XFEL
- Photon Beamline and Experiments -

Kensuke Tono
XFEL Utilization Division, JASRI

Contents

1. Photon beam properties
2. Hard X-ray Beamline
3. Experimental stations
4. Experiments at SACLA

XFEL: Properties and sciences

- Short pulse (<10 fs)
- High peak power (>30 GW)
- Coherent

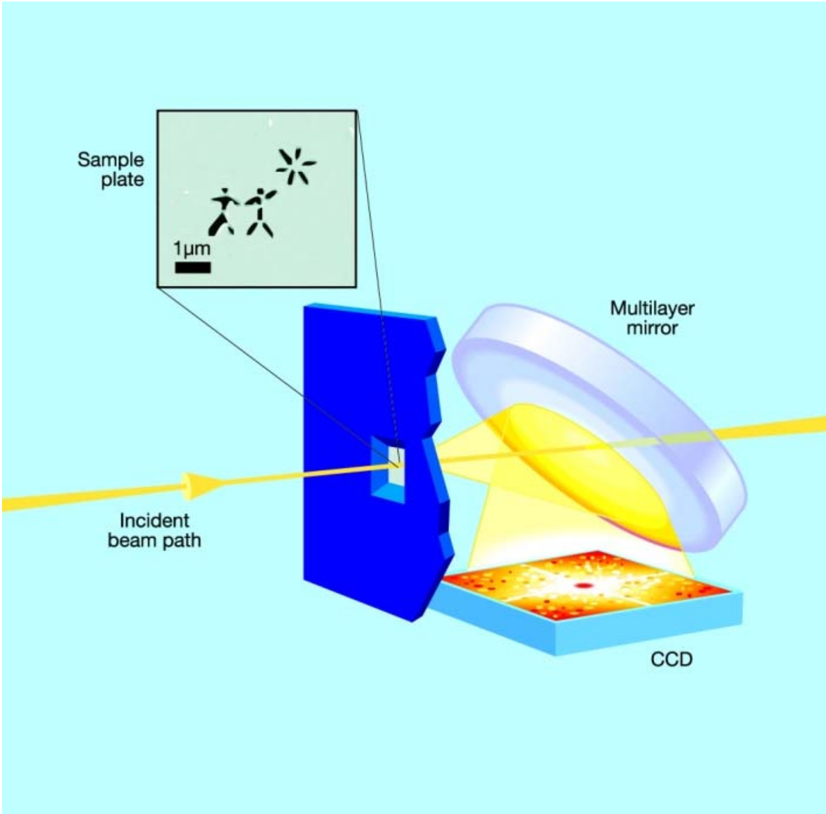
Ultrafast observation beyond the speed of atomic motion

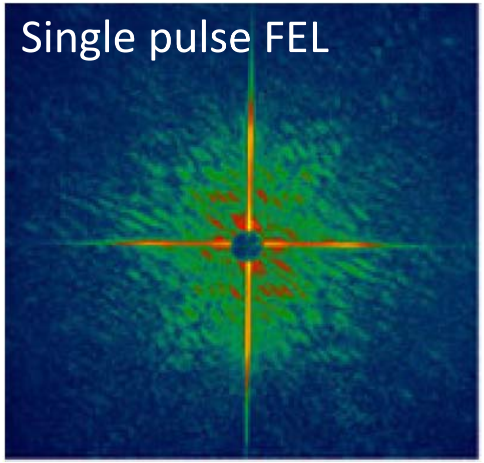
- Beyond static image
  - Imaging functions (motion pictures of chemical reaction, phase transition, etc.)
- Beyond statistical image
  - Imaging fluctuations, rare events

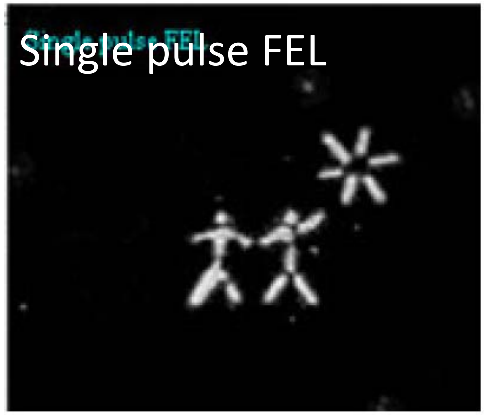
Ultrahigh peak-intensity X-ray sciences

- New regime of X-ray-matter interactions (Nonlinear optics, quantum optics, etc.)

Femtosecond snapshot of sample







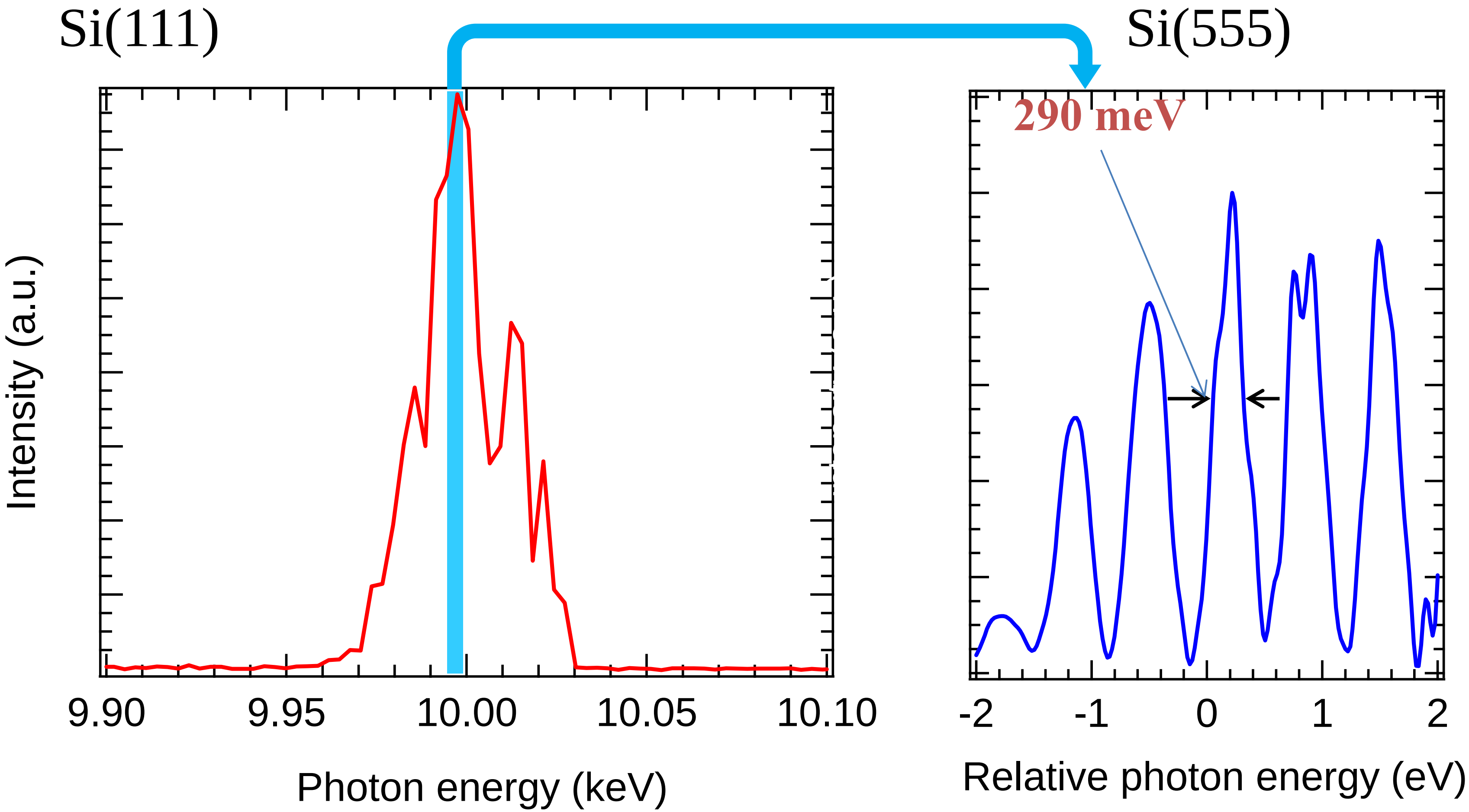
Chapman et al., *Nature Physics* **2**, 839 (2006)

SASE XFEL

- Short pulse (<10 fs)
- High peak power (>30 GW)
- Coherent (spatial only)
- Multimode
- Shot-by-shot fluctuation

Spectrum of single XFEL pulse

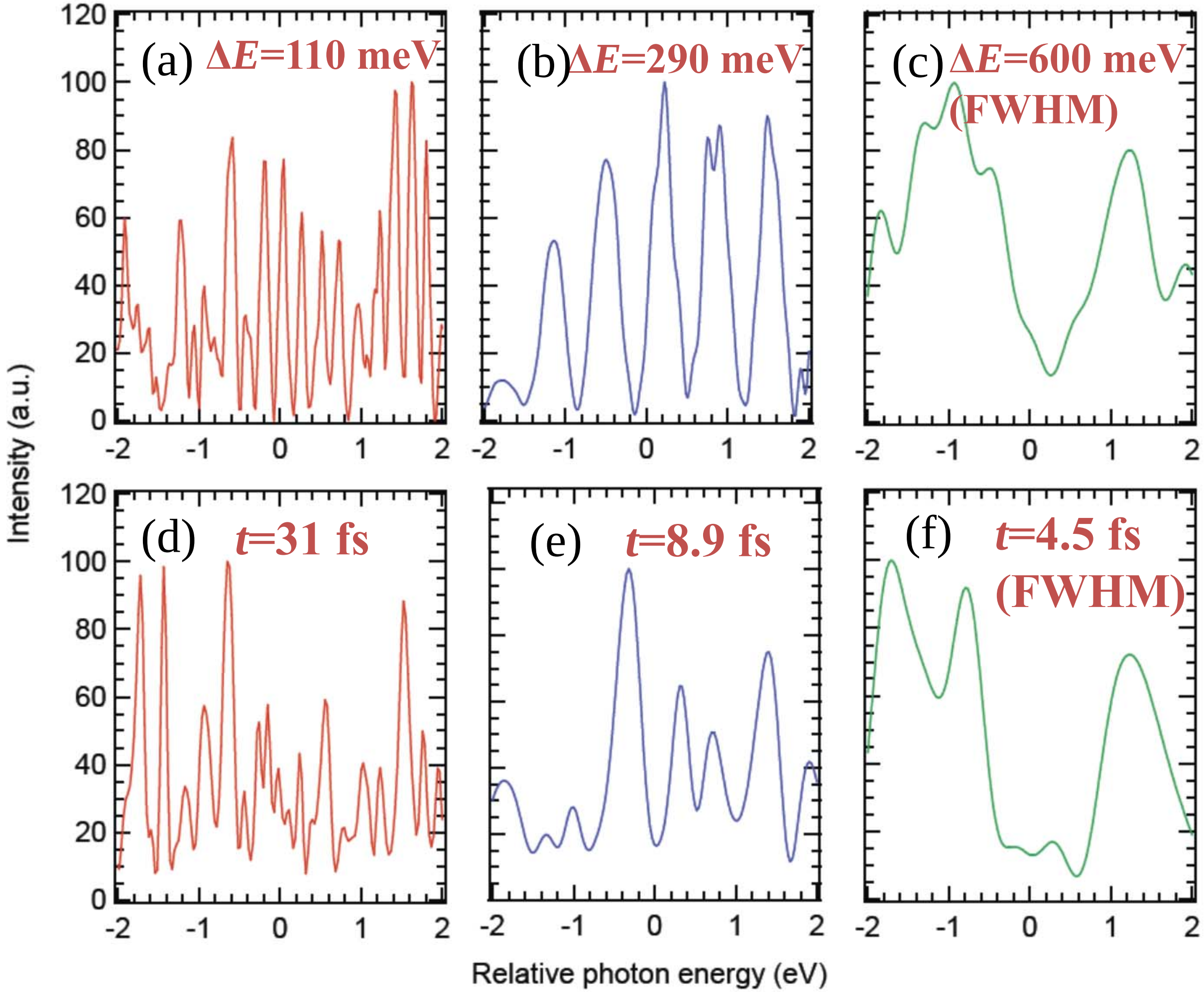
Spikes due to multi optical modes



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

Spectra at different pulse widths

Inubushi (RIKEN) et al.

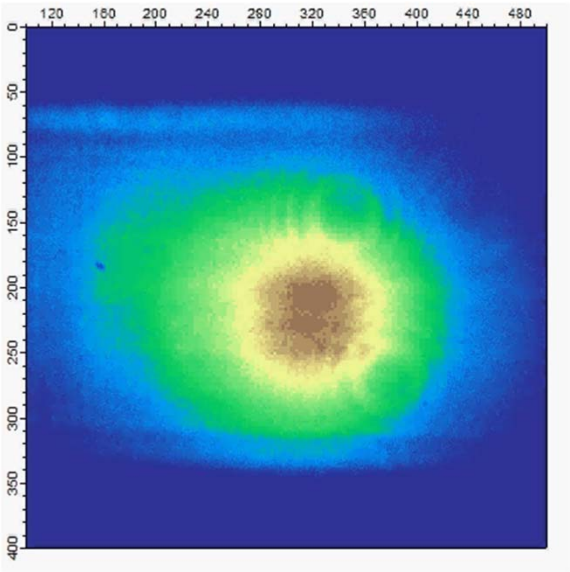


Measured Spectra

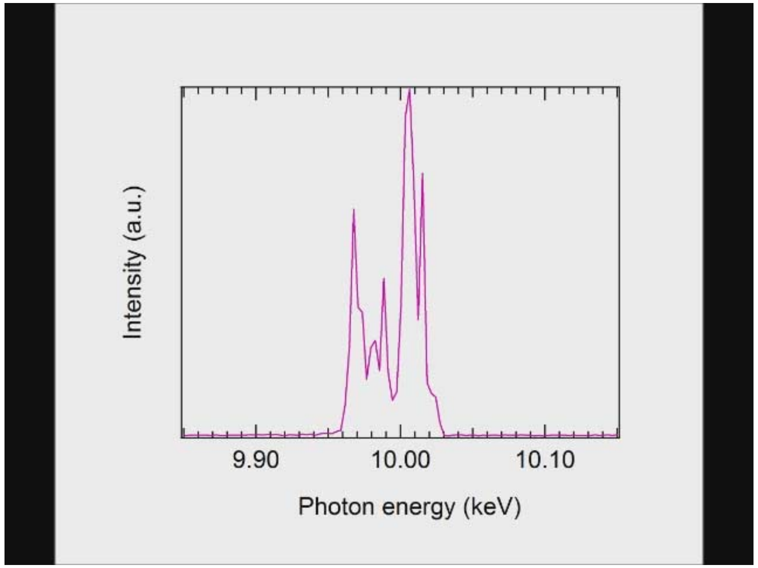
Simulated spectra

Shot-by-shot fluctuation

Intensity/position



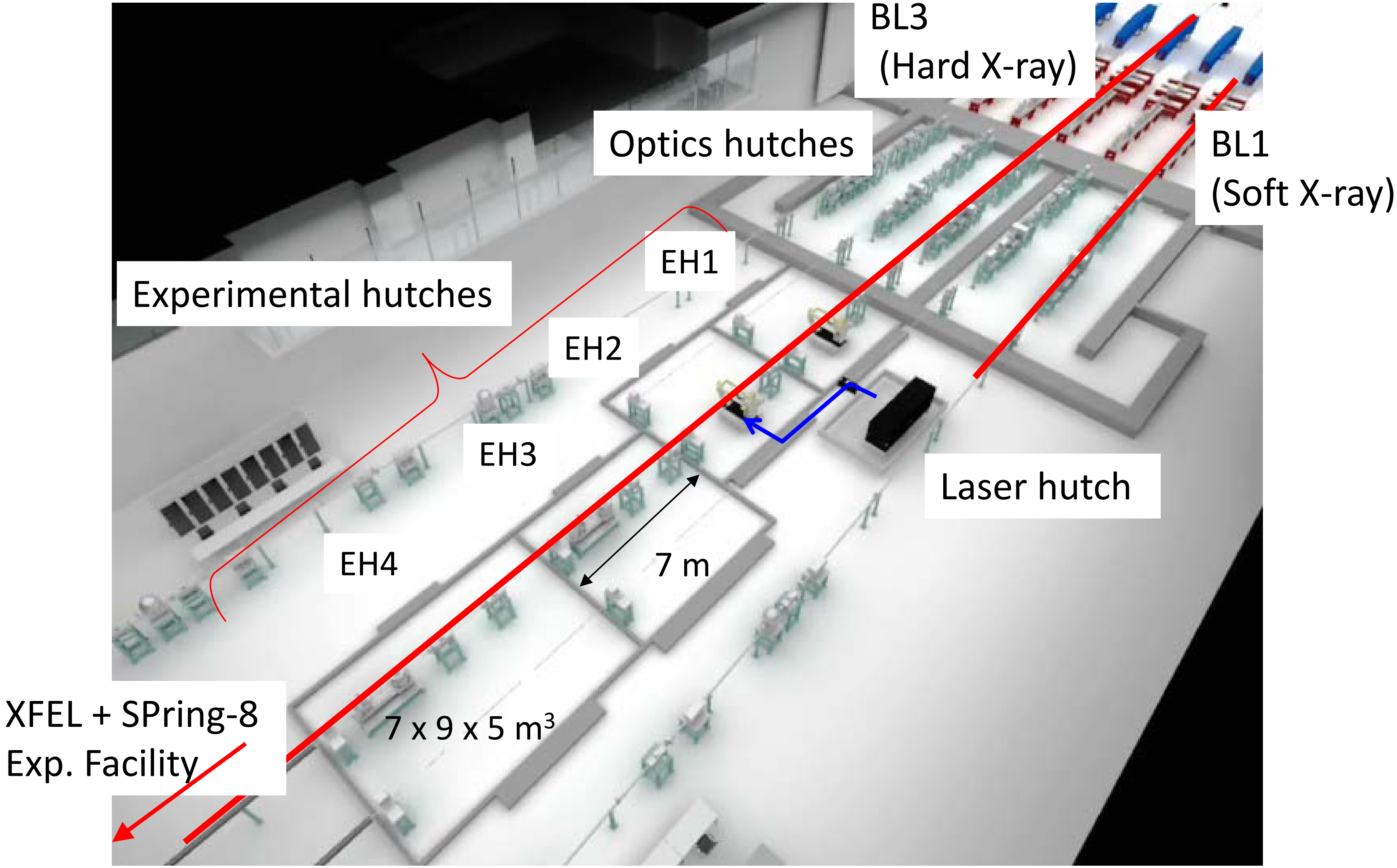
Spectrum



Shot-by-shot measurement is mandatory in photon diagnostics and experiments.

Contents

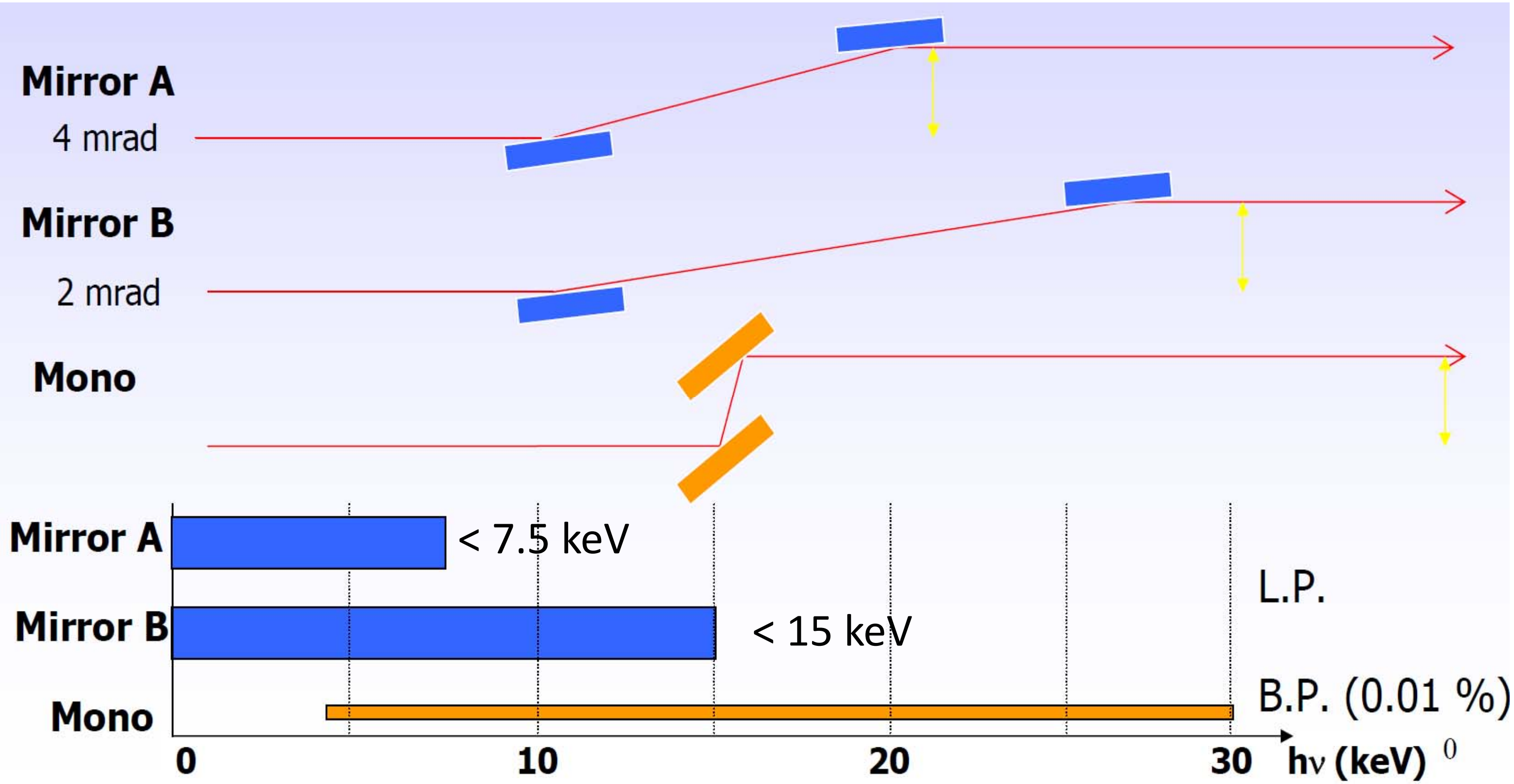
Photon beamlines of SACLA



Beamline optics

Transport XFEL & filter out unnecessary lights

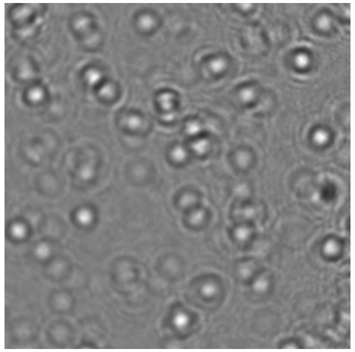
- Double plane mirrors (2 sets): Low-pass filter
- Double crystal monochromator (DCM, Si 111): Band-pass filter



Demands on optical elements

XFEL features	Demands on beamline optics
Short pulse (10 fs)	Damage free
High peak power (30 GW)	
Coherent	Speckle free

Speckles



Damage-free optics

Small atomic-number elements (Be, B, C, N, O) with small X-ray absorption coefficient

- Be windows, diamond fluorescent screens, carbon-coated mirrors, etc.

Koyama et al., Optics Express Vol.21 (2013)

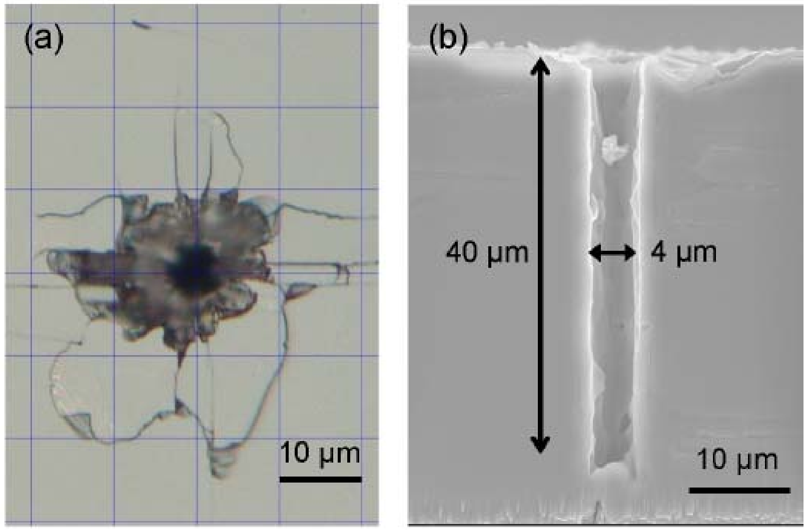
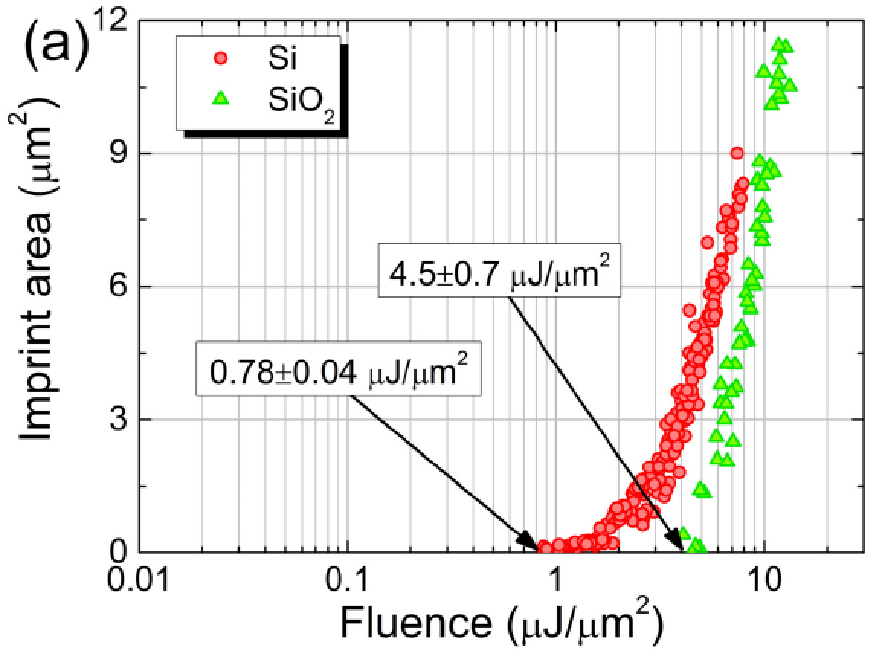


Fig. 2. (a) Optical microscope image of irradiated silicon viewed from surface at fluence of 57 $\mu J/\mu m^2$. (b) Cross sectional SEM image of (a) prepared by focused ion beam sampling.



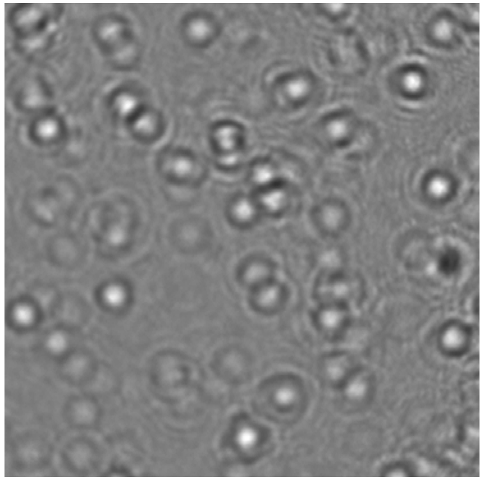
Spackle-free optics (1)

Goto et al., Proc. of SPIE Vol.6705 (2007)

Coherent-X-ray transmission images of Be x-ray windows

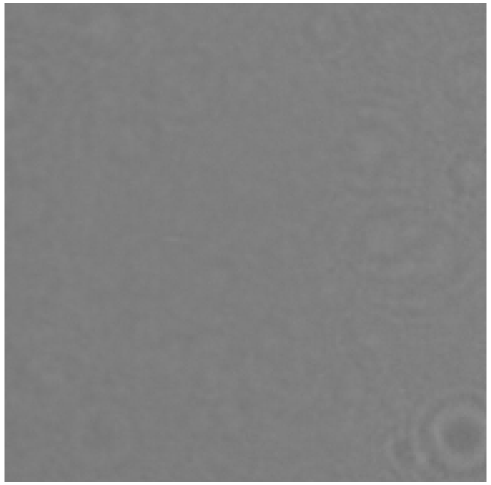
With a *rough surface* and/or *internal voids*

Speckles



With a smooth surface and uniform density

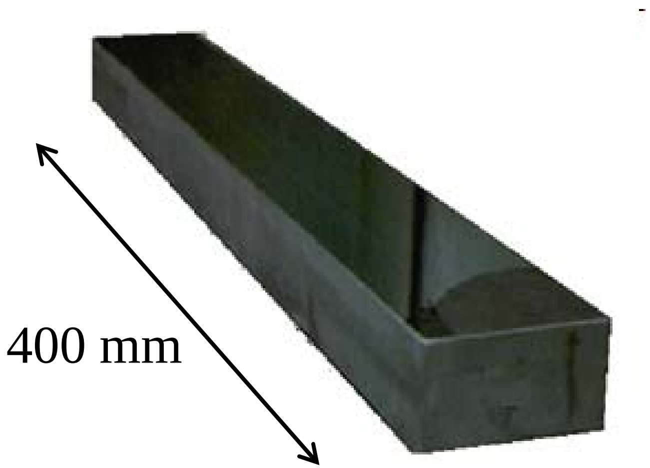
Speckle-free

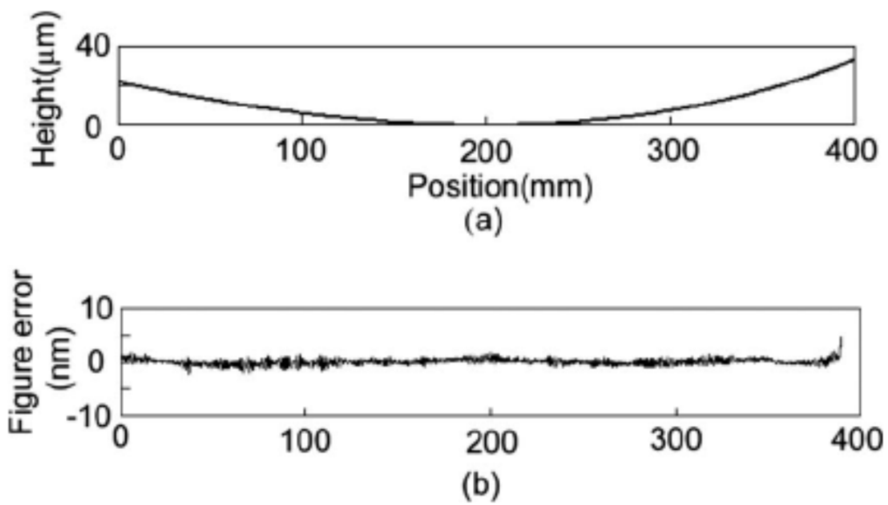


Spackle-free optics (2)

Ultraprecise x-ray mirror

Mirror surface is finished by EEM (Elastic Emission Machining)



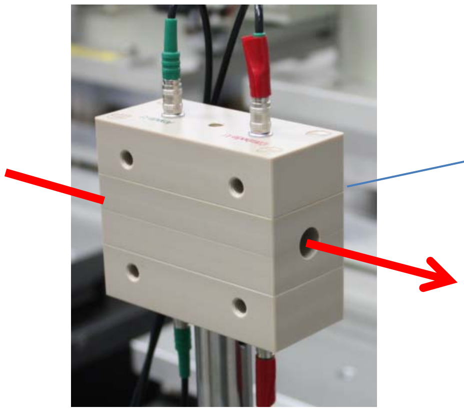


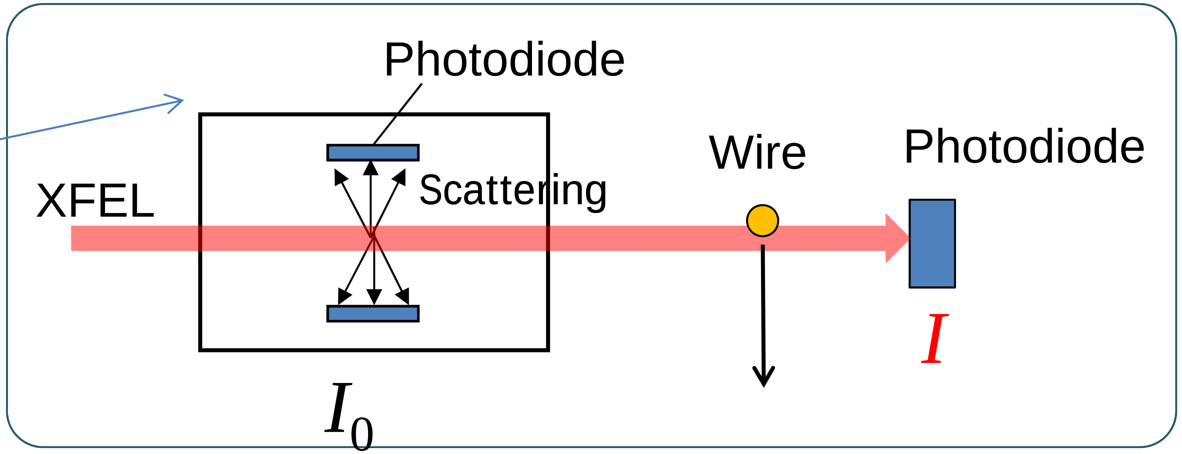
Mimura et al., Rev. Sci. Instrum. **79**, 083104 2008

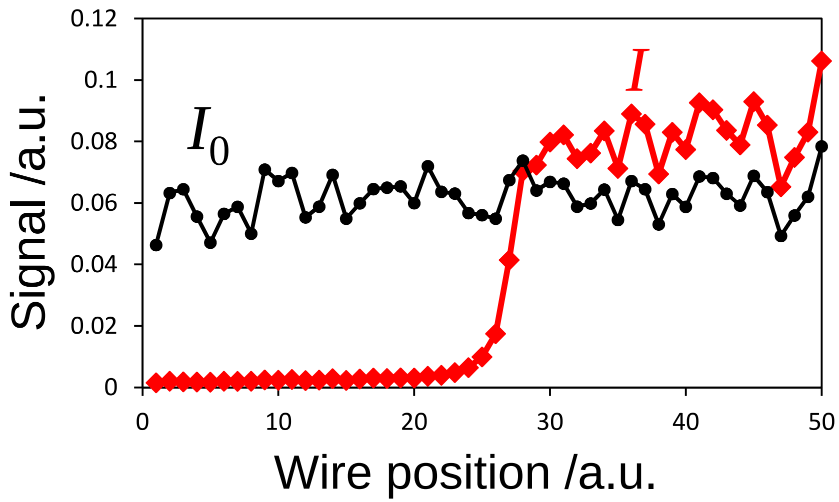
Photon diagnostics on beamline

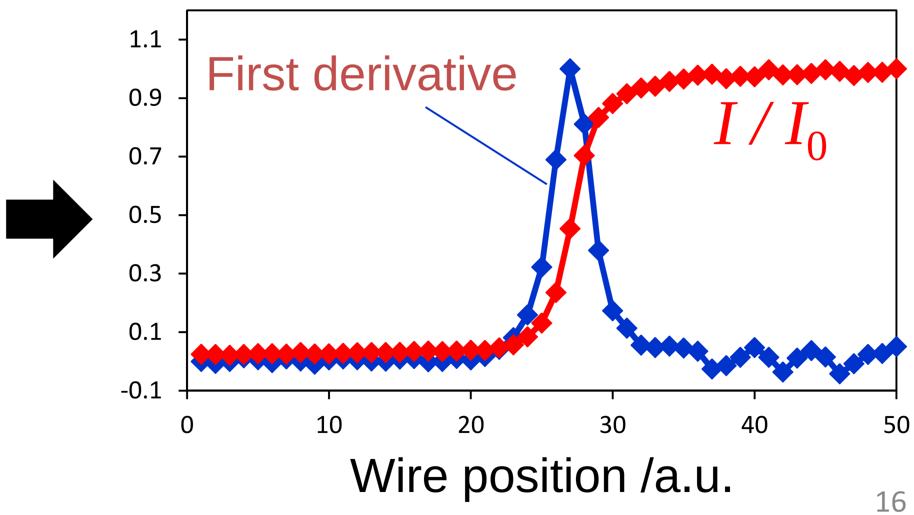
Nondestructive, shot-by-shot monitoring is mandatory.

Beam-size measurement (wire scan method)

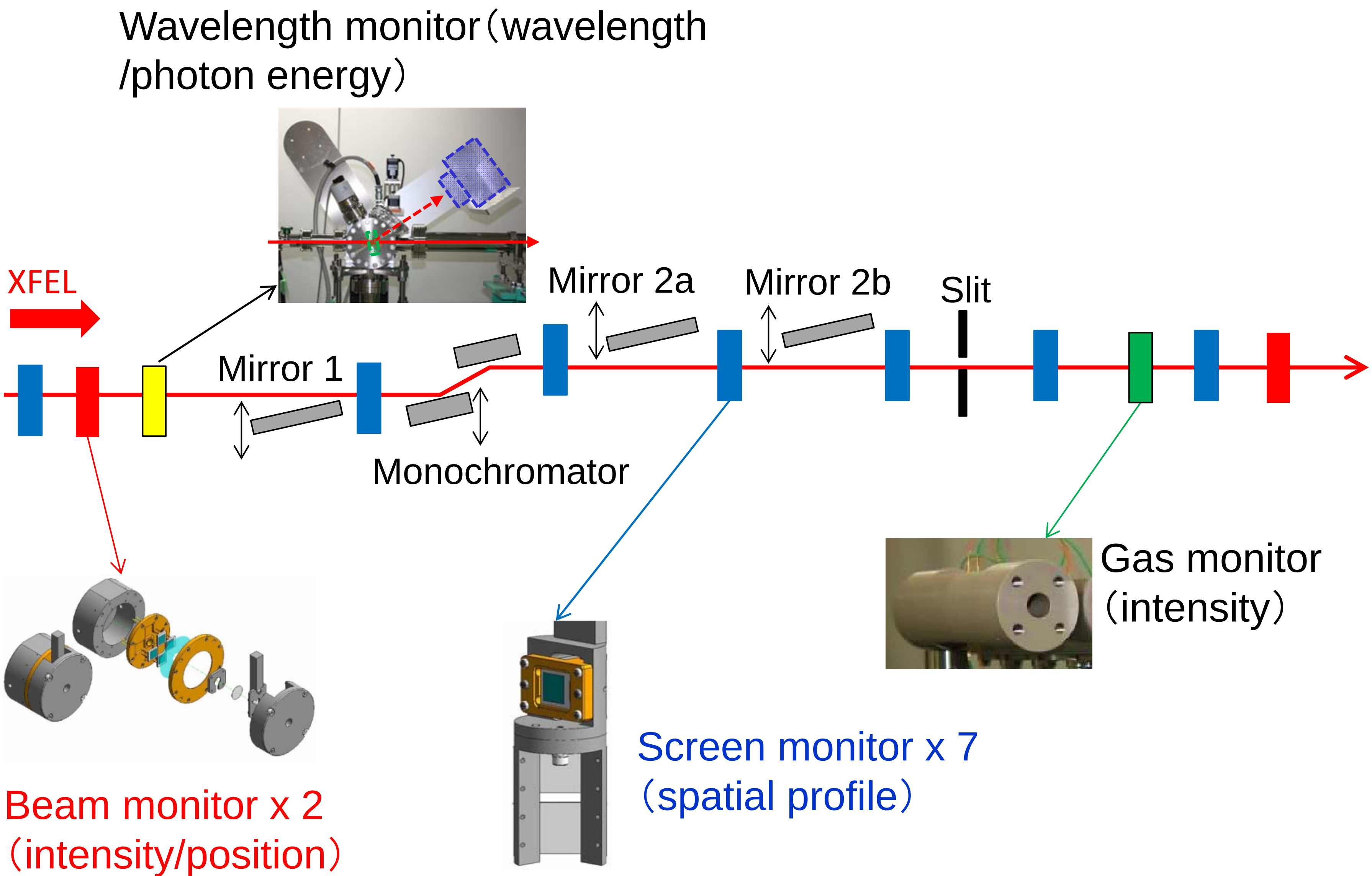








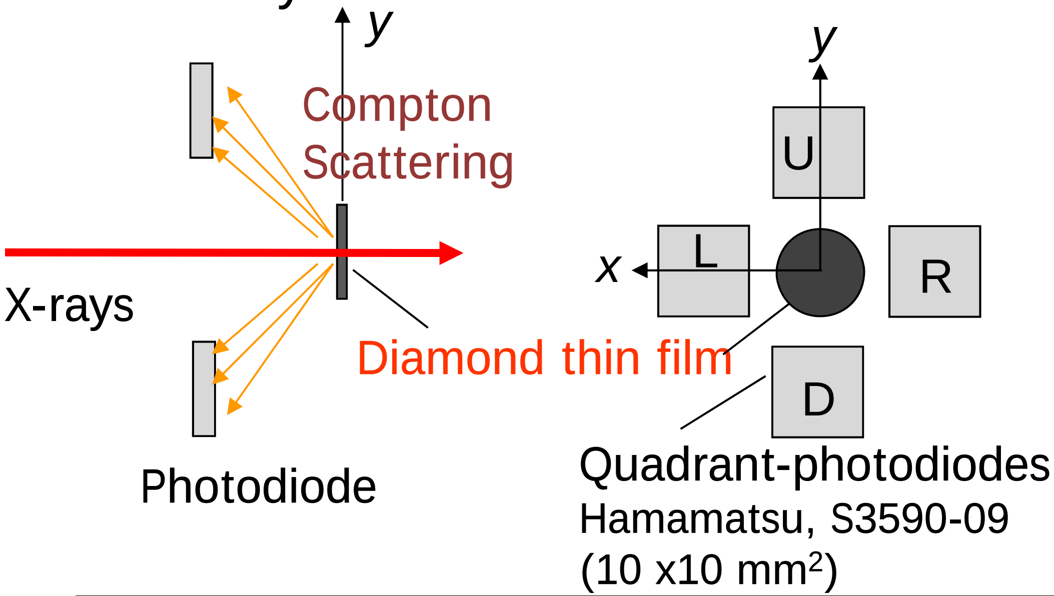
Photon diagnostics system on BL3

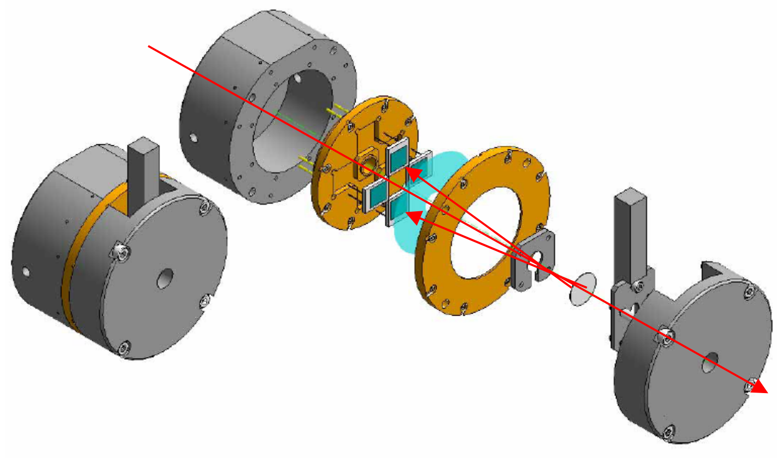


Beam monitor (intensity/position)

Geometry

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

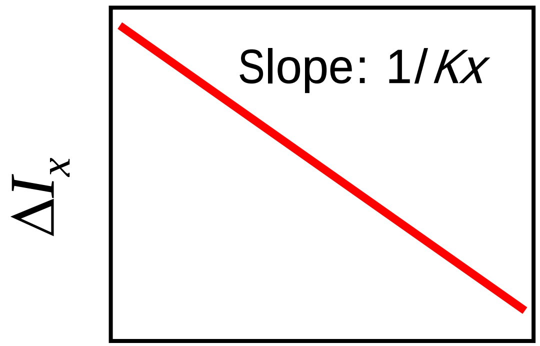




Intensity $$I \propto \left(I_L + I_R + I_U + I_D\right)$$

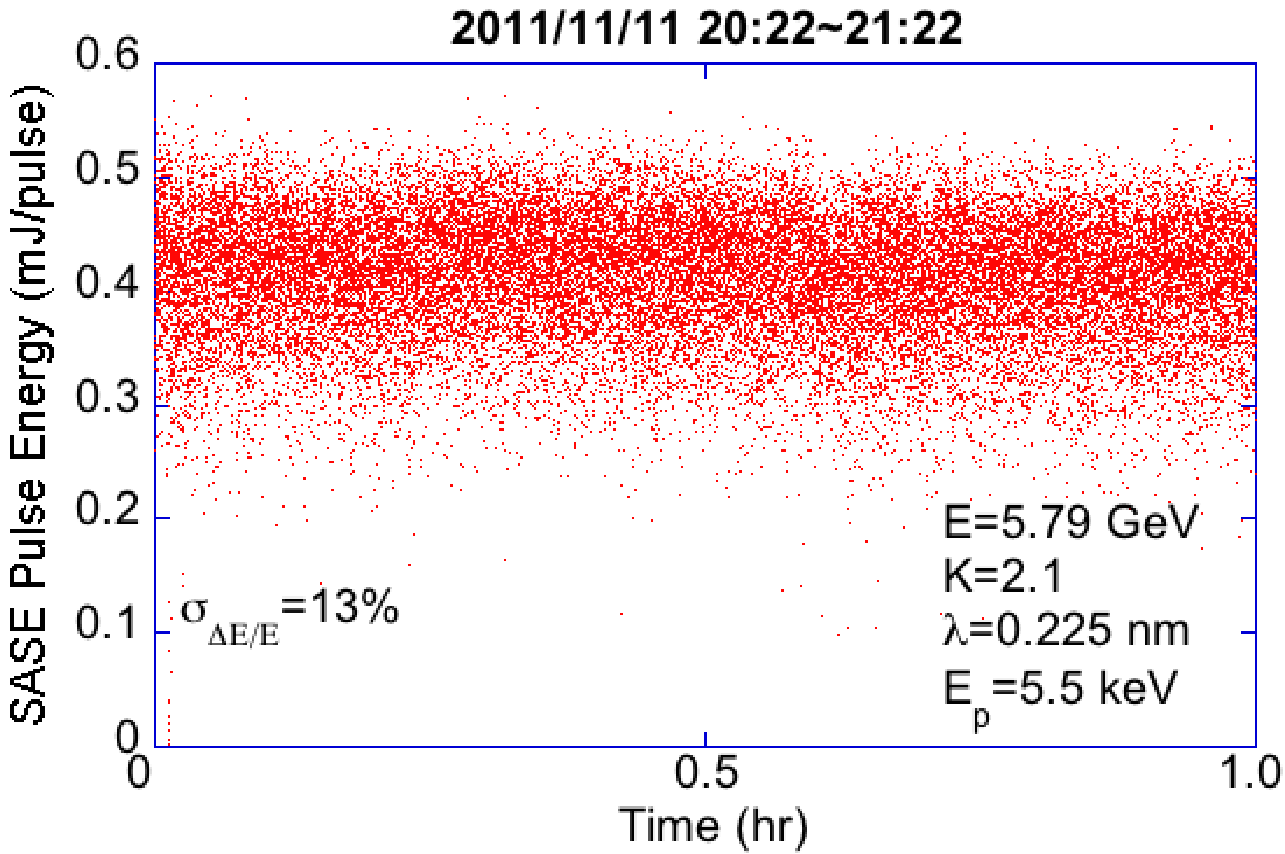
Position $$x = K_x \frac{I_\mathrm{L} - I_\mathrm{R}}{I_\mathrm{L} + I_\mathrm{R}} = K_x \Delta I_x$$

$$y = K_y \frac{I_\mathrm{U} - I_\mathrm{D}}{I_\mathrm{U} + I_\mathrm{D}} = K_y \Delta I_y$$



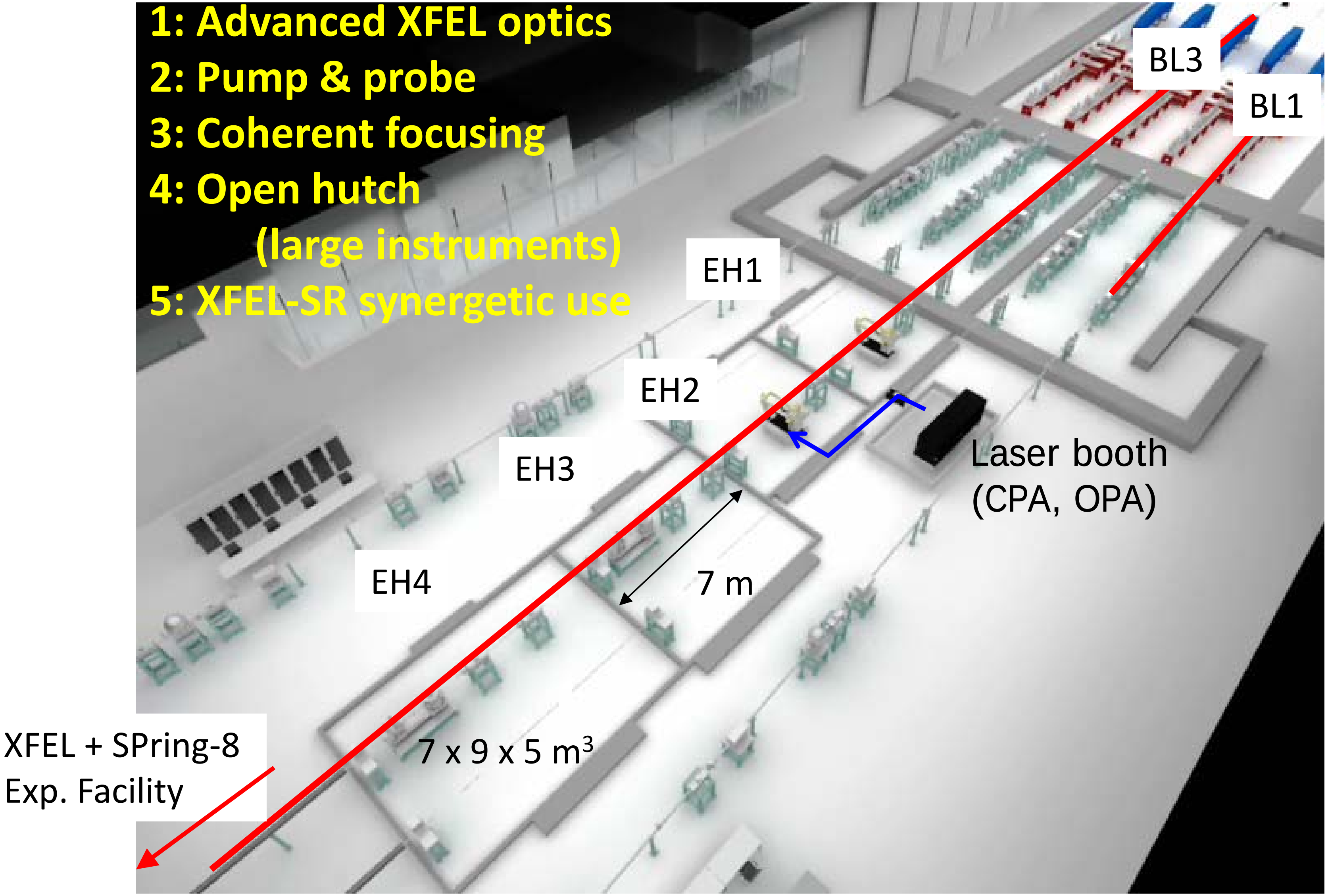
Alkire et al., *J. Syn. Rad.* 7, 61 (2000).

Shot-by-shot measurement of pulse energy



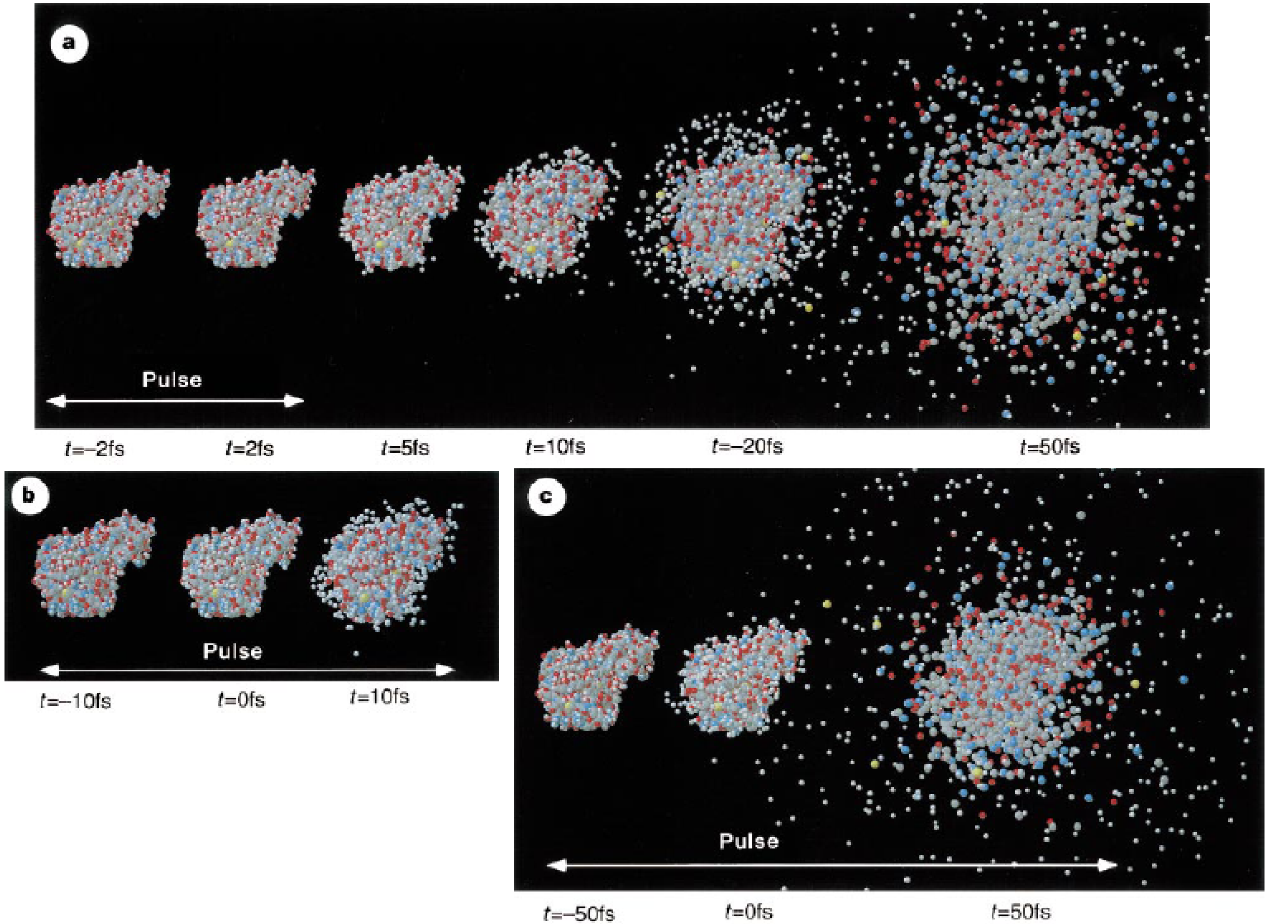
Contents

Experimental stations



Single-shot measurement is mandatory

Even a single pulse destroys a sample.



Neutze et al., Nature 406, 752 (2000)

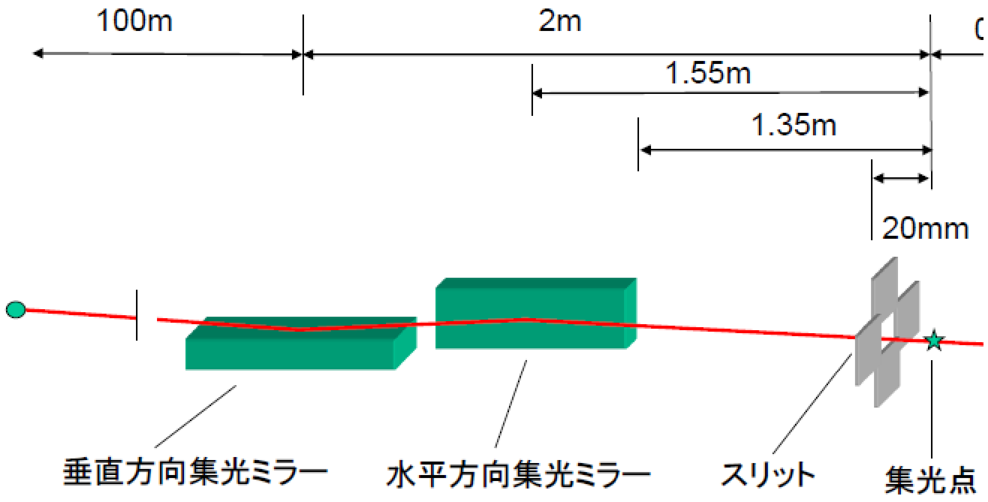
Instrumentation for single-shot measurement

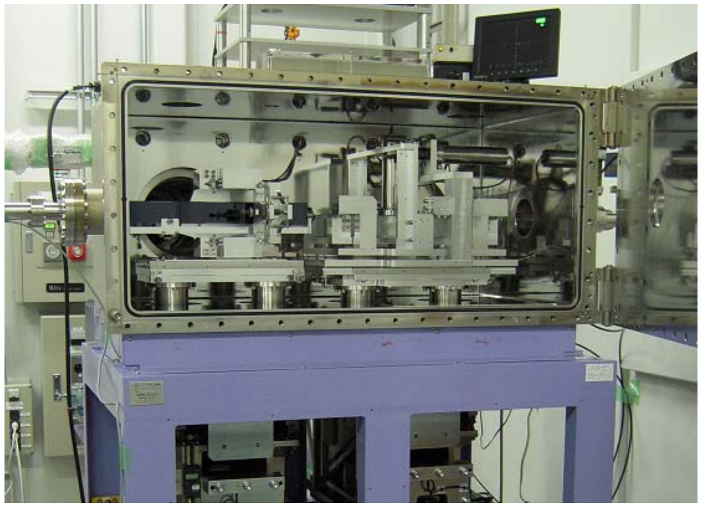
- High photon flux
  - Focusing
- Sample exchange
  - Injectors
  - Fixed targets with a fast scanning system
- Sensitive X-ray detection
  - High performance detectors
    - ✓ High sensitivity, high frame rate, high dynamic range, large area, …
- Fast & reliable data acquisition system
  - High performance computers
  - High speed network
  - Storage system
  - Software

Focusing

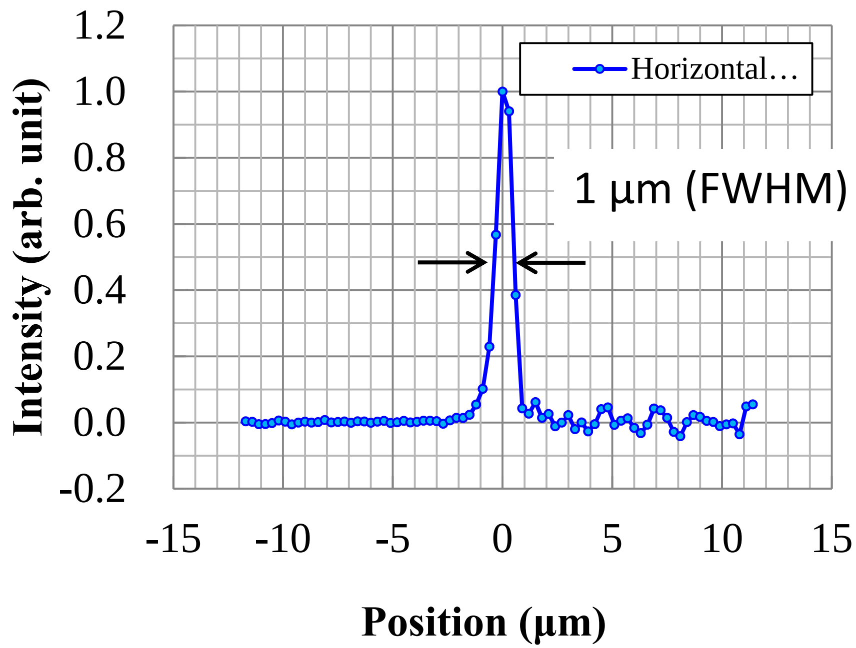
Yumoto et al., *Nat. Photon.* Vol.**7** (2013)

KB mirrors at EH3





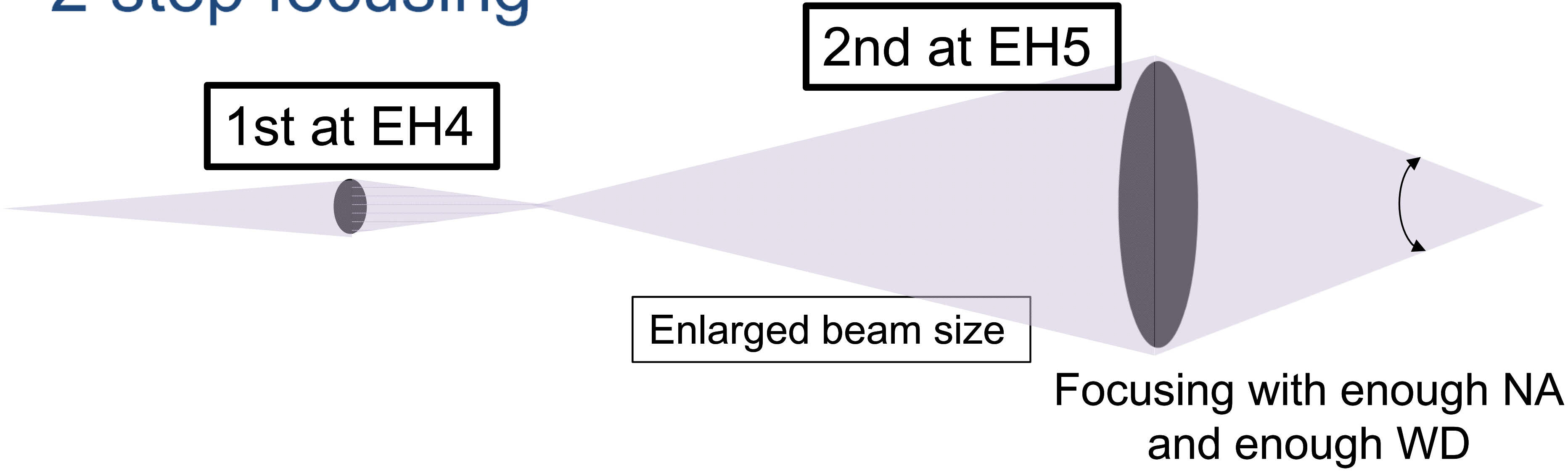
Beam profile (horizontal)

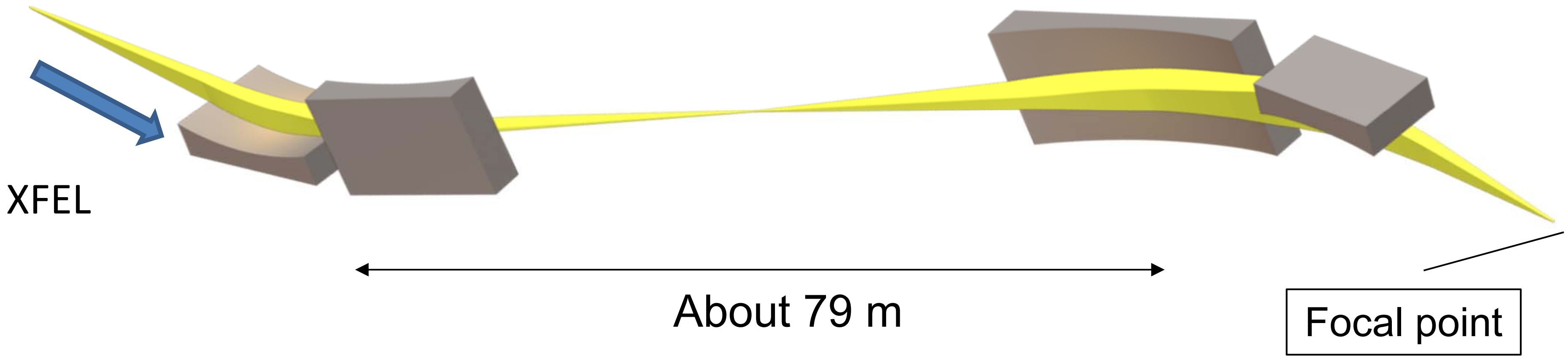


2 step focusing optics for nano-beam

Mimura (U. Tokyo)
Yamauchi et al. (Osaka U.)
Yumoto et al. (SPring-8)

2 step focusing

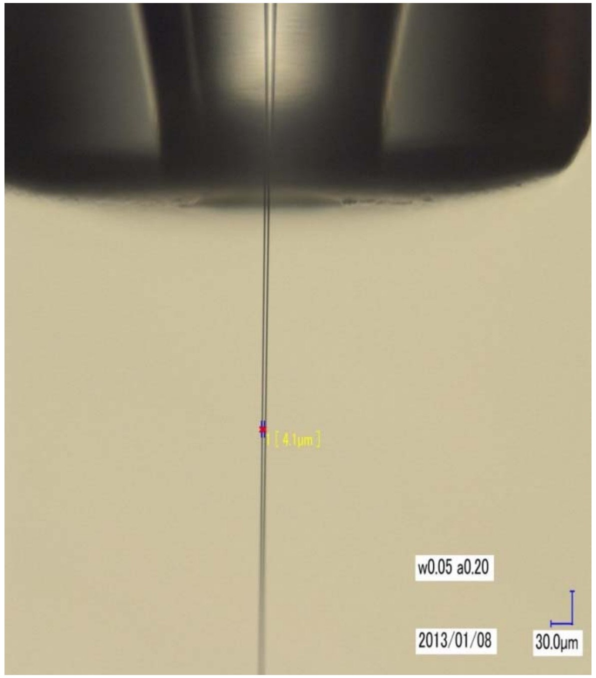




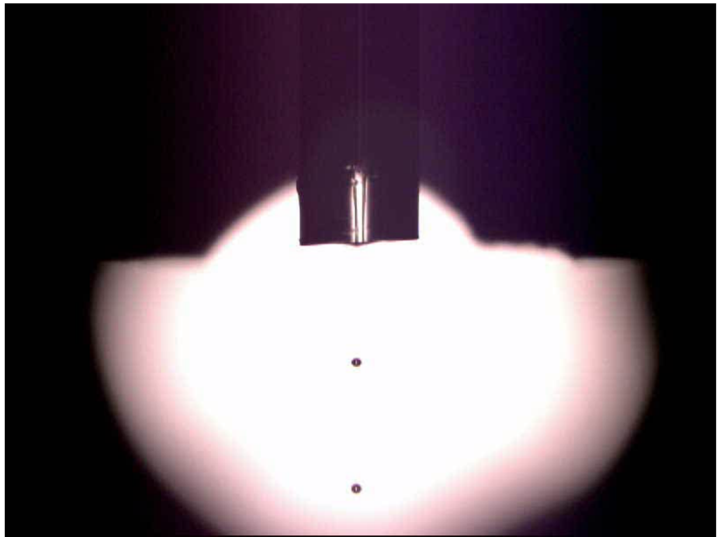
Injectors

Song (RIKEN) et al.
Mafune (U Tokyo)

Continuous beam



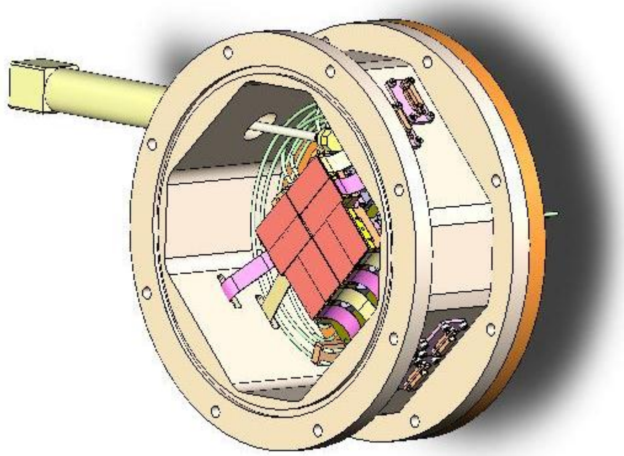
Droplets



Detector

Kameshima (JASRI)
Hatsui (RIKEN) et al.

- Multi-port CCD (MPCCD)
  - High sensitivity
  - Low noise
    - (single-photon detection capability
  - Fast (60 fps)
  - Large area（□100 mm）

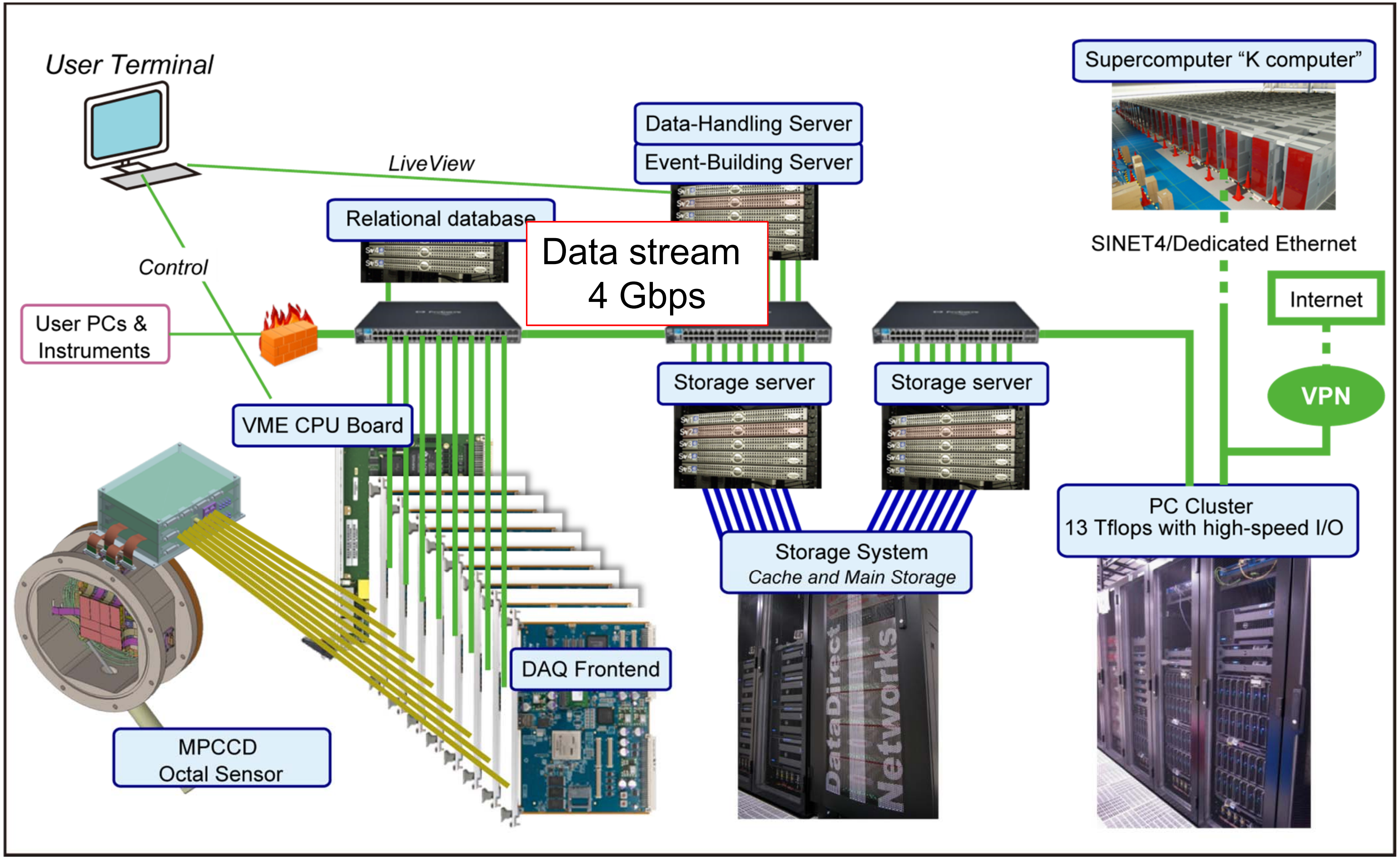


Octal Sensor Detector (100 x 100 mm)
2048 x 2048 pixels

Specification	
Frame rate	≥60 fps
Pixel size	50 μm
Noise	300e$^-$
Q.E.	~70 % @ 6 keV ~20 % @ 12 keV
Dynamic range	14 bits
System noise	< 0.2 ph.@ 6 keV
Full well	~ 3000 ph. @6keV ~ 1500 ph. @12keV

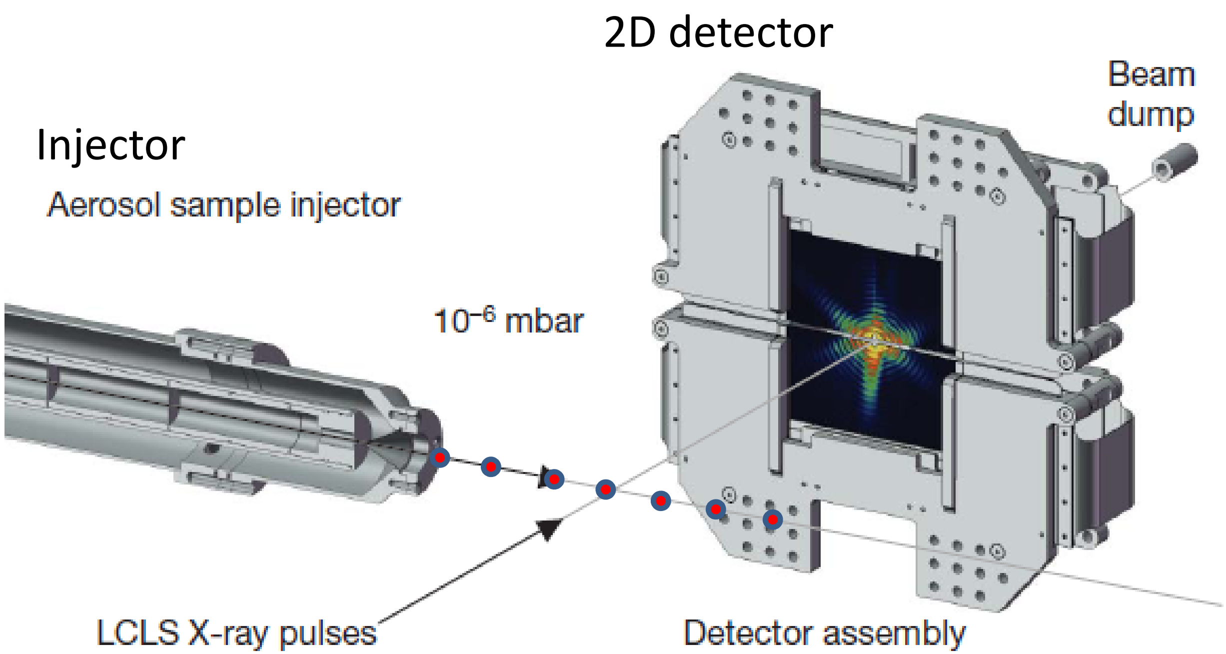
Data acquisition (DAQ)

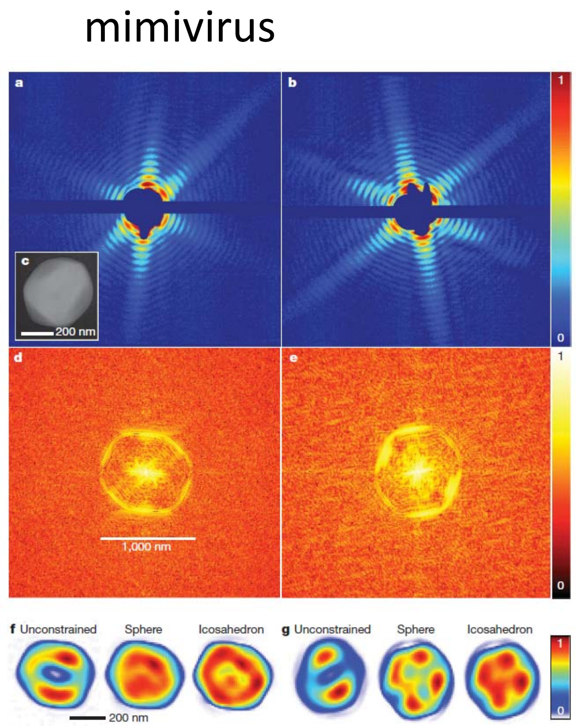
Joti, Kameshima (JASRI)
Hatsui (RIKEN) et al.



Contents

Typical experiment at SACLA (1): Coherent diffraction imaging (CDI)



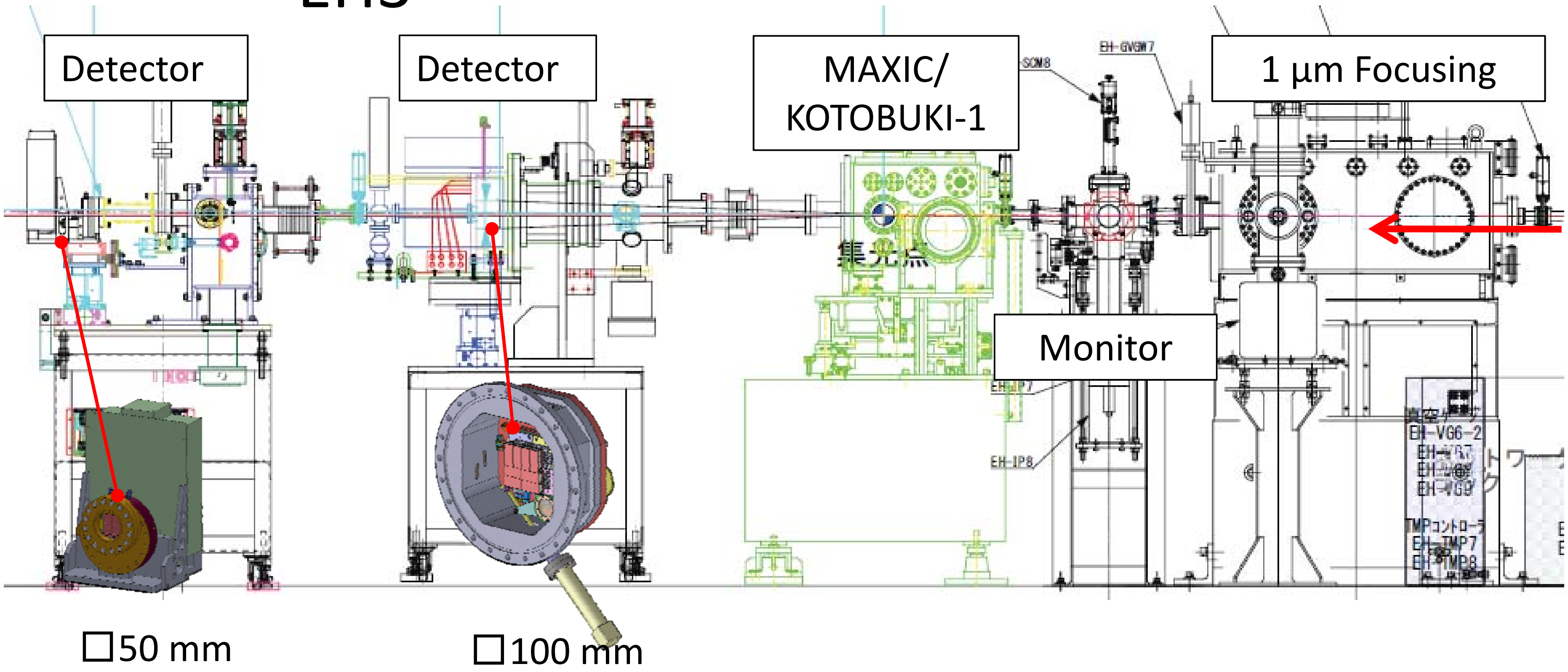


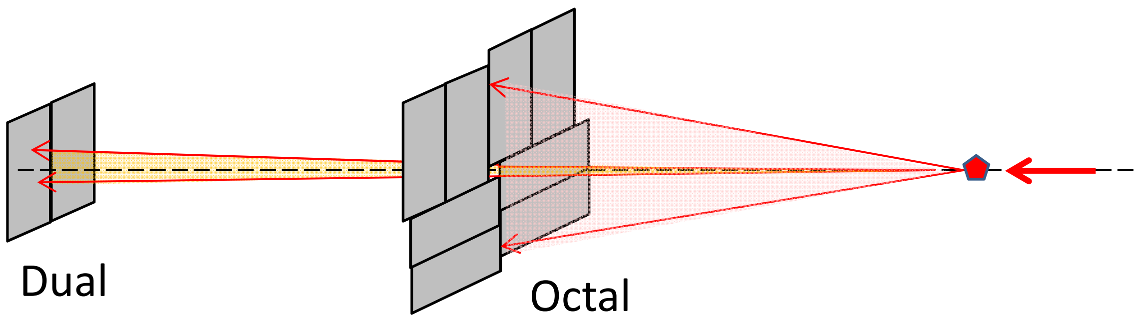
Seibert et al., *Nature* 470, 78 (2011)

CDI experiment at SACLA

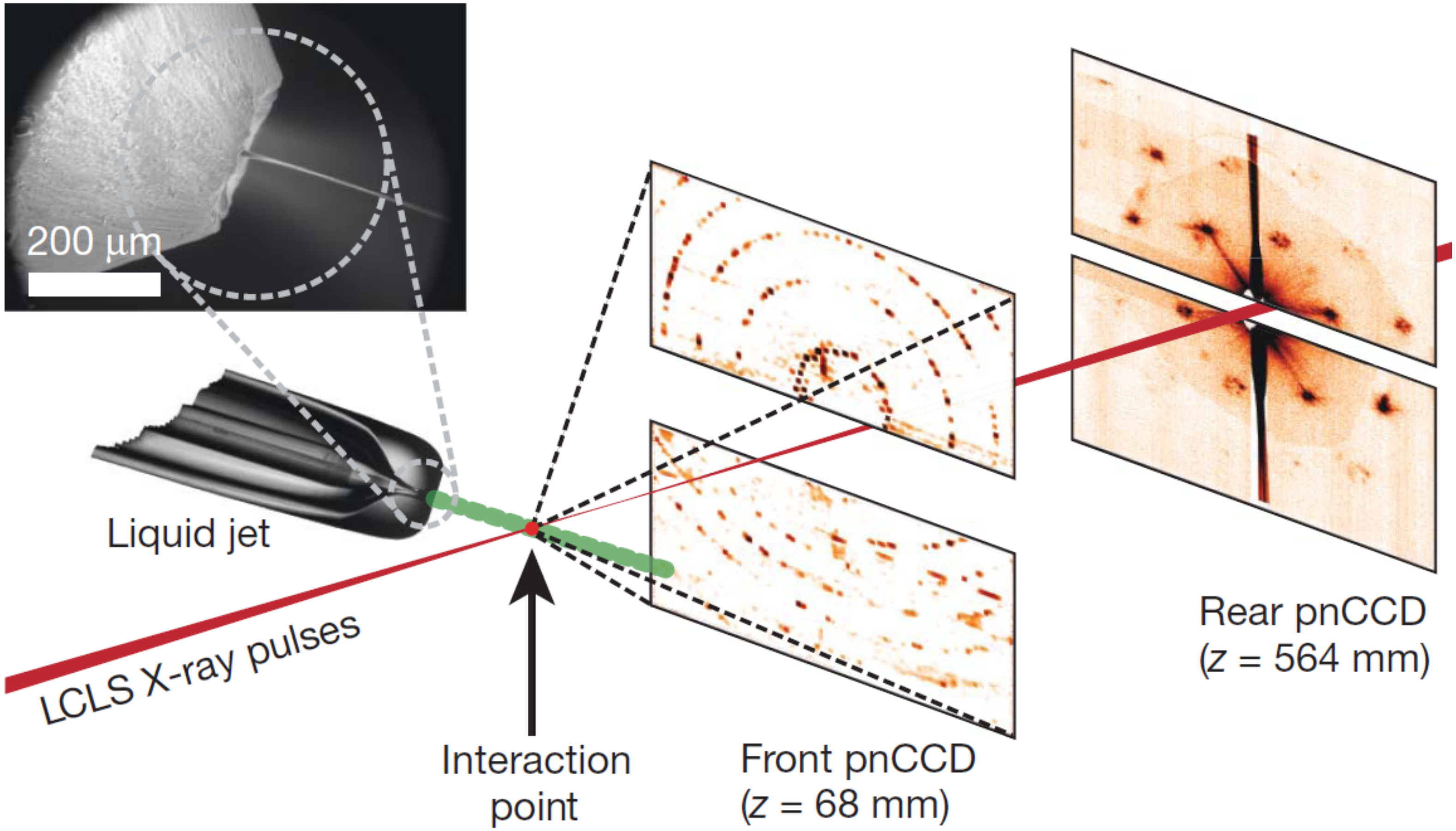
Nakasako (Keio U) et al., Rev. Sci. Instrum. in press (2013)
Song (RIKEN) et al.

EH3





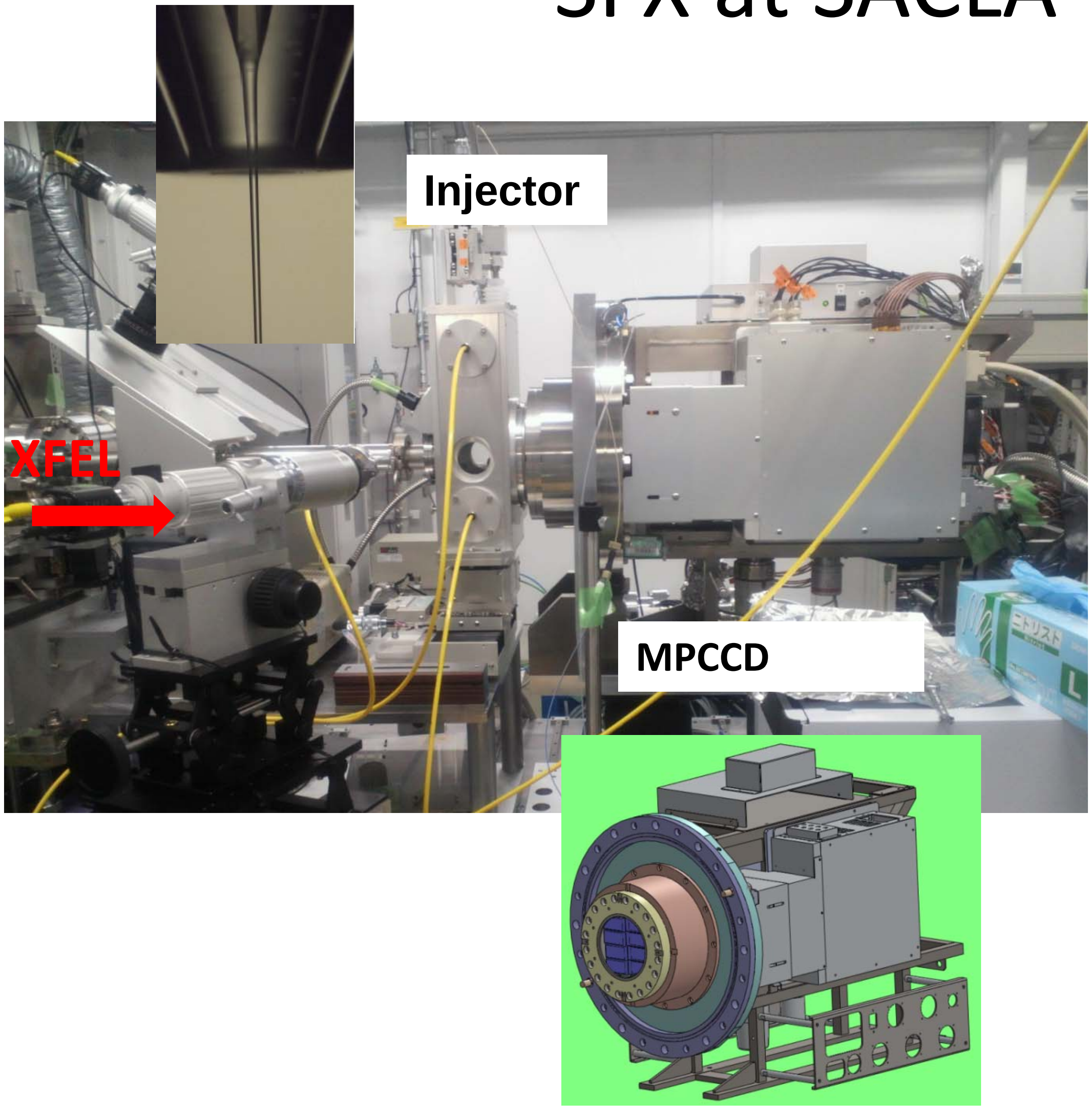
Typical experiment at SACLA (2): Serial femtosecond crystallography (SFX)

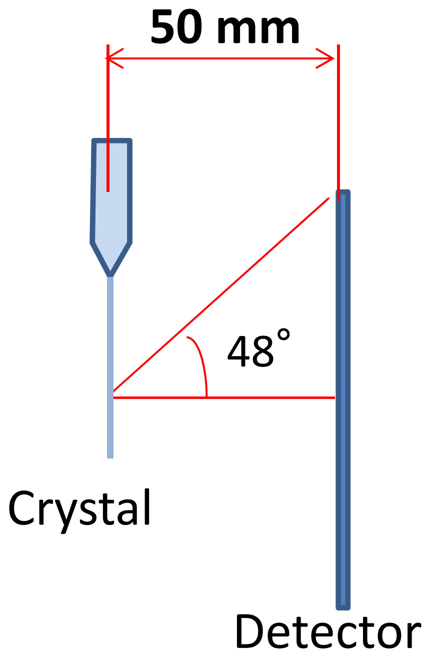


Chapman et al., *Nature* 470, 73 (2011)

SFX at SACLA

Iwata (RIKEN) et al.





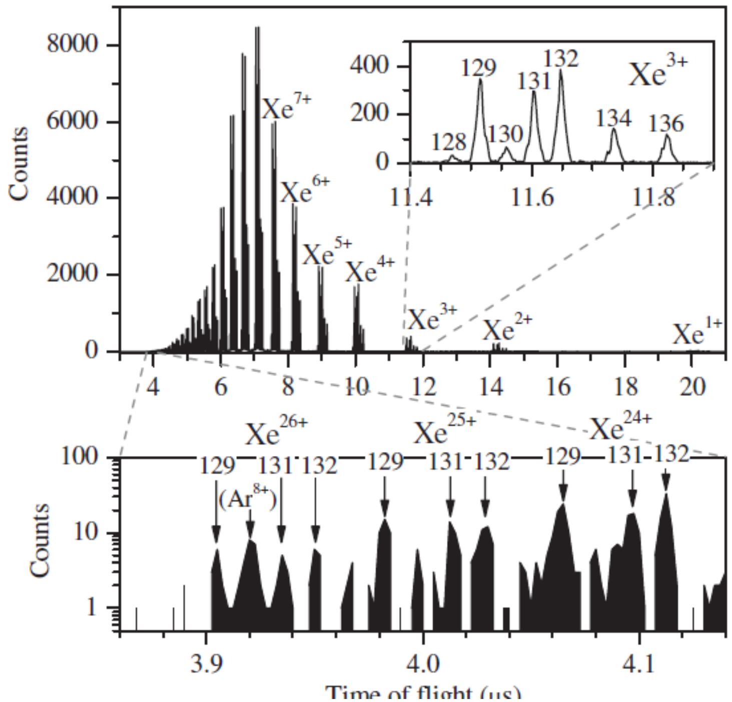
High fluence application: Multiphoton ionization of Xe

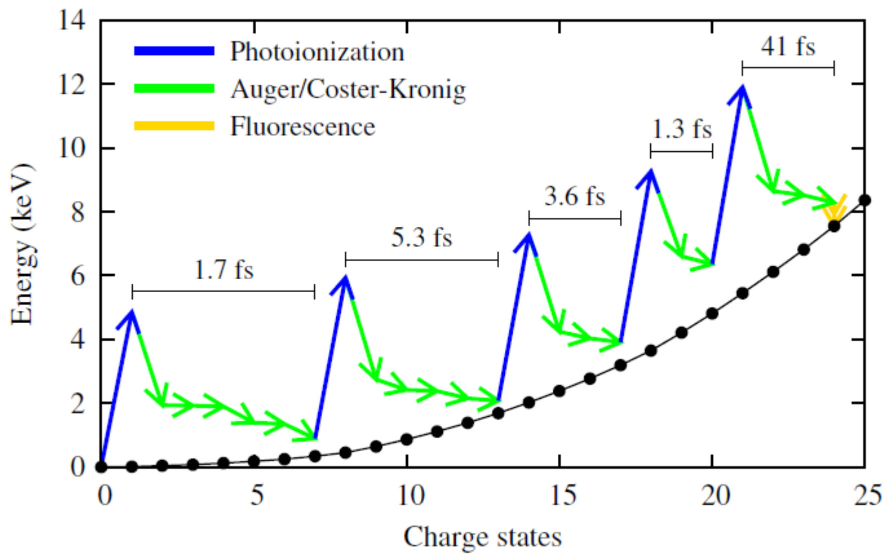
~50 uJ/um^2
@5.5 keV

PRL **110**, 173005 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

Deep Inner-Shell Multiphoton Ionization by Intense X-Ray Free-Electron Laser Pulses

H. Fukuzawa,[1,2] S.-K. Son,[3] K. Motomura,[1] S. Mondal,[1] K. Nagaya,[2,4] S. Wada,[2,5] X.-J. Liu,[6] R. Feifel,[7] T. Tachibana,[1] Y. Ito,[1] M. Kimura,[1] T. Sakai,[4] K. Matsunami,[4] H. Hayashita,[5] J. Kajikawa,[5] P. Johnsson,[8] M. Siano,[9] E. Kukk,[10] B. Rudek,[11,12] B. Erk,[11,12] L. Foucar,[11,13] E. Robert,[6] C. Miron,[6] K. Tono,[14] Y. Inubushi,[2] T. Hatsui,[2] M. Yabashi,[2] M. Yao,[4] R. Santra,[3,15,*] and K. Ueda[1,2,†]



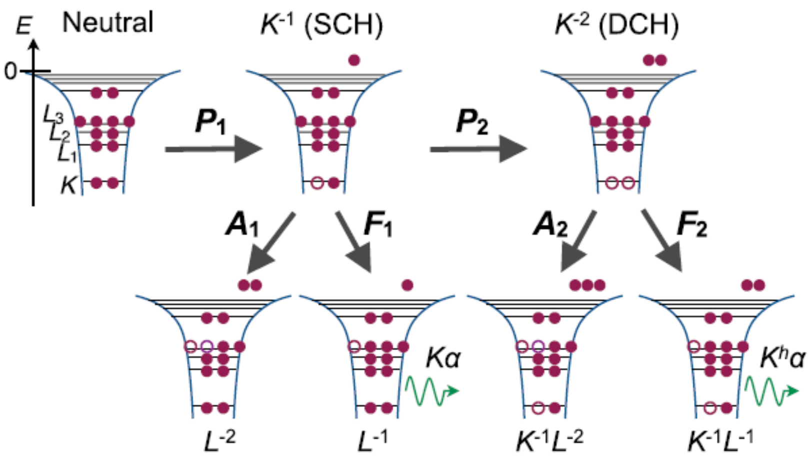


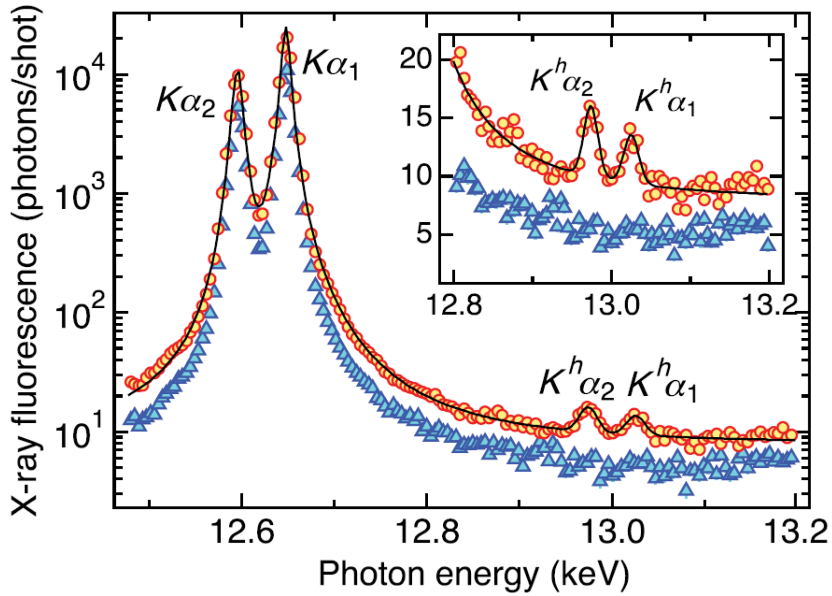
Non linear X-ray optics
Emission from double core hole state

K. Tamasaku et al, PRL Vol.111 (2013)

- 100 uJ/10 fs = 10 GW (after 1-μm KB)
- Focusing size: ~1x1 μm^2
- 10 GW/(1 μm)^2~ 10^{18} W/cm^2

Double core hole of Kr





And more

- Pump-probe experiments
  - X-ray diffraction/scattering
  - X-ray absorption/emission spectroscopy
  - Photoelectron spectroscopy
- X-ray nonlinear optics
- X-ray photon correlation spectroscopy

Summary

- Novel properties and sciences of XFEL
  - Ultra-brilliant, ultra-short, and coherent
  - Beyond static, statistical, perturbative pictures

- Beamline for XFEL
  - Damage-free & speckle-free optics
  - Single-shot, nondestructive diagnostics

- Experimental instrumentation for single-shot measurement
  - focusing optics, sample injectors, detectors, femtosecond laser

- Experiments at SACLA
  - Femtosecond snapshots of samples
  - X-ray-matter interaction under ultra-high photon flux
  - Pump-probe measurement