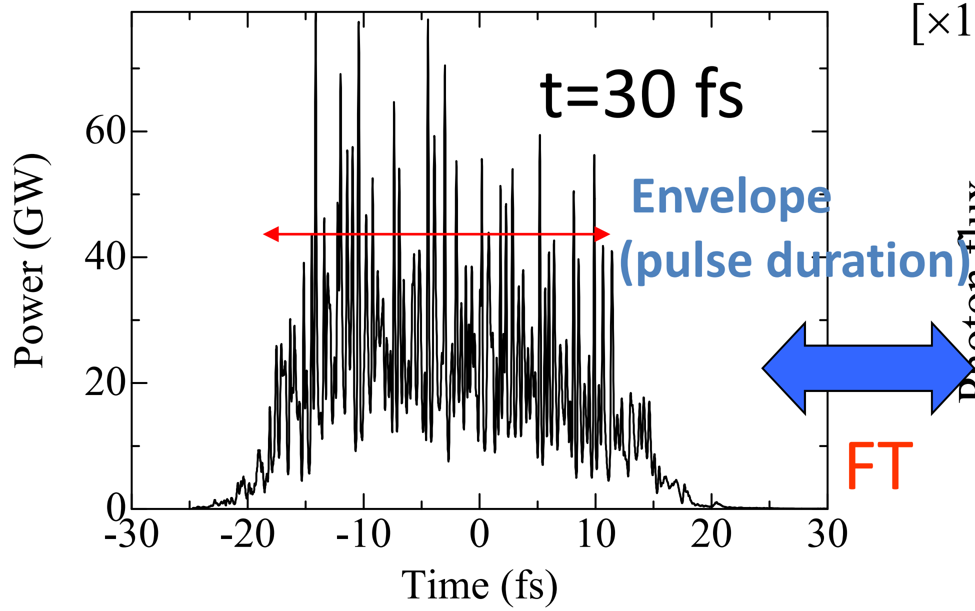


Large bandwidth/long pulse

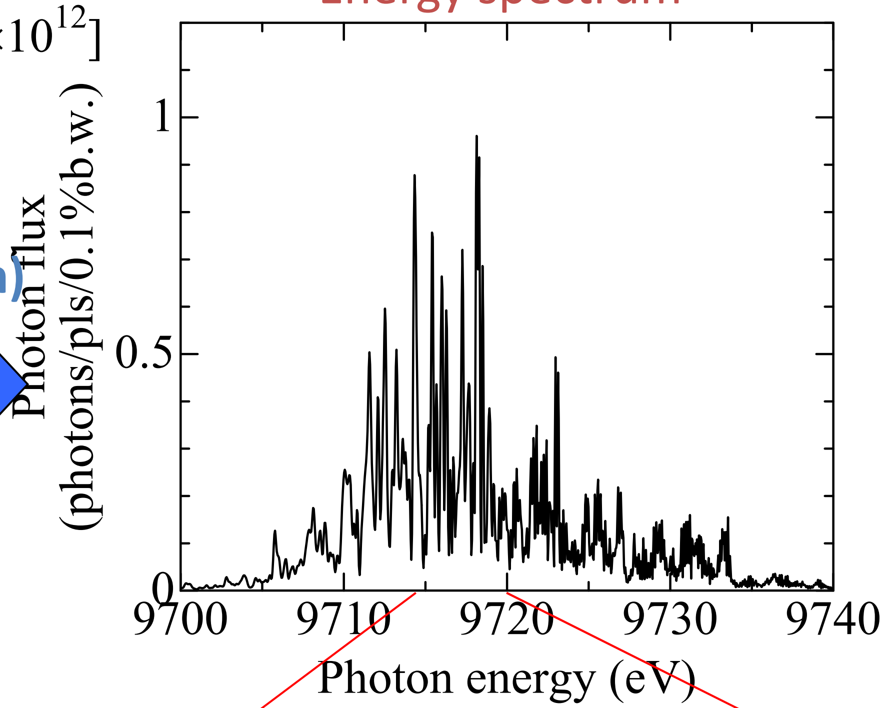
- Distribution in frequency domain *E*(ω) <- FT -> Distribution in temporal domain A(θ)

Simulation for SASE-FEL (I): Longer pulse

Temporal profile



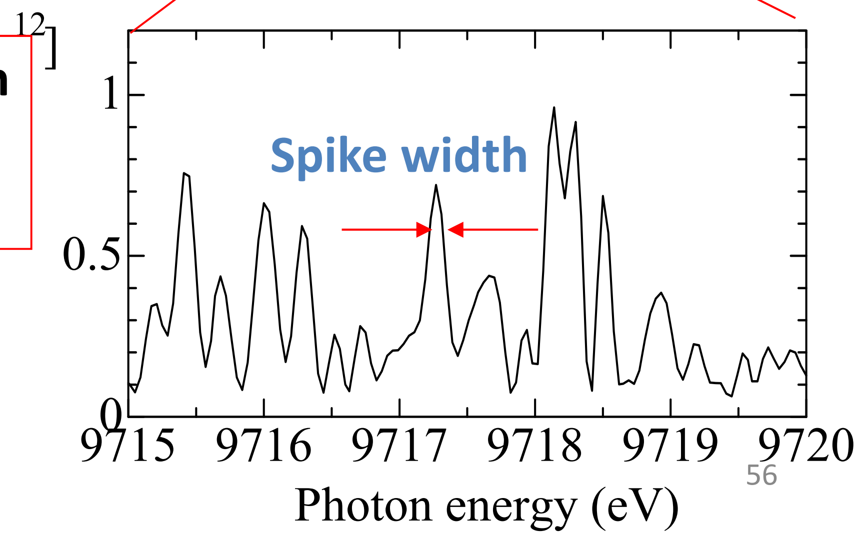
Energy spectrum



Time domain
Envelope
Spike

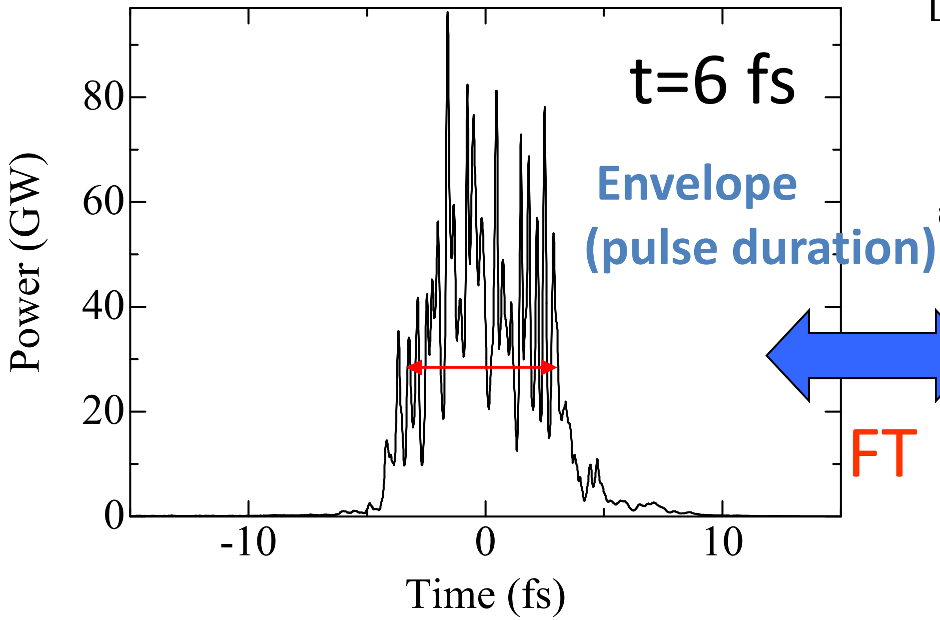
FT ⟺

Frequency domain
Spike
Envelope



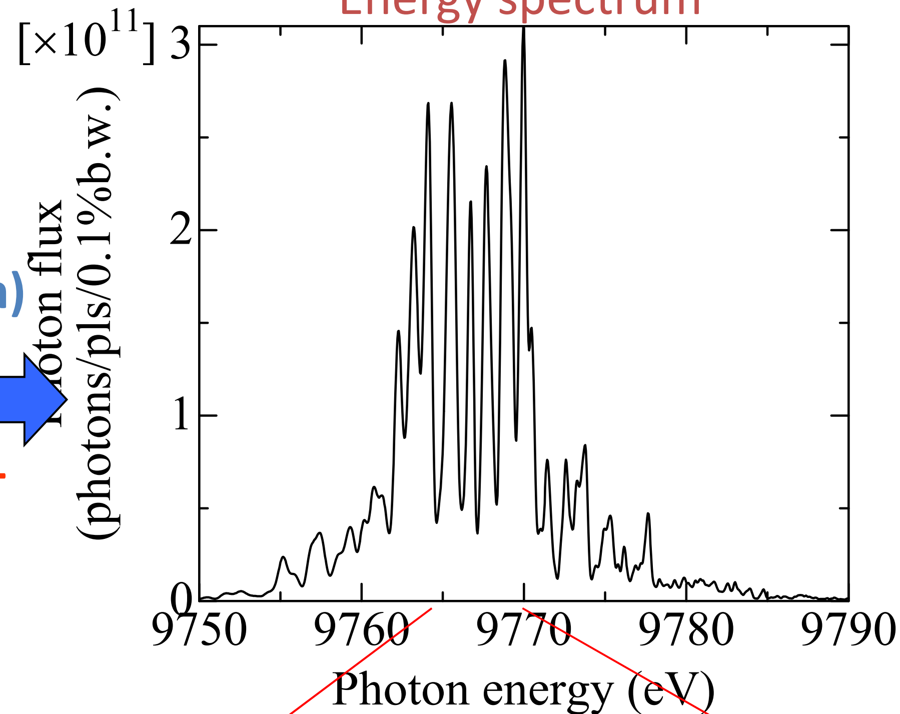
Simulation for SASE-FEL (II): Shorter pulse

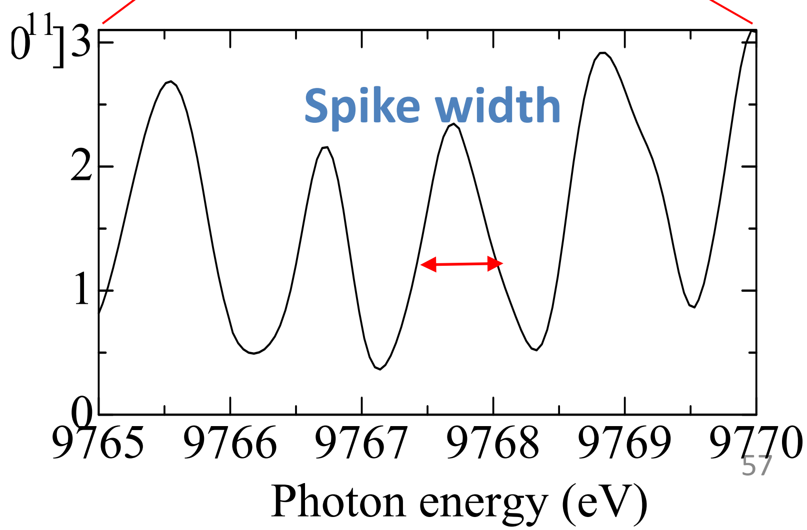
Temporal profile



FT

Energy spectrum





Pulse duration

Shorter

Longer

Spike width

Wider

Narrower

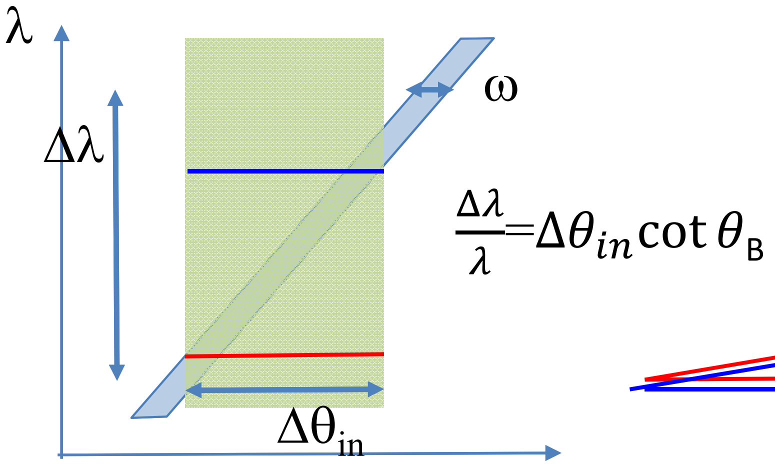
Measurement of energy spike
(high resolution)

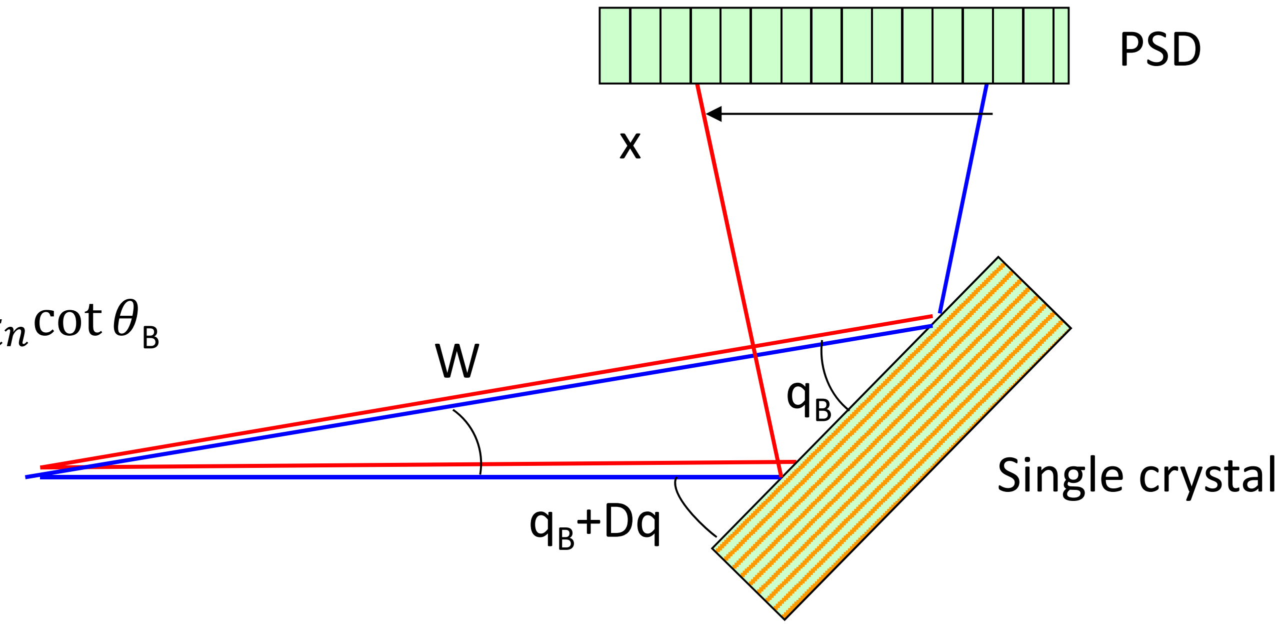
Evaluation of pulse duration

Measurement with perfect-crystal spectrometer

Divergent beam + flat crystal analyzer

Single-shot detection





$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta E}{E} = \Delta\theta \cot\theta_B$$

Energy Angle

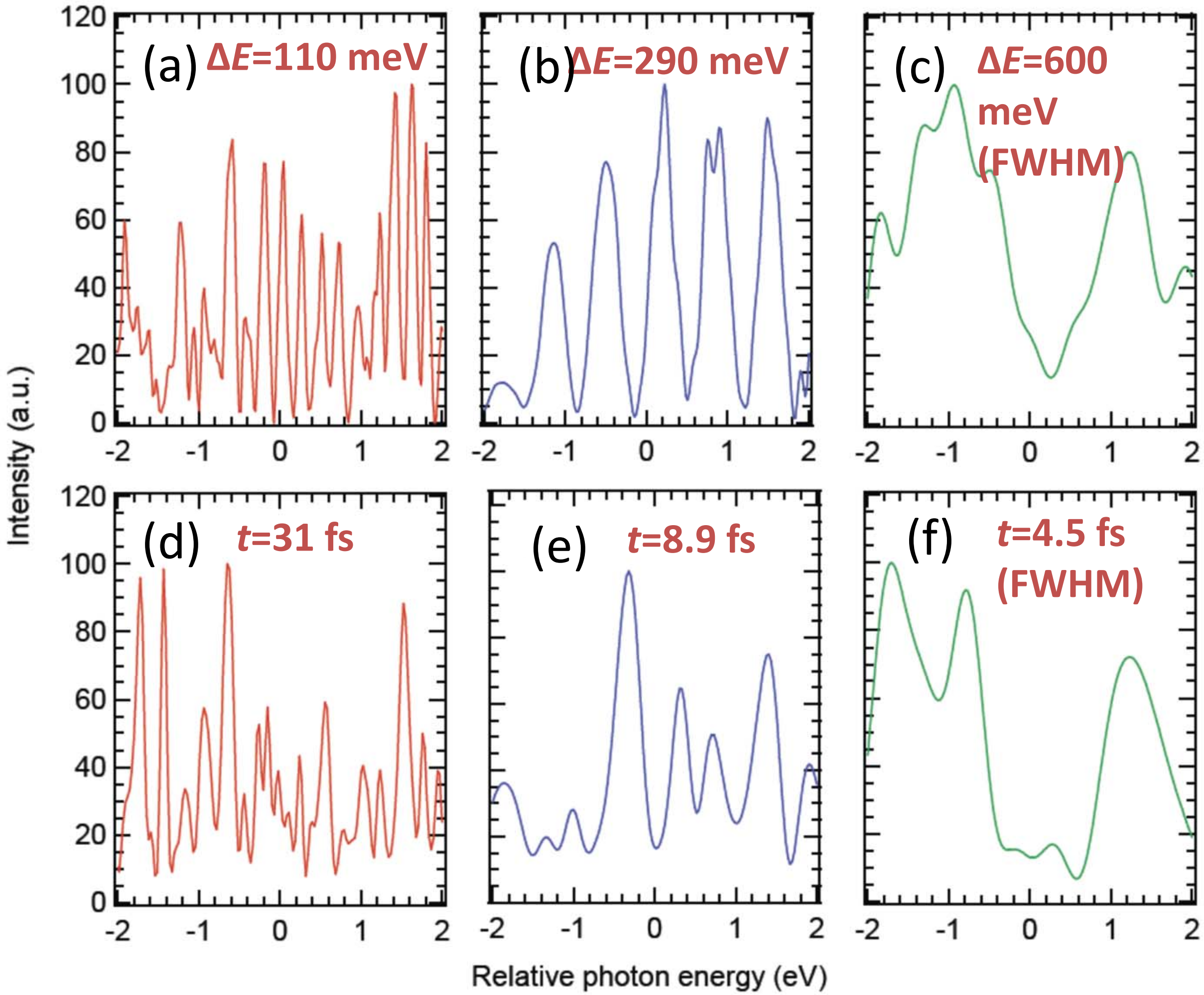
$$\xi = L\Delta\theta = \frac{\Delta E}{E} L \tan\theta_B$$

Position

Example

Measurement at SACLA

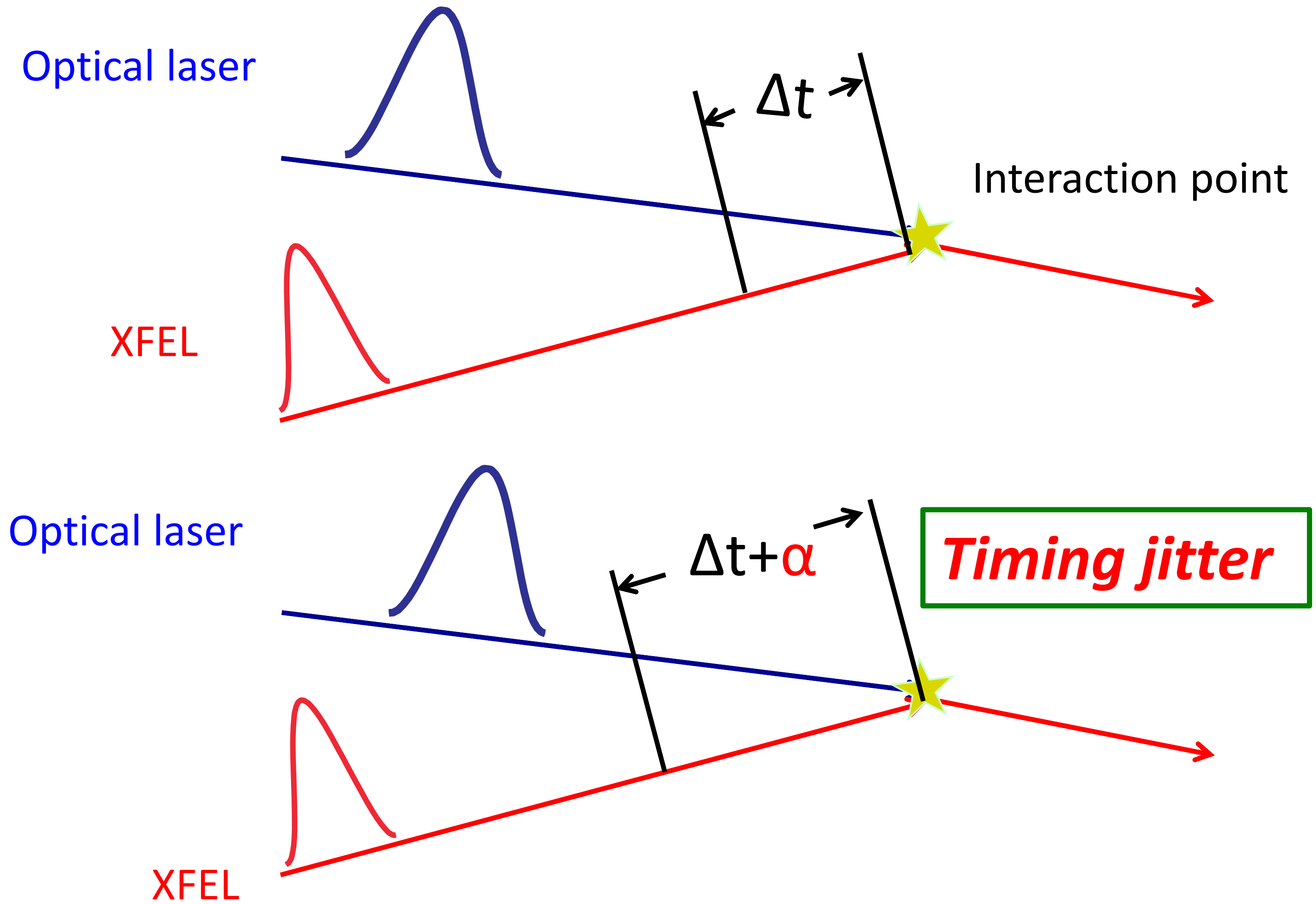
FEL simulation (SIMPLEX by Takashi Tanaka)



Y. Inubushi *et al.*, *Phys. Rev. Lett*. **109**, 144801 (2012).

Contents

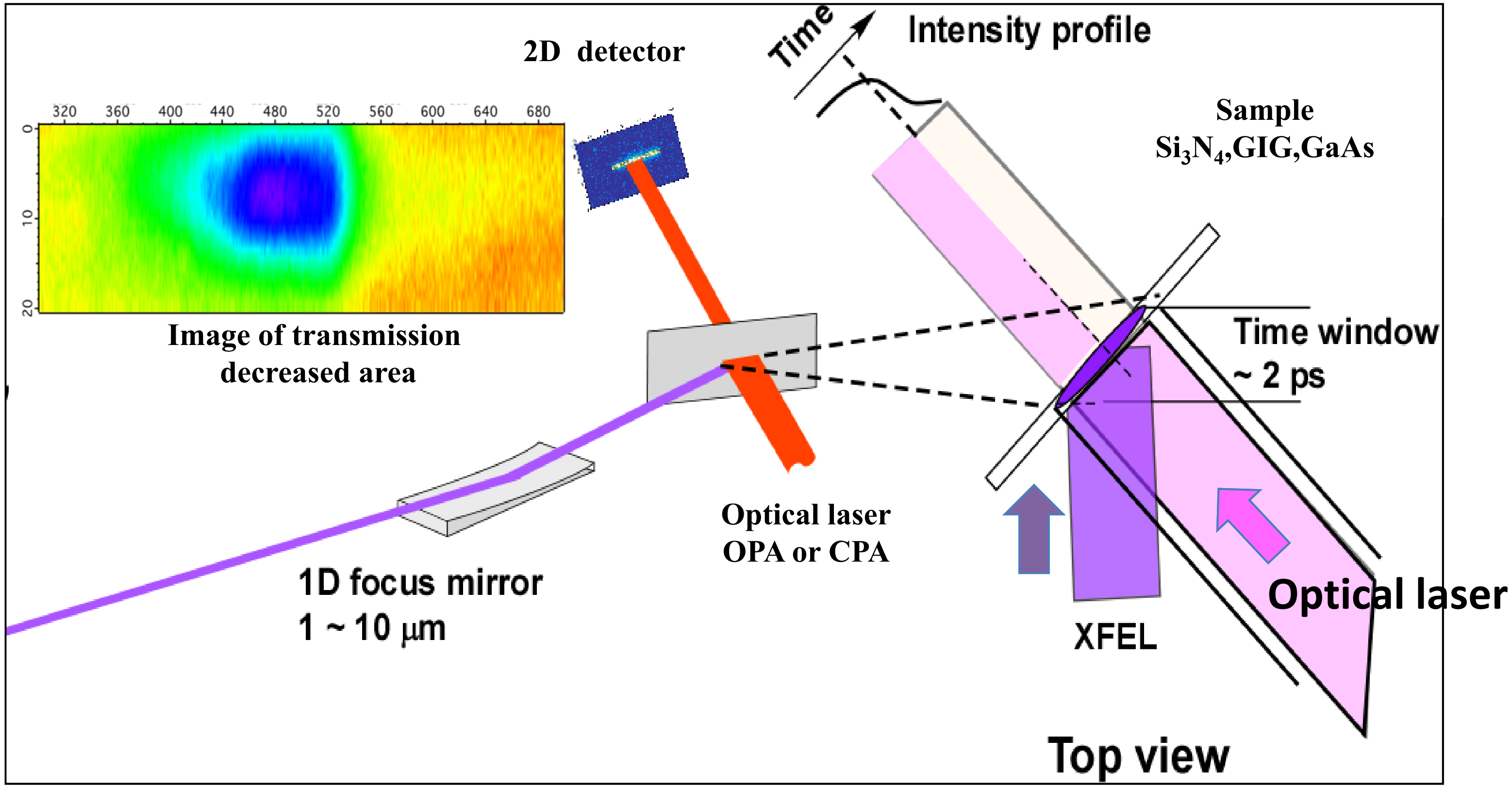
Arrival timing



Measure timing jitter for every pulse ➡ Sorting with “tag” information

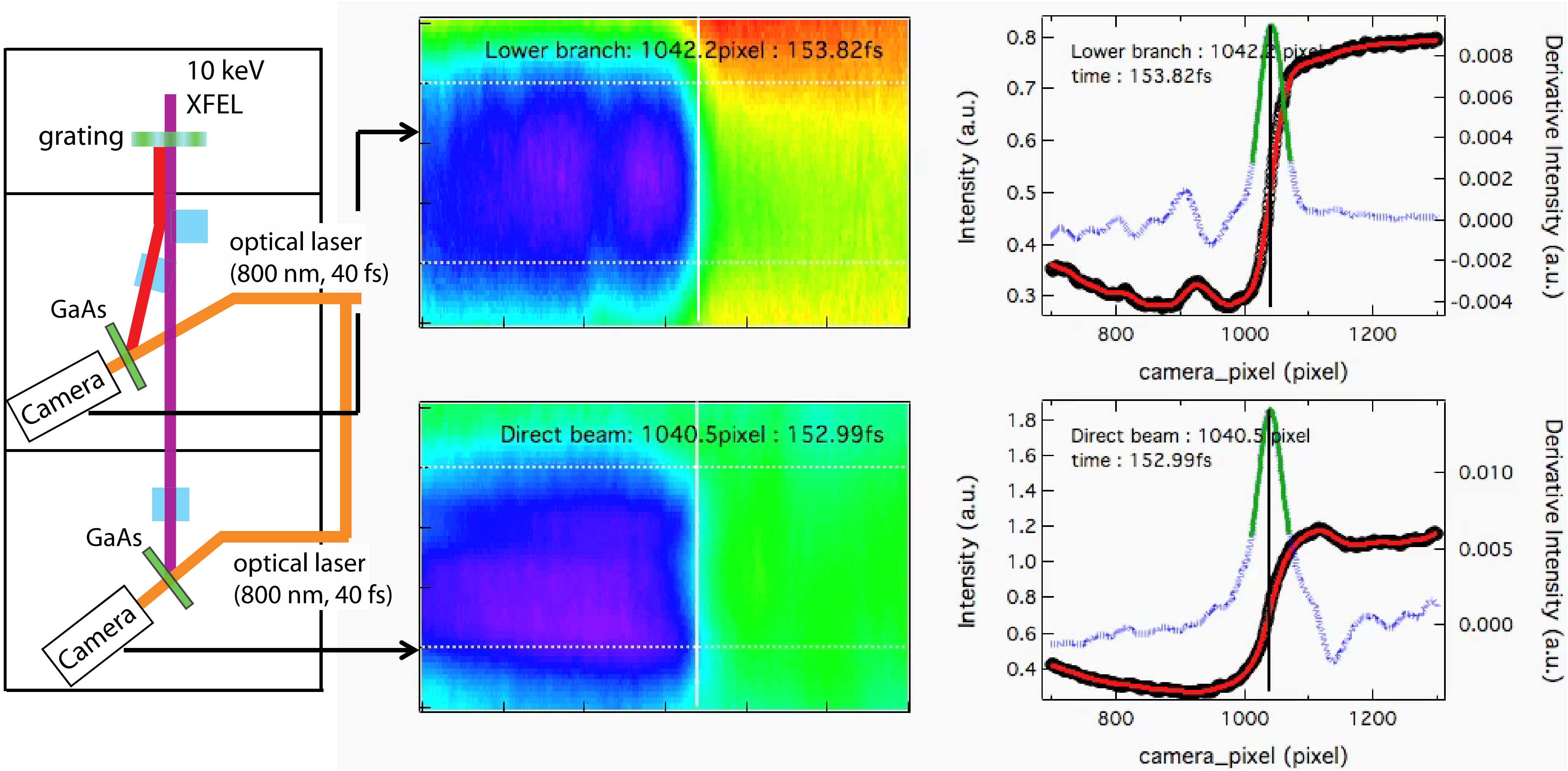
Arrival timing measurement

XFEL excites electronic system in fs scale→ probed by change of optical transmittance
Spatial encoding technique: cross-beam geometry between XFEL and optical laser

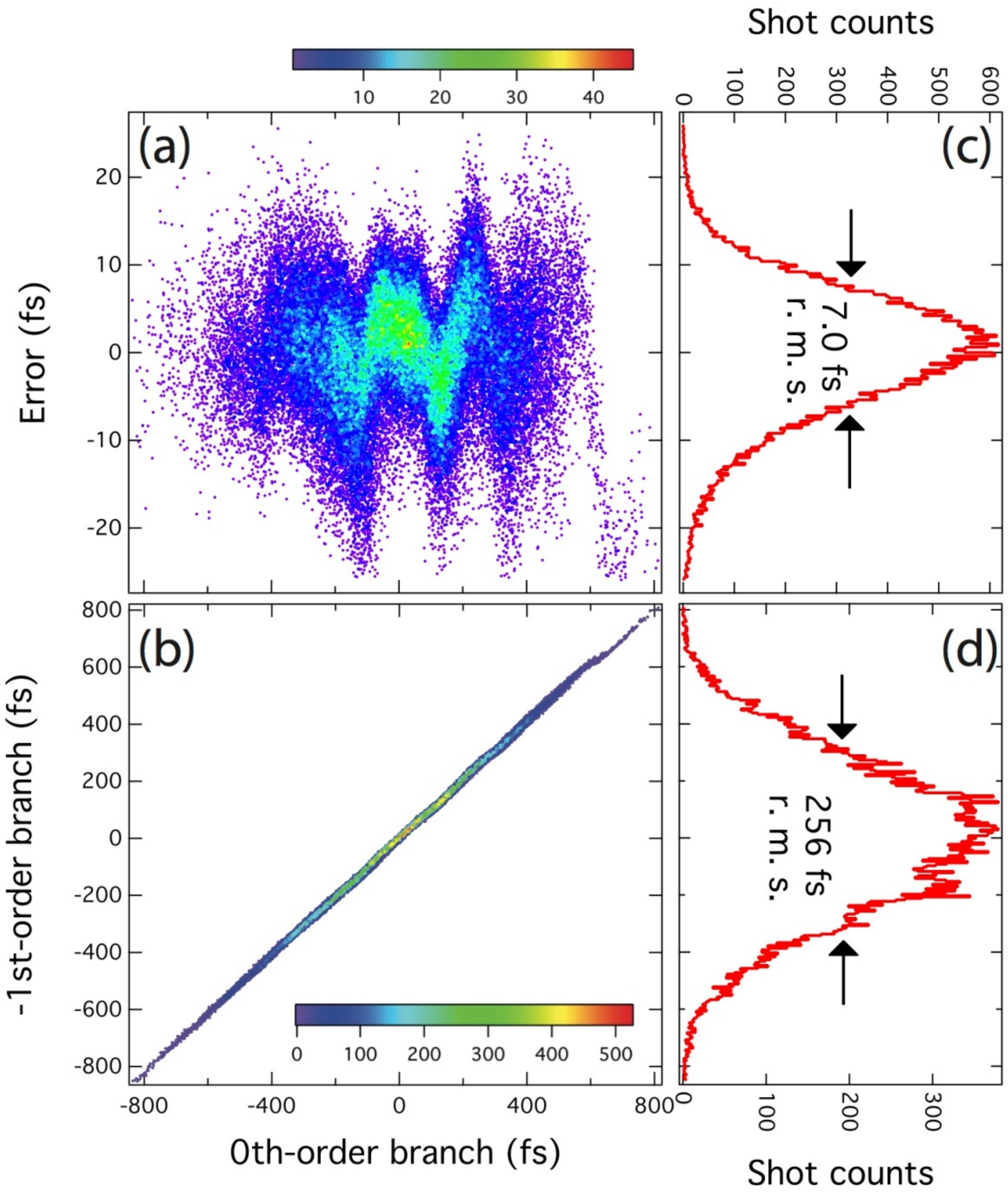


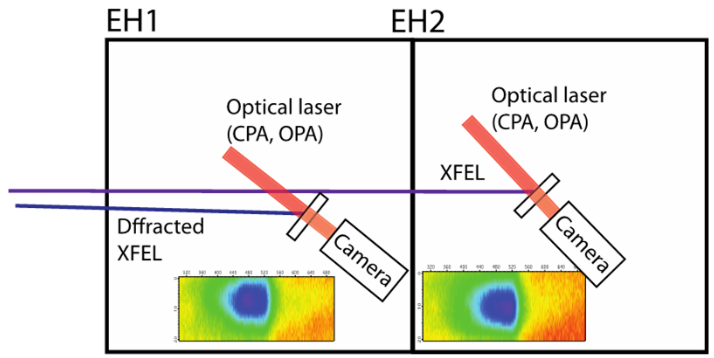
Harmand et al., Nature Photon **7** 215 2012
Gahl et al., Nature Photon **2** 165 2008
T. Sato et al APEX **8**, 012702 (2015)

Correlation measurement between two independent setup



Correlation between independent measurements





- Error from the linear fit (in 1.6 ps range): 7.0 fs (RMS)
- Intrinsic jitter : 256 fs (RMS)

Katayama et al., Strut. Dynamics 3 (2016) 034301

Short summary

- New developments are on-going for characterizing XFEL beam properties, especially towards achieving high resolution
- Cross-check among different schemes is important for assuring reliability

References:

- K. Tono et al., New Journal Phys. **15** (2013) 083035: Review of x-ray beamline and diagnostics of SACLA
- Harmand et al., Nature Photon **7** (2012) 215: Arrival timing monitor at LCLS

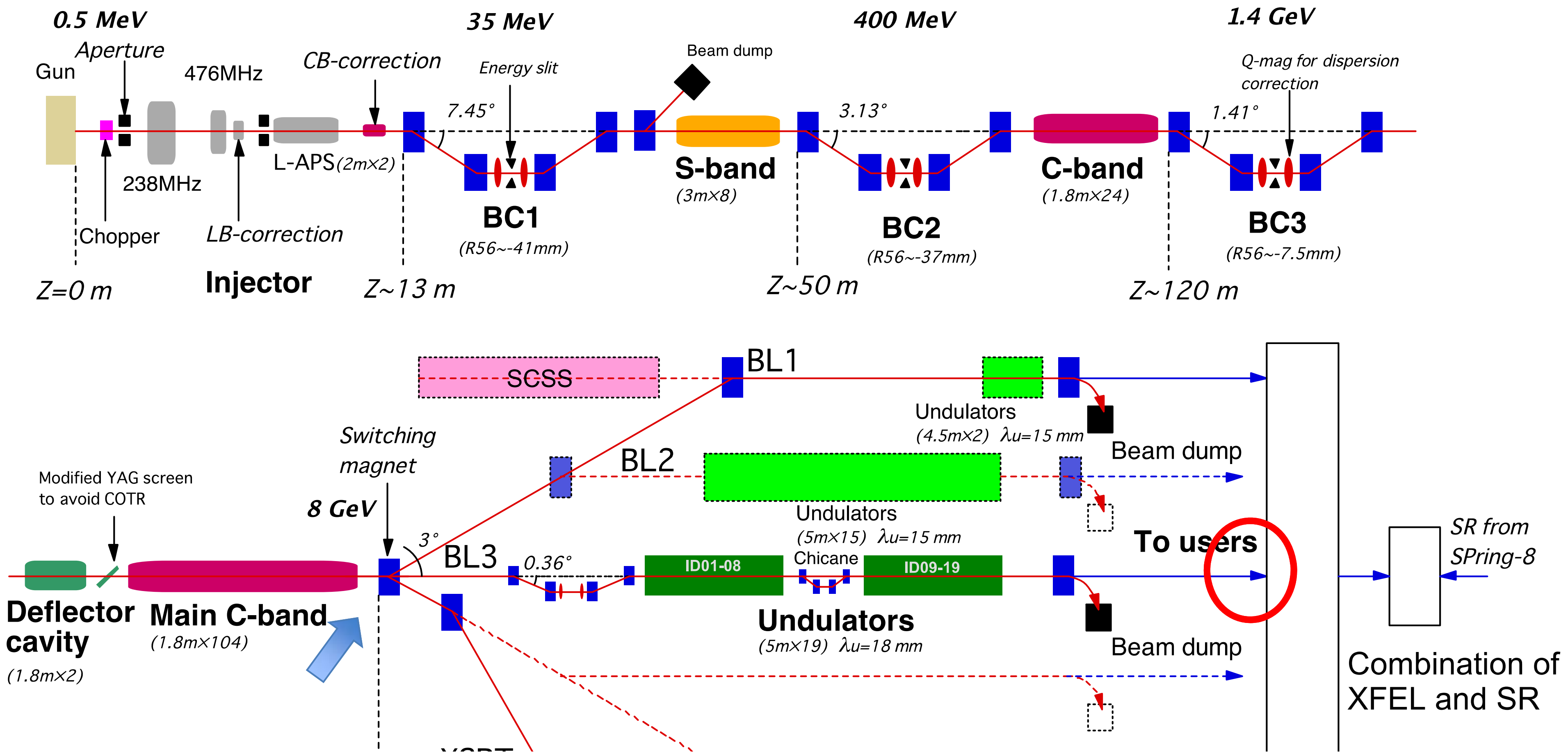
Contents

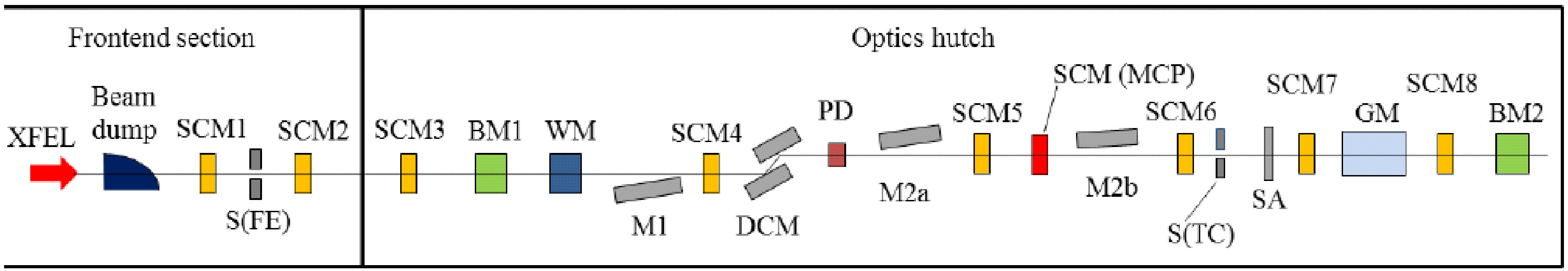
1. Introduction: Brief history of photon beamlines for SR/XFEL
2. Preparatory: Phase space
3. X-ray optics
4. X-ray diagnostics
5. Design of XFEL beamline

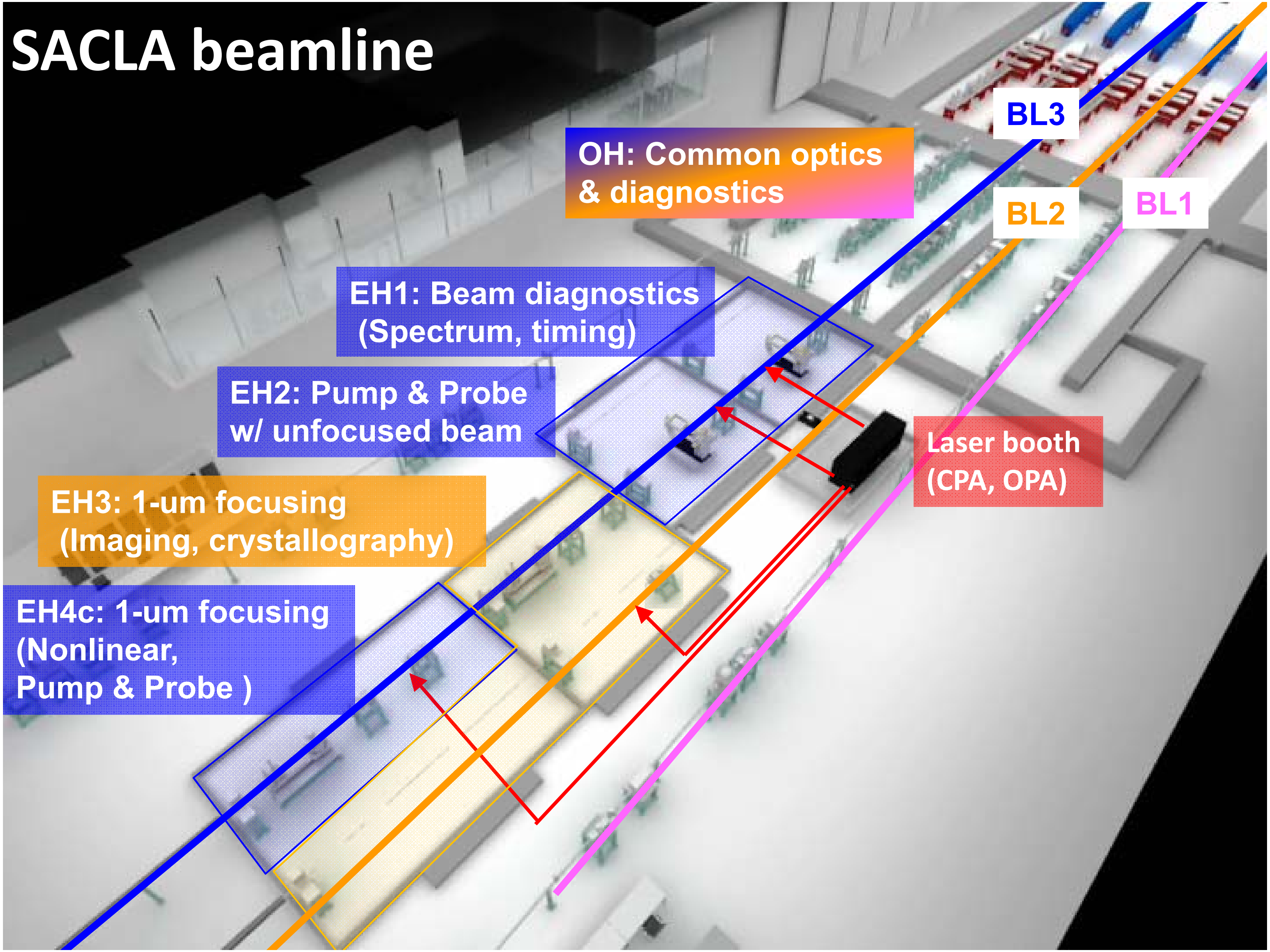
   Example: SACLA

   K. Tono et al., New Journal Phys. **15** (2013) 083035
6. Summary

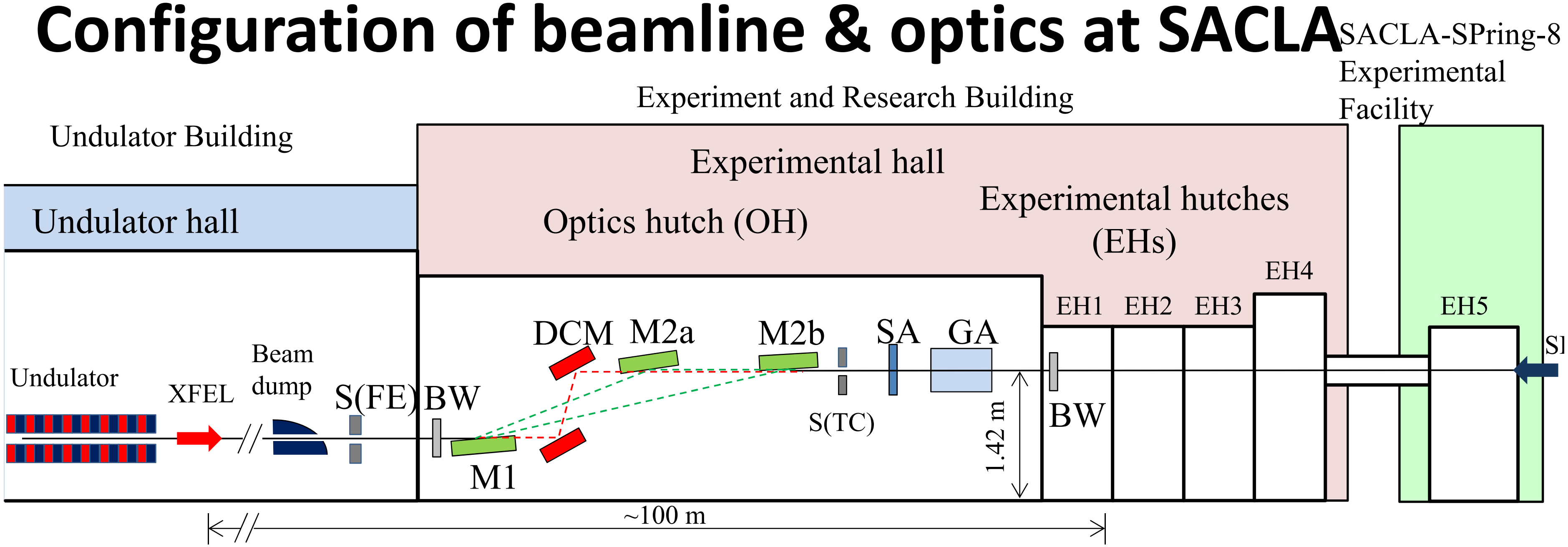
Example: SACLA






SACLA beamline
BL3
OH: Common optics & diagnostics
BL2
BL1
EH1: Beam diagnostics (Spectrum, timing)
EH2: Pump & Probe w/ unfocused beam
Laser booth (CPA, OPA)
EH3: 1-um focusing (Imaging, crystallography)
EH4c: 1-um focusing (Nonlinear, Pump & Probe)

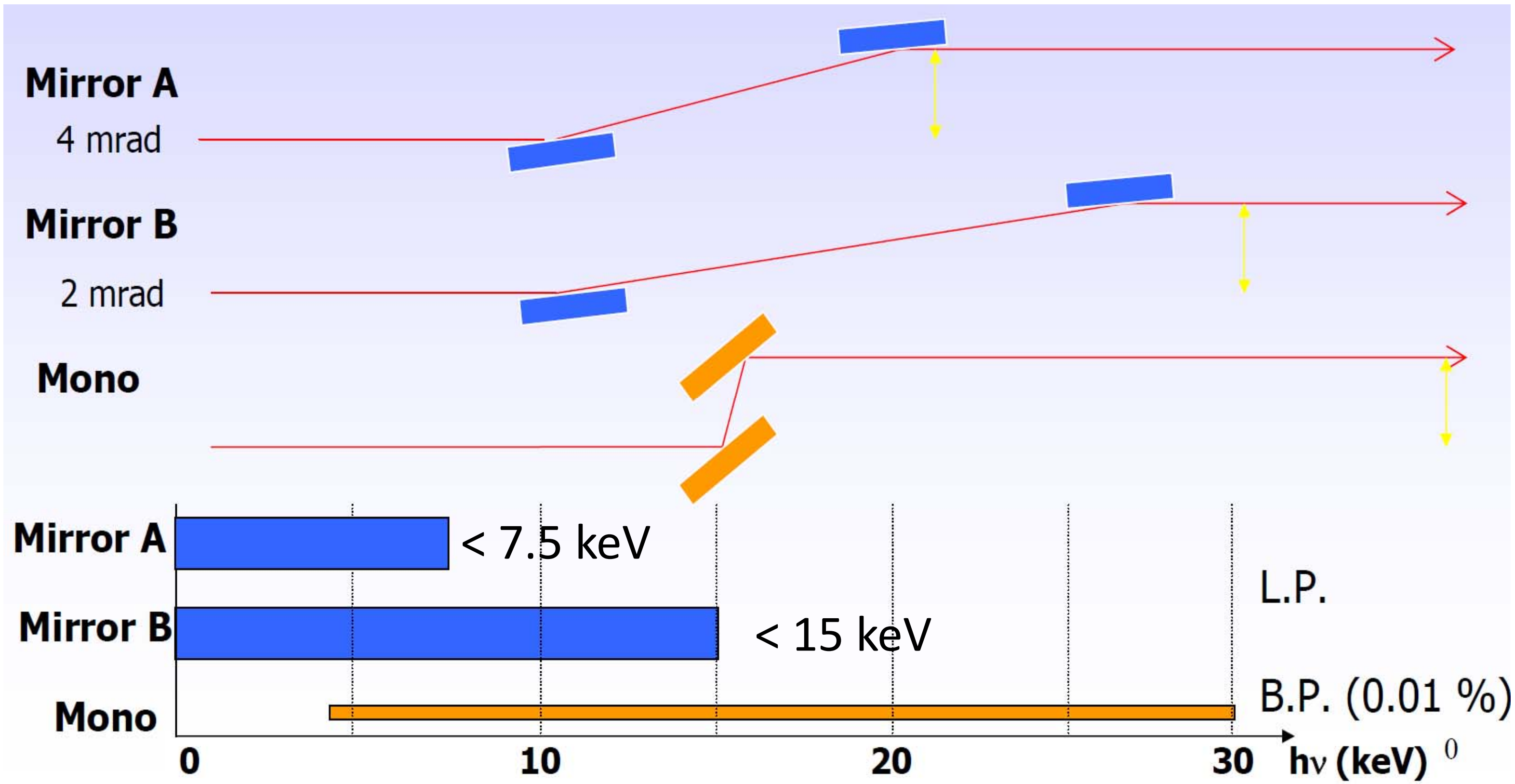
Configuration of beamline & optics at SACLA



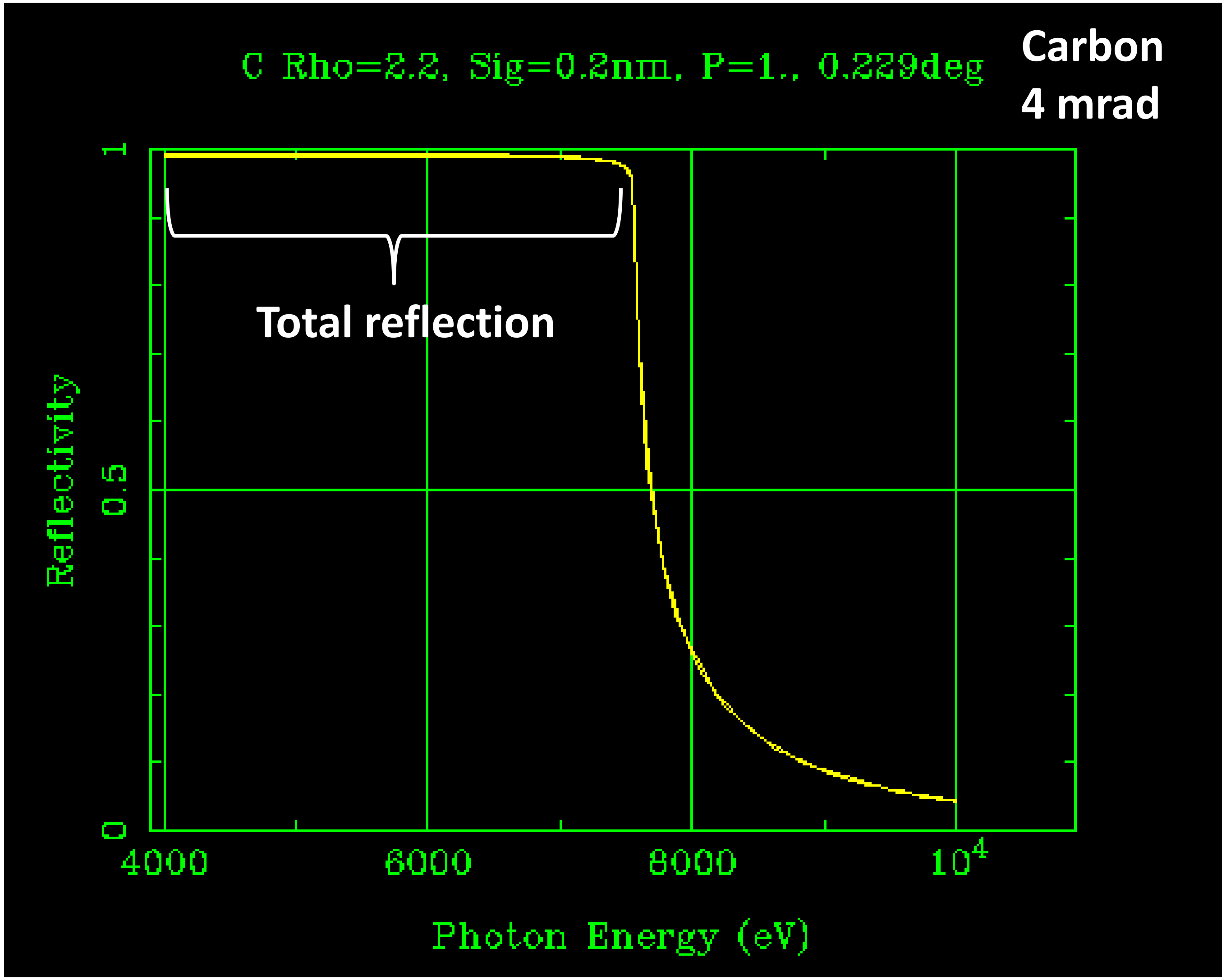
	Name	Function
S(FE)	Frontend slit	Filtering (spatial)
BW	Be optical window	Vacuum protection Filtering (high pass)
M1, M2a, M2b	Plane mirrors	Filtering (low pass)
DCM	Double crystal monochromator	Filtering (band pass)
S(TC)	4-way slit	Filtering (spatial)
SA	Solid attenuator	Attenuation
GA	Gas attenuator	Attenuation

Basic optics

- Plane mirrors（A & B）: rejection of high-energy harmonic and gamma-rays
- Double-crystal monochromator（Si 111）: Band-pass filter



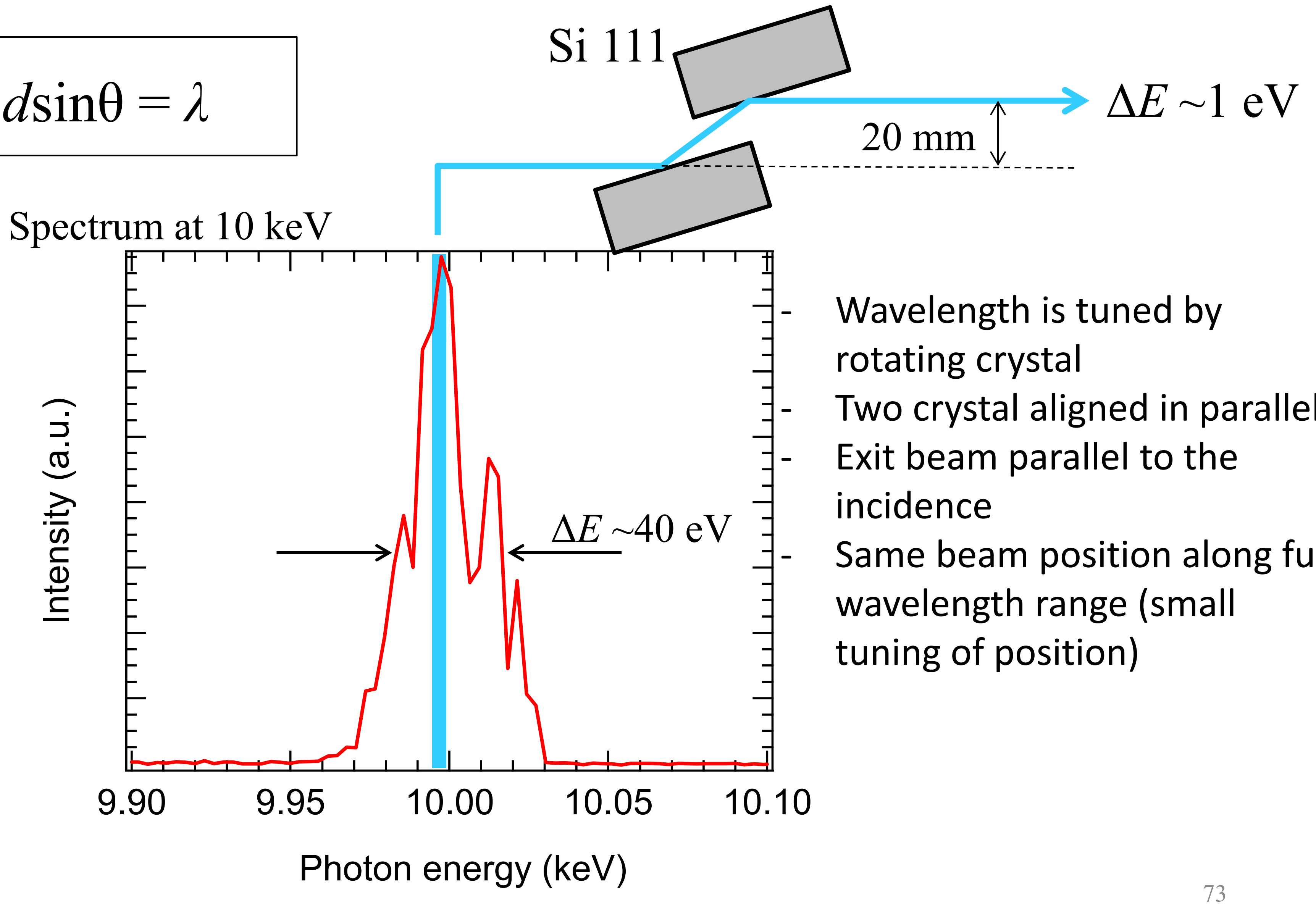
Mirrors for harmonic rejection



B.L. Henke, E.M. Gullikson, and J.C. Davis, Atomic Data and Nuclear Data Tables Vol. **54** (no.2), 181-342 (1993)

Double-crystal monochromator

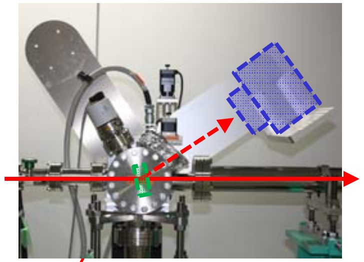
$$2d\sin\theta = \lambda$$



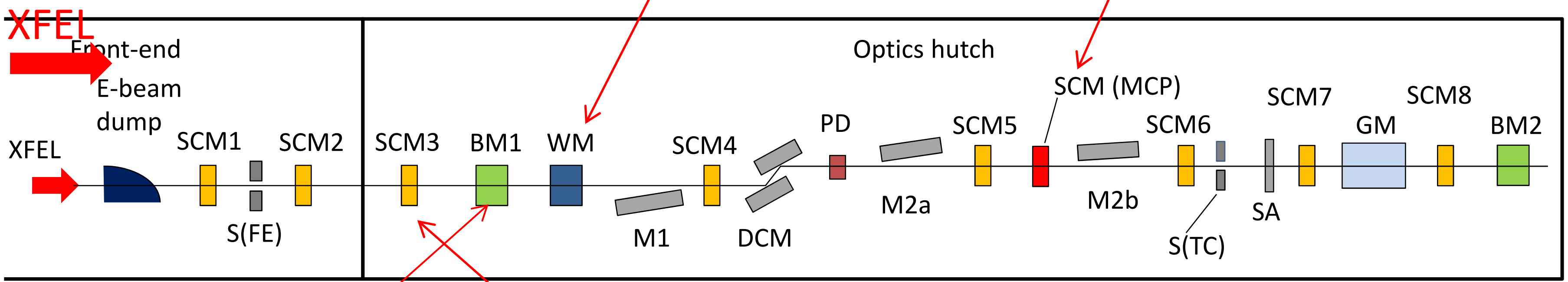
- Wavelength is tuned by rotating crystal
- Two crystal aligned in parallel
- Exit beam parallel to the incidence
- Same beam position along full wavelength range (small tuning of position)

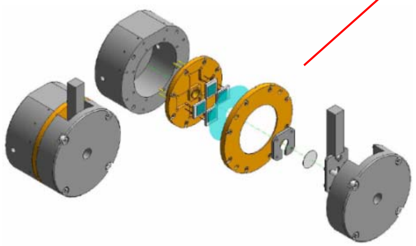
X-ray Diagnostics

Wavelength monitor (ND)

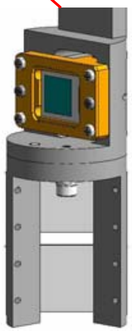


High-sensitivity screen monitor for spontaneous x-ray detection

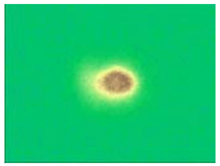




Pulse energy x2



Screen monitor x7



Fixed point monitor for XFEL beam position with semi-transparent B-doped diamond; 20 um/100 m = 0.2 urad accuracy

2015/9/25

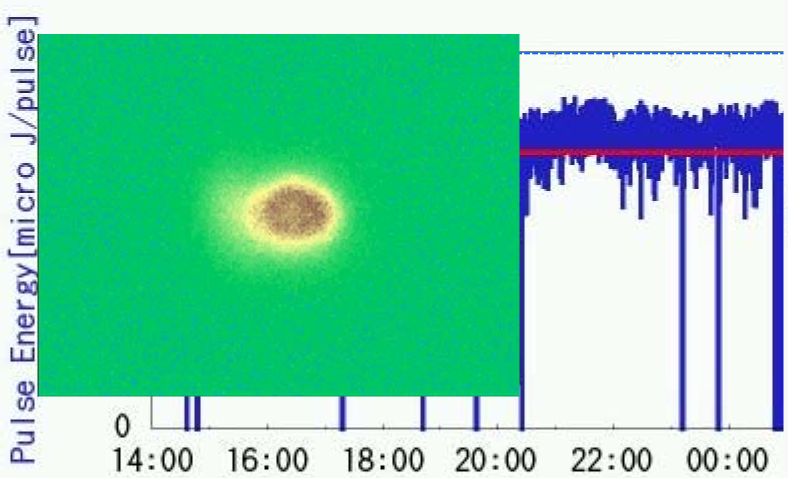
SACLA Operation Status

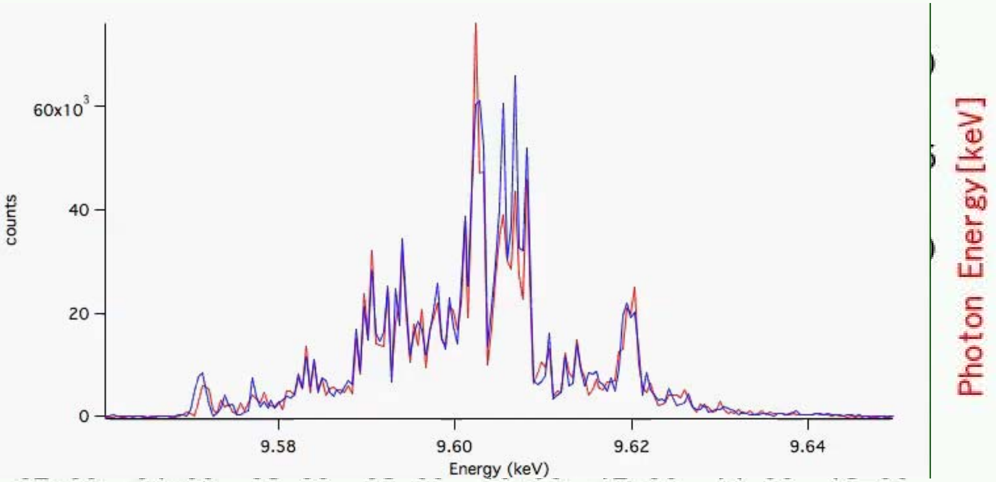
14:22:40

Operation Mode	
BL3 User Operation	
Hutch in Use	
BL3 EH2	
Pulse Energy	**Photon Energy / Wavelength**
230.9 micro J/pulse	15.0 keV / 0.082 nm
Repetition Rate	**Intensity Fluctuation in 30 shots (STD)**
30 Hz	14.8 %

~ 500 uJ @ 10 keV

<10 fs pulse duration





Summary

- Connection between XFEL machine and beamline/optics becomes much important in advanced x-ray sources, including XFEL, DLSR and XFEL-O
- Tighter communications among electron & photon people (i.e., broader view) should significantly contribute to development of new light sources

Acknowledgement

Drs. Shunji Goto, Kensuke Tono, Tetsuo Katayama, Yuichi Inubushi, (SPring-8/SACLA)

Thank you for your attention

End