FEL13

SPring-8 Angstrom Compact free-electron LAser

Beamline Instrumentation for Precise Characterization of X-ray FELs

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August 27, 2013 @New York

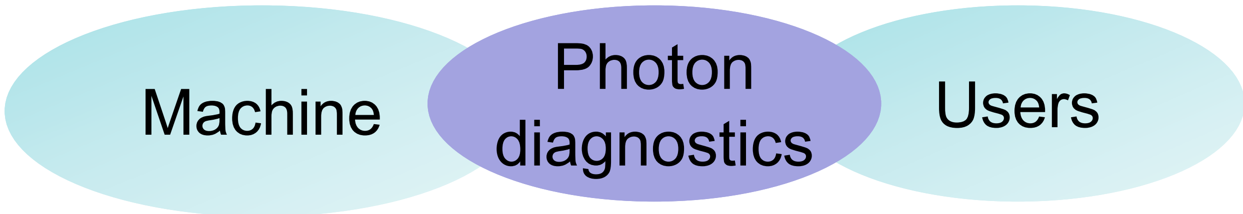
Contents

Why are photon diagnostics important for XFEL facilities ?

- Photon beam is a final product of XFEL source to user experiments
  - e.g. studies on X-ray nonlinear interactions

$$Peak\ Power\ (W/cm^2) \sim \frac{Pulse\ energy}{(Pulse\ duration)(Beam\ size)}$$

- Photon beam contains a number of key information for machine operation
  - could be more accurate and robust than electrons
- Photon diagnostics become strong linkage between machine and users

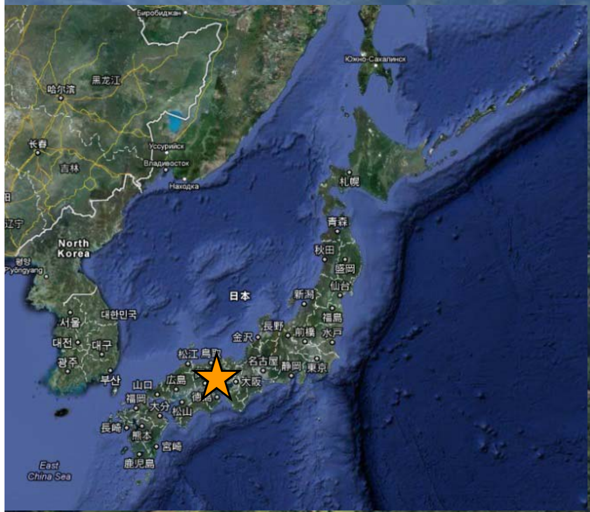


Objective

1. X-ray beam profiles in 6-D phase space
   - Total photon number (pulse energy)
   - Spatial profile, centroid
   - Wavefront/Angular divergence
   - Spectrum
   - Temporal profile
   - Arrival timing to external laser
   - Polarization
2. Key
   - Shot-to-shot (non-average)
   - Nondestructive (for users)
   - Wide dynamic range (spontaneous to fully saturated x-rays)

Introduce experiences at SACLA

SACLA @SPring-8

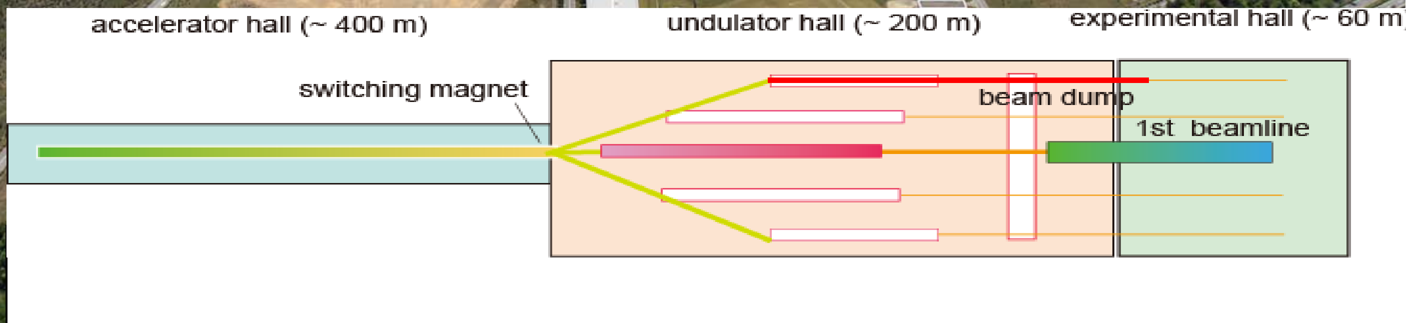


Compact XFEL

Construction: FY2006~2010

First lasing: June 2011

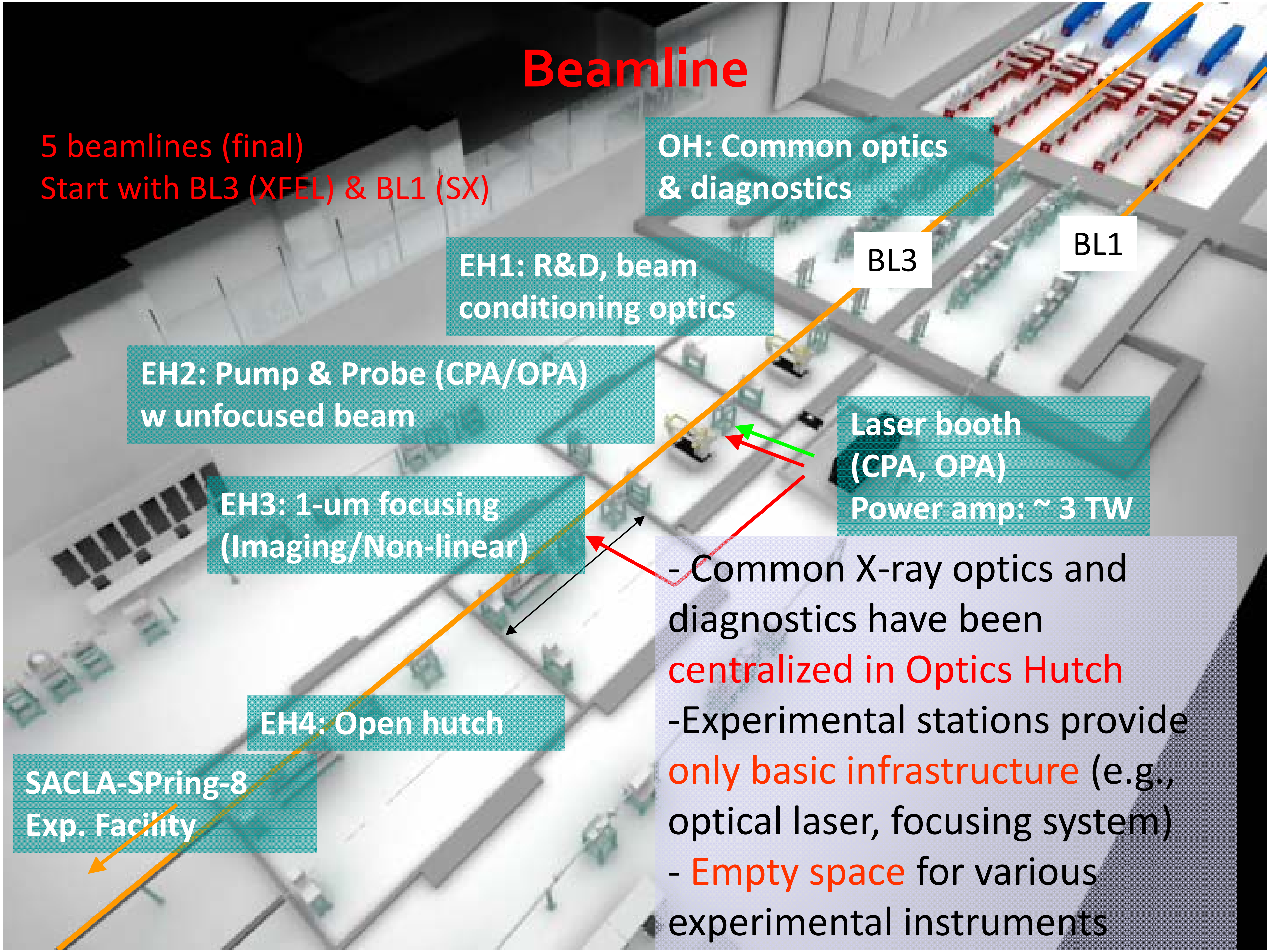
User Operation: **March 2012~**



Experimental Building

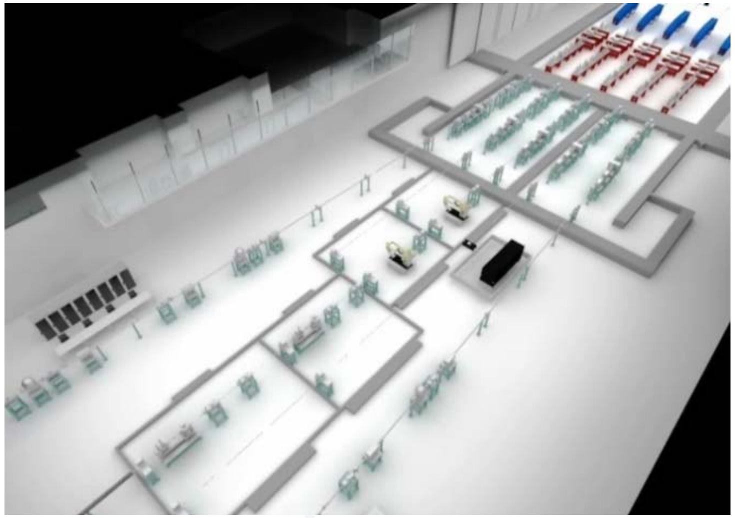
Beamline

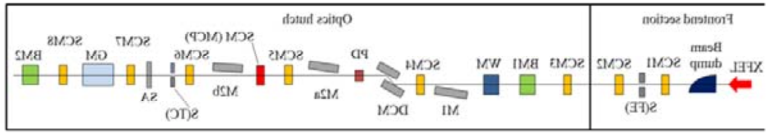
5 beamlines (final)
Start with BL3 (XFEL) & BL1 (SX)

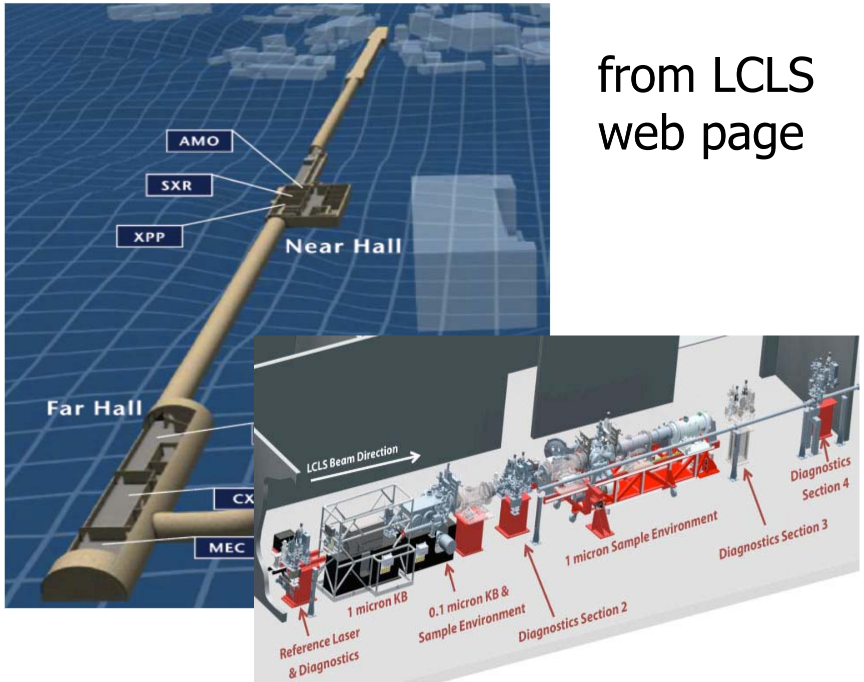


- Common X-ray optics and diagnostics have been centralized in Optics Hutch
-Experimental stations provide only basic infrastructure (e.g., optical laser, focusing system)
- Empty space for various experimental instruments

Comparison of BL design concept: SACLA vs. LCLS





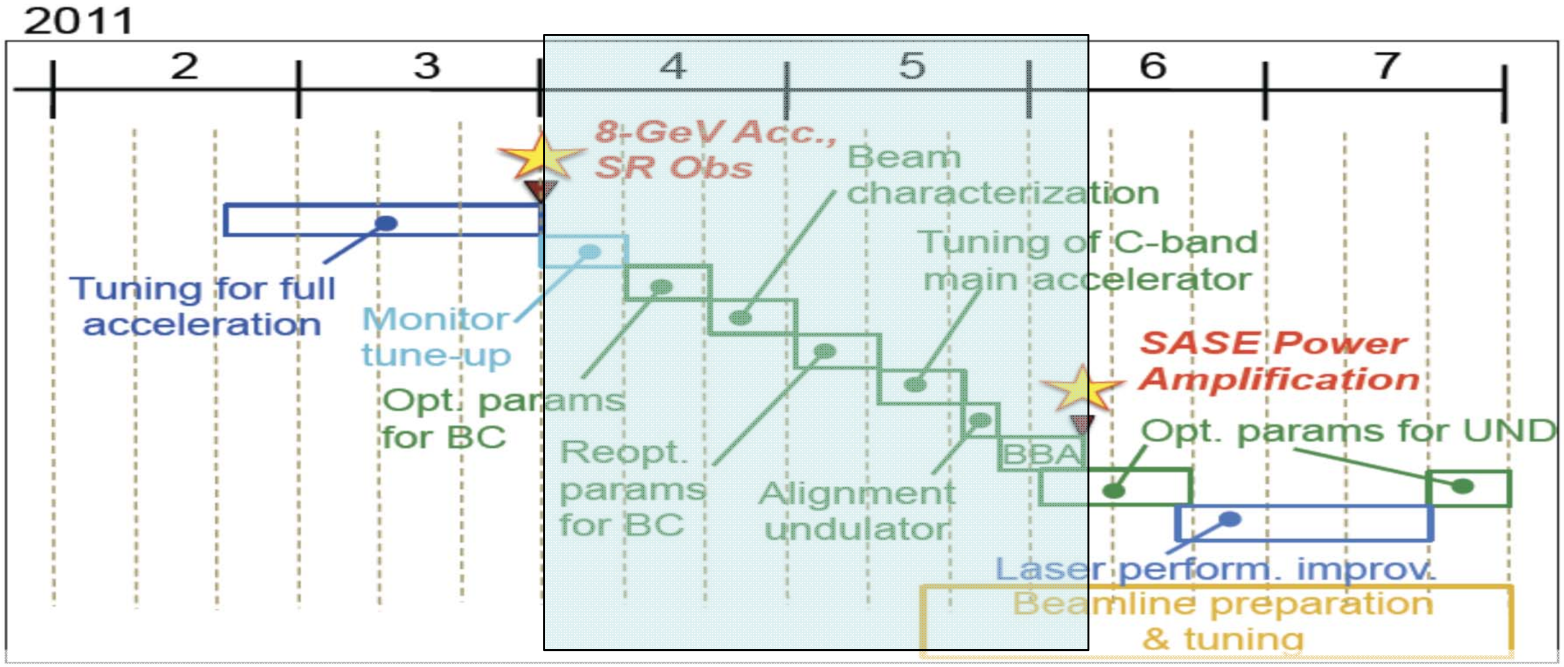


from LCLS web page

- Brand-new machine with unknown electron-beam properties
- Mitigate risks by introducing photon diagnostics
- Utilize X-ray diagnostics in optics hutch for both machine and users

- Machine can operate with matured e-diagnostics
- X-ray optics & diagnostics are located in every experimental hutch (only for users)

Example: Commissioning of SACLA



X-ray beamline (optics and photon diagnostics) played a key role for enabling quick lasing in two months

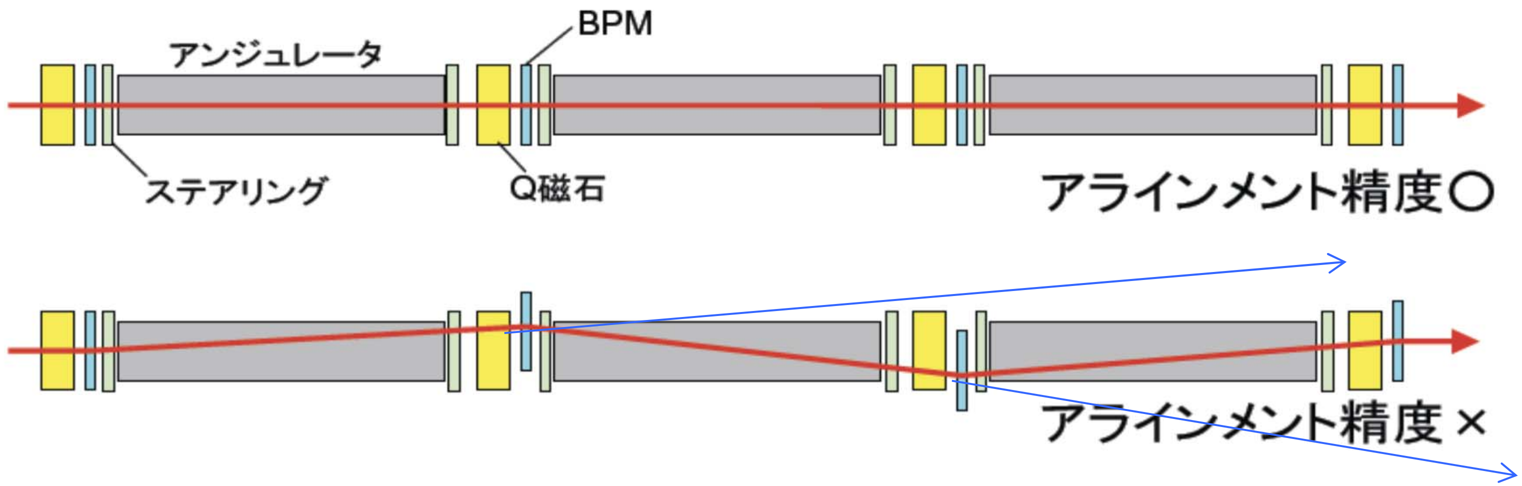
nature photonics
LETTERS
PUBLISHED ONLINE: 24 JUNE 2012 | DOI: 10.1038/NPHOTON.2012.141

A compact X-ray free-electron laser emitting in the sub-ångström region

Hitoshi Tanaka and Makina Yabashi *et al.**

Nat. Photon **6**, 540 (2012)

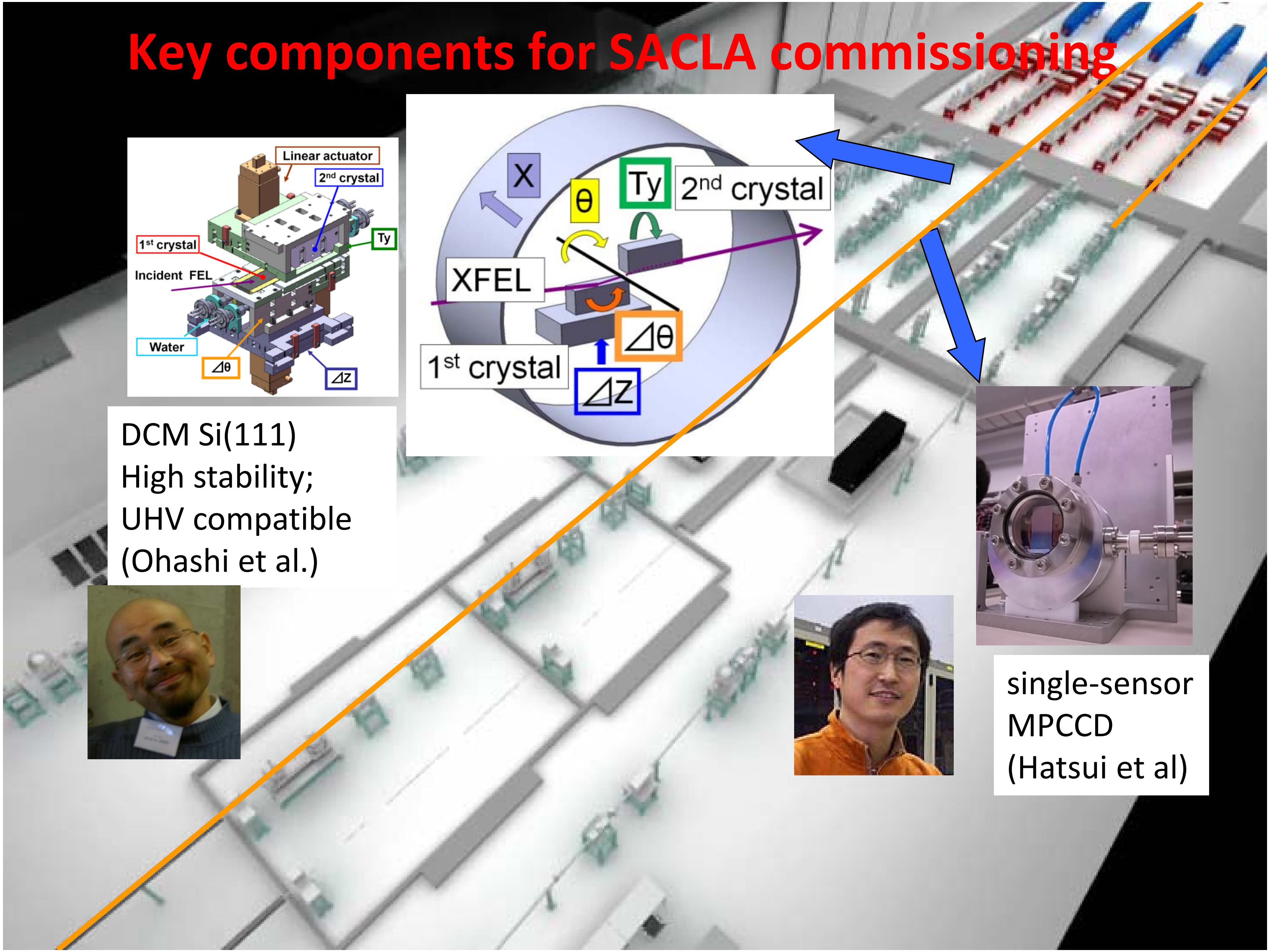
Precise ID tuning using beamline optics/diagnostics



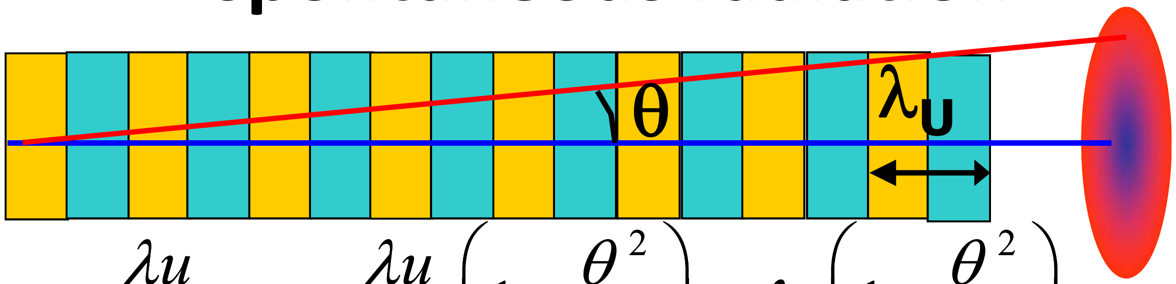
- Overlap between e- and p-beam with an accuracy of ~urad is required
- E-beam trajectory easily bends at the edges of undulator modules
- P-beam goes through along the e-beam in the undulator
- P-beam can be used to monitor the e-beam trajectory in each undulator module

Cf. central cone of the undulator radiation

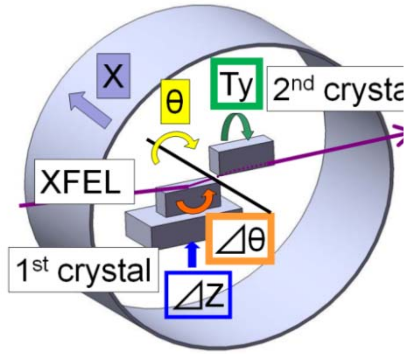
1/g= 1/16000 = 60 urad for 8 GeV

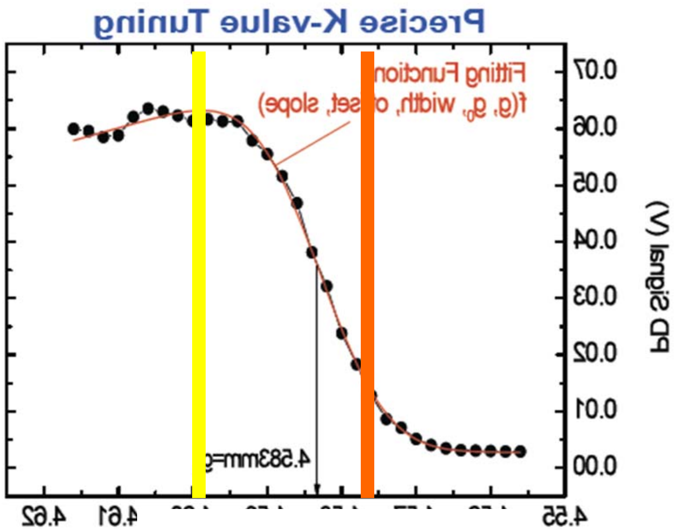

Key components for SACLA commissioning
Linear actuator
2nd crystal
1st crystal
Ty
Incident FEL
Water
⊿θ
⊿z
X
θ
Ty
2nd crystal
XFEL
1st crystal
⊿θ
⊿Z
DCM Si(111)
High stability;
UHV compatible
(Ohashi et al.)
single-sensor
MPCCD
(Hatsui et al)

Spatial profile of monochromatic spontaneous radiation



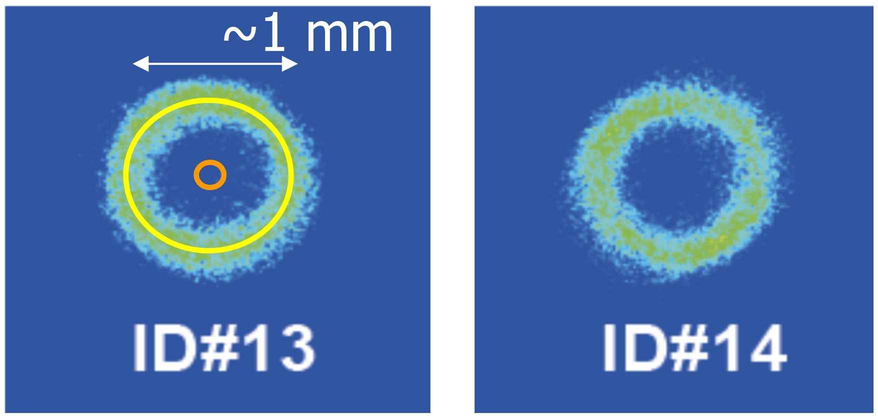
$$\lambda = \frac{\lambda u}{2\gamma^2 \cos\theta} = \frac{\lambda u}{2\gamma^2}\left(1+\frac{\theta^2}{2}\right) = \lambda_R\left(1+\frac{\theta^2}{2}\right)$$





Photon energy

rofile of monochromatic spontaneous rad



Angular diameter: ~10 urad
Centroid: 1 urad

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 110701 (2012)

Undulator commissioning by characterization of radiation in x-ray free electron lasers

Takashi Tanaka,* Shunji Goto, Toru Hara, Takaki Hatsui, Haruhiko Ohashi, Kazuaki Togawa, Makina Yabashi, and Hitoshi Tanaka

T. Takashi et al
PRST 12

SACLA: Summary of Performance

Pulse Energy	0.4 mJ @10 keV
Photon energy range	4.5 to 15 keV
Stability Intensity $\sigma_{\delta I/I}$	$\leq$ 10%
Pointing	3 ~7% of beam size
Repetition rate	20 Hz (Max. 60 Hz)

Contents

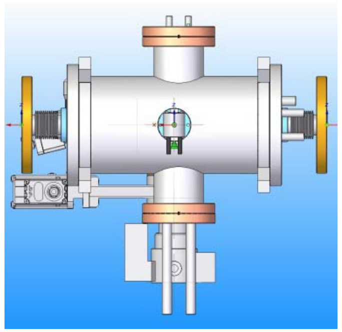
1. Introduction
2. Photon diagnostics (I): pulse energy & transverse phase space
3. Photon diagnostics (II): longitudinal phase space
4. Summary

Pulse energy measurement

Pulse-to-pulse, wide dynamic range w/o saturation

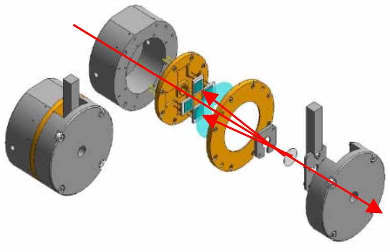
Ion chamber using gas ionization

○semi-transparent in wide wavelength range
○absolute measurement
△need care to nonlinearity
△need cost space for vacuum system



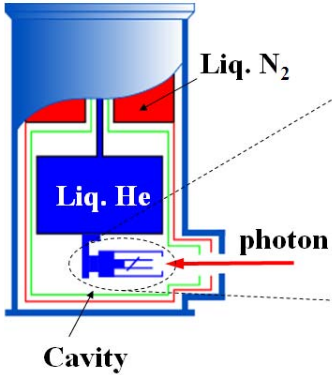
Foil-based backscattering monitor

○semi-transparent above a few keV
△need care to damage to foil



Calorimeter

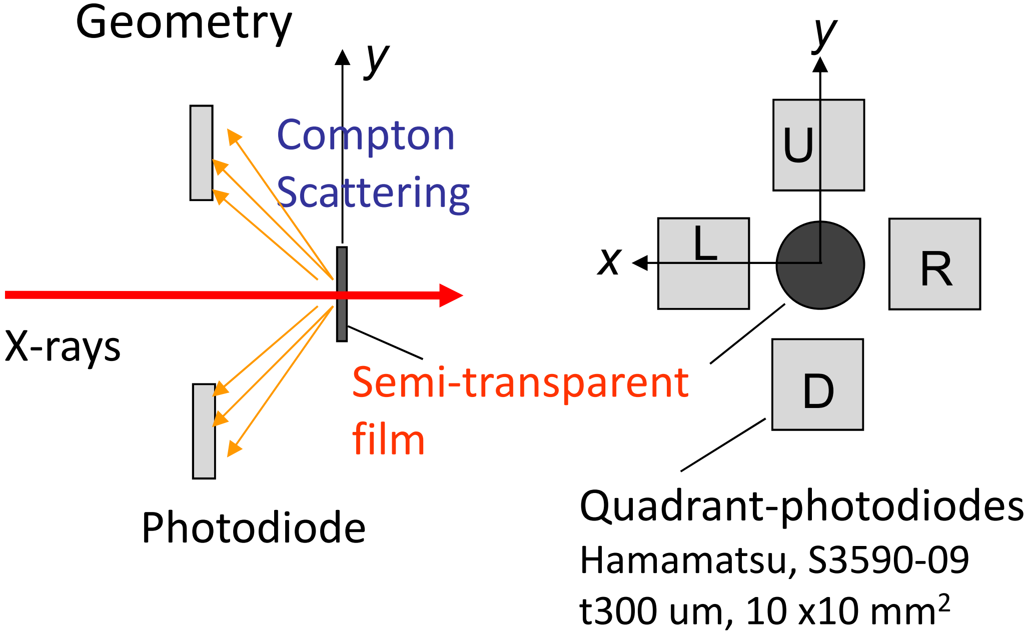
○absolute measurement
△destructive
△average measurement



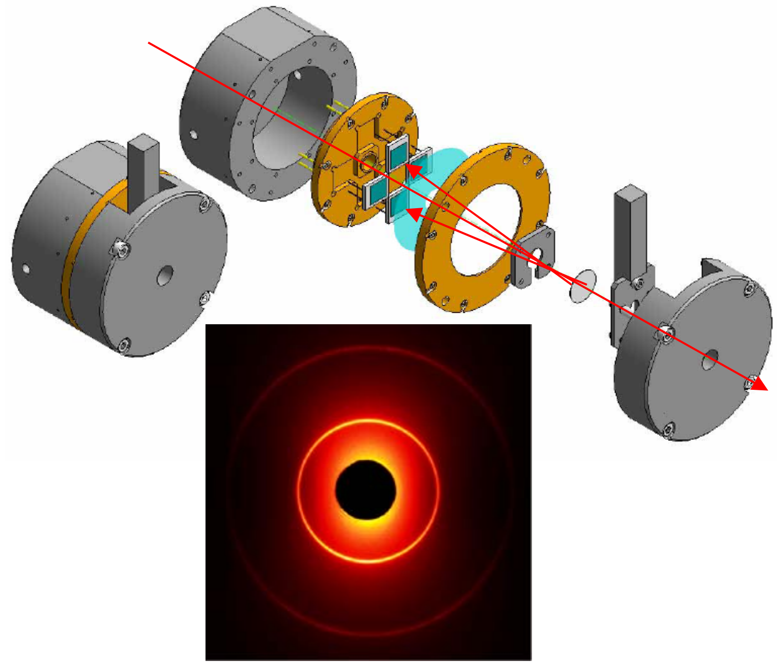
Pulse energy diagnostics: Thin-foil backscattering monitor

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

Geometry



Collaboration with LCLS



Intensity $$I = I_L + I_R + I_U + I_D$$

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

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

CVD- "nano" Diamond

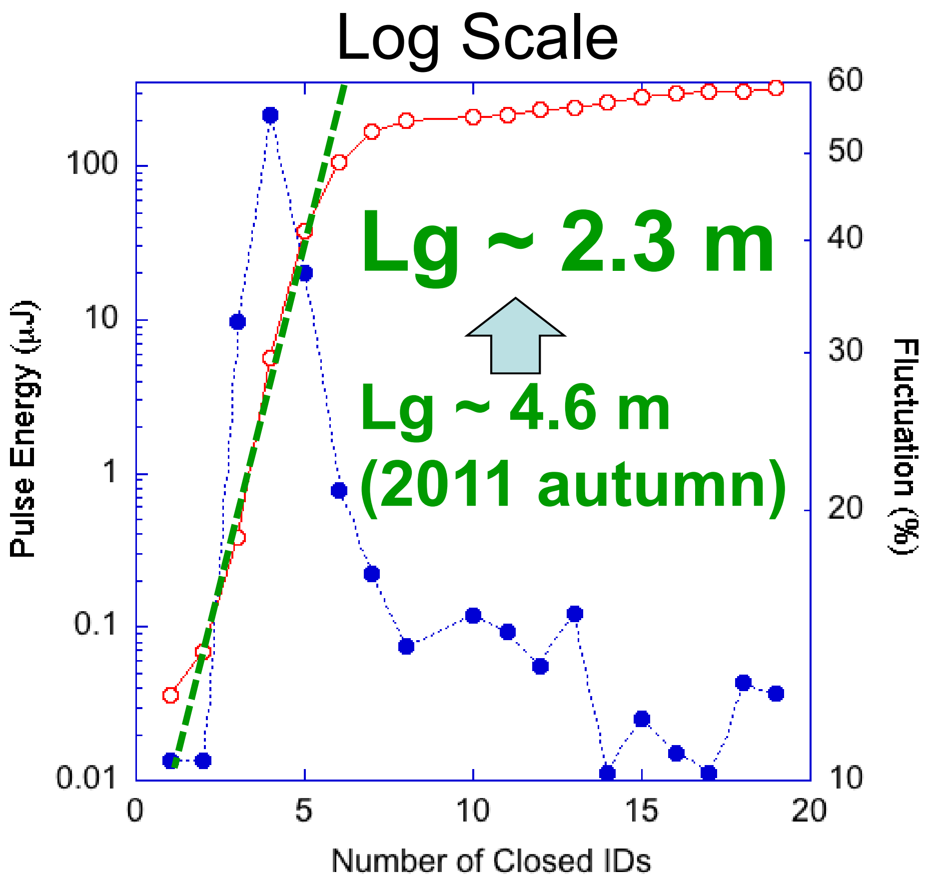
Smooth Debye-Scherrer ring

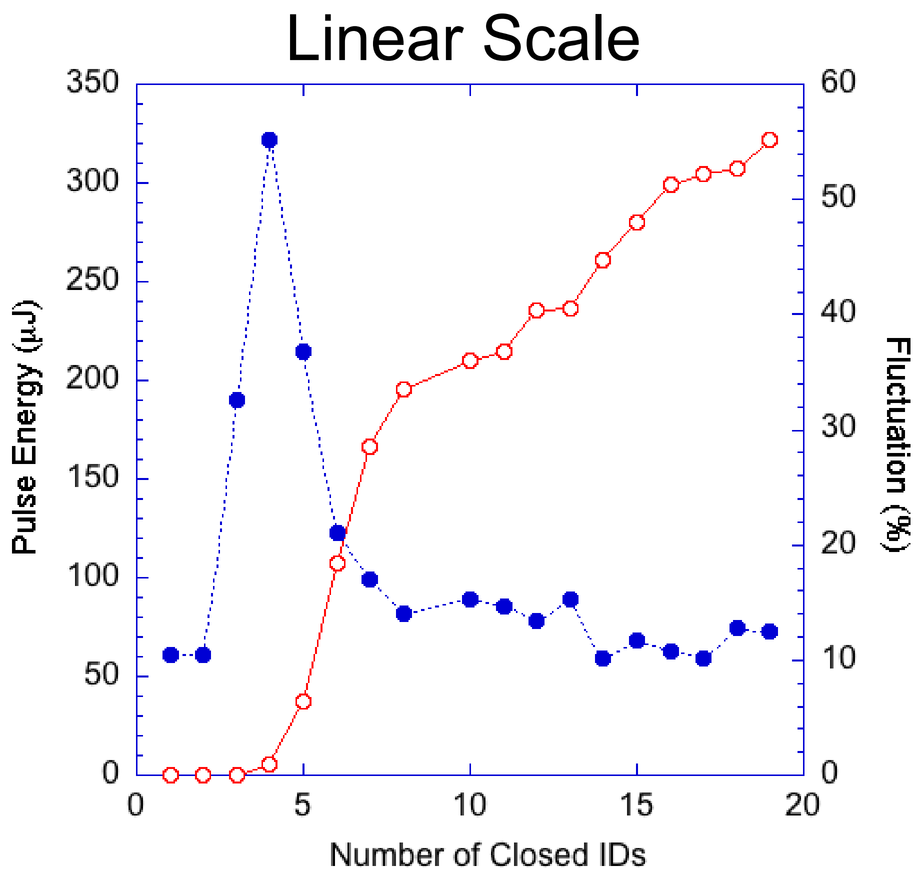
Speckle-free

Semi-transparent (>97%@10 keV)

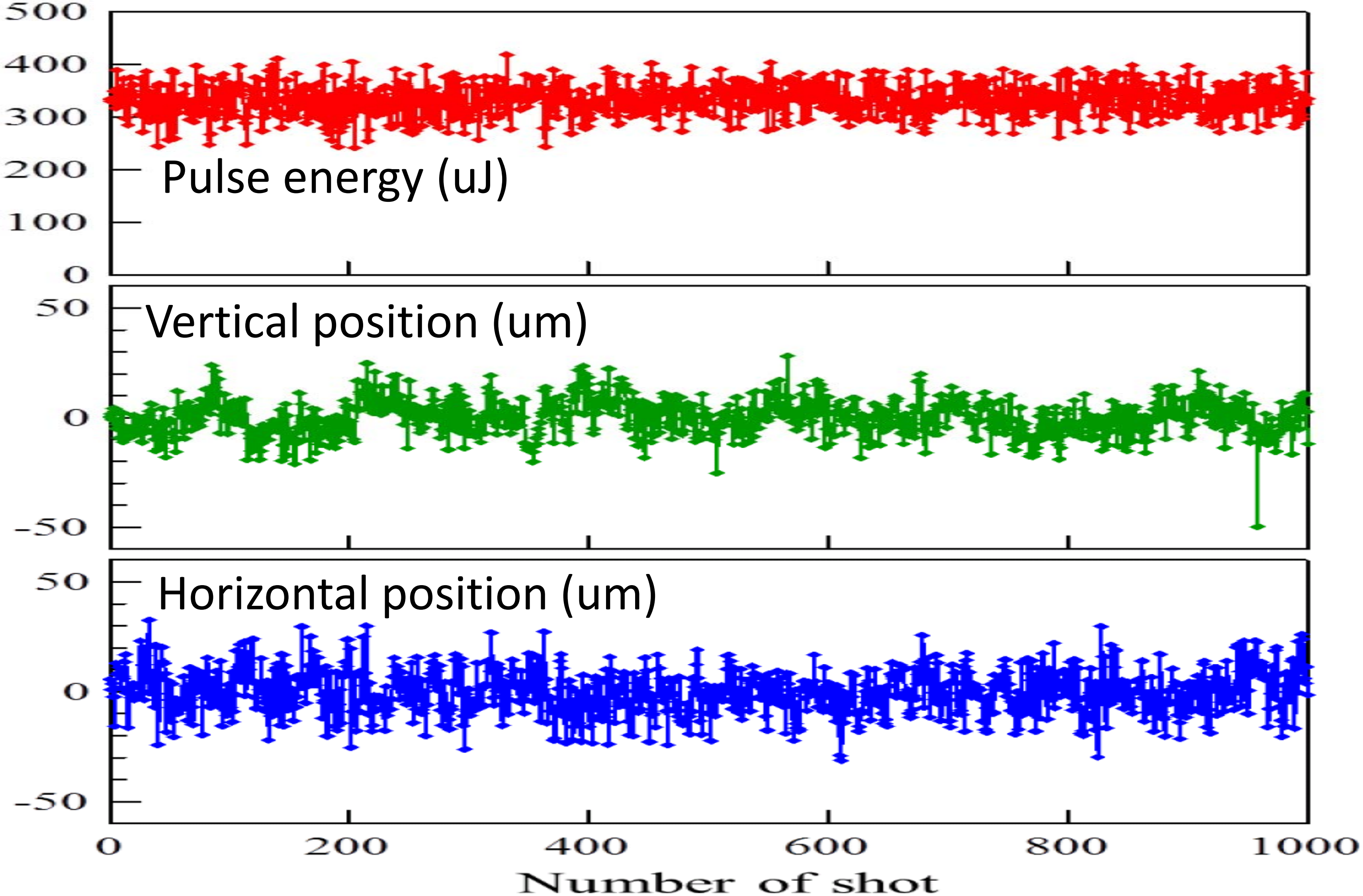
Wide d-range (10 nJ ~ 10 mJ)

Application (1): Gain curve measurement

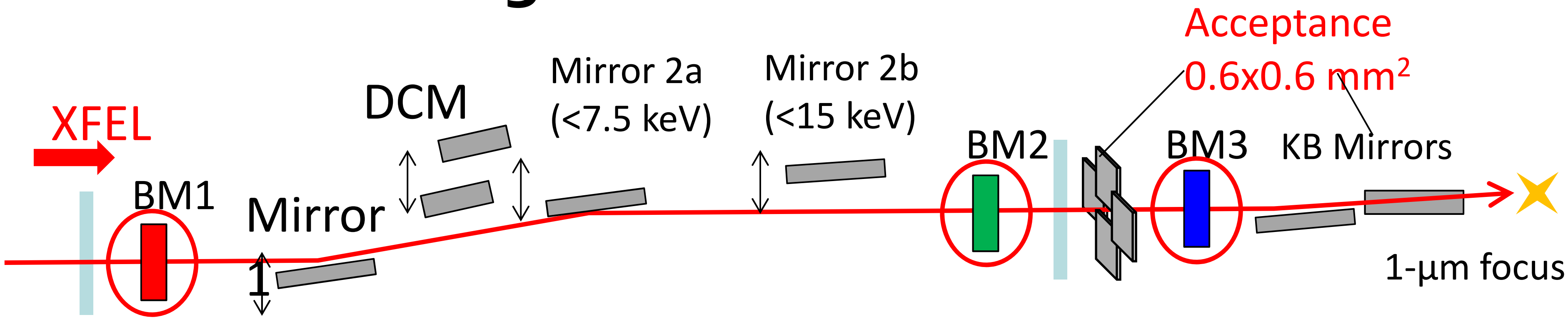




Application (2)
Routine monitoring at control room

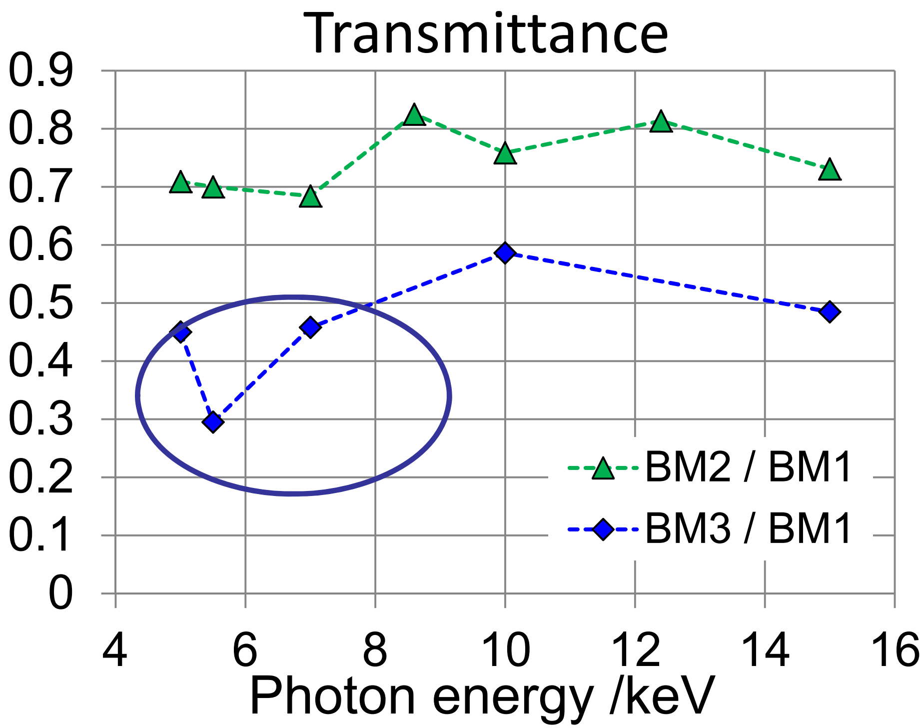


Application (III)
Monitoring of Beamline Transmittance



Mismatch between beam size and mirror acceptance

Increase of mirror acceptance

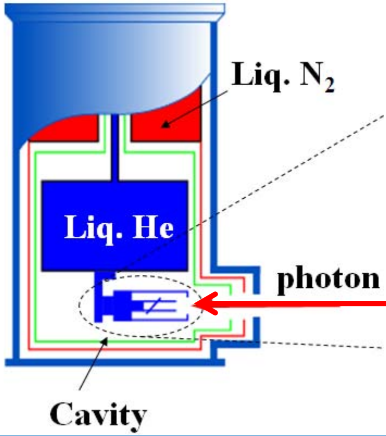


“From Relative to Absolute”

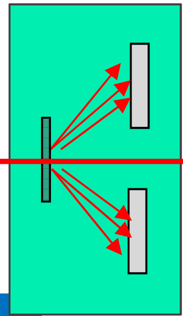
International Collaboration

Calorimeter (AIST)

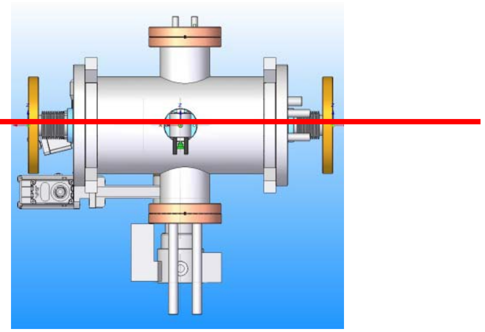
RT-type: Worked!



Thin-foil monitor (SACLA)



Gas monitor detector (DESY/PTB)



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	---

Max. Deviation = 3.3%

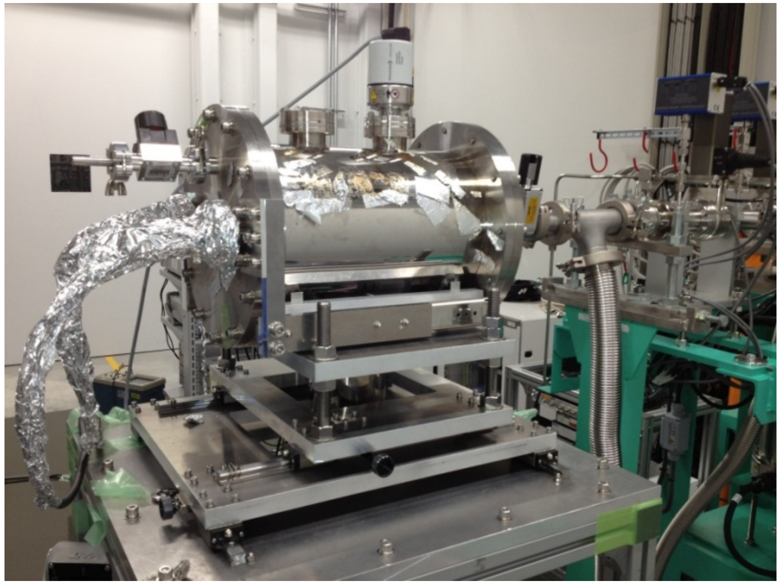
Kato *et al, Appl. Phys. Lett.* 101, 023503 (2012)

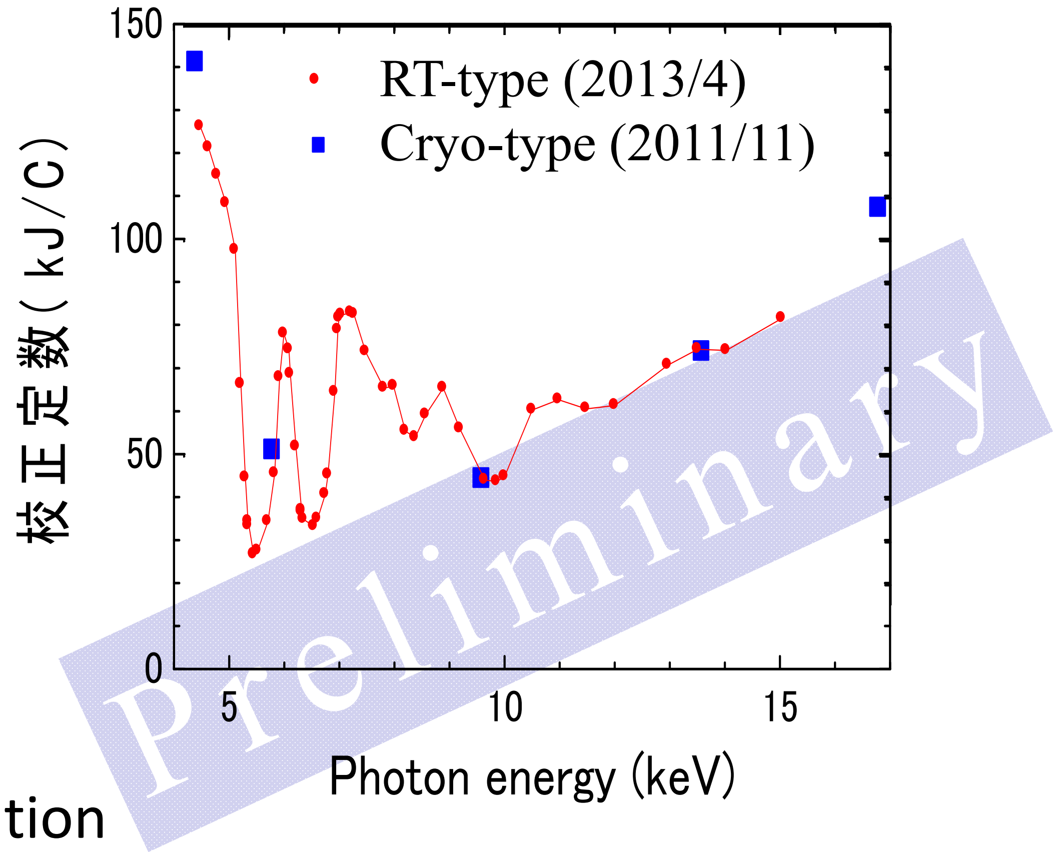
T. Tanaka et al., NIMA 659, 528 (2011).
K. Tiedtke et al., JAP. 103, 94511 (2008).

New portable calorimeter operating at room temperature

Saito-san (AIST)

Developed by AIST and RIKEN, tested on April 2013



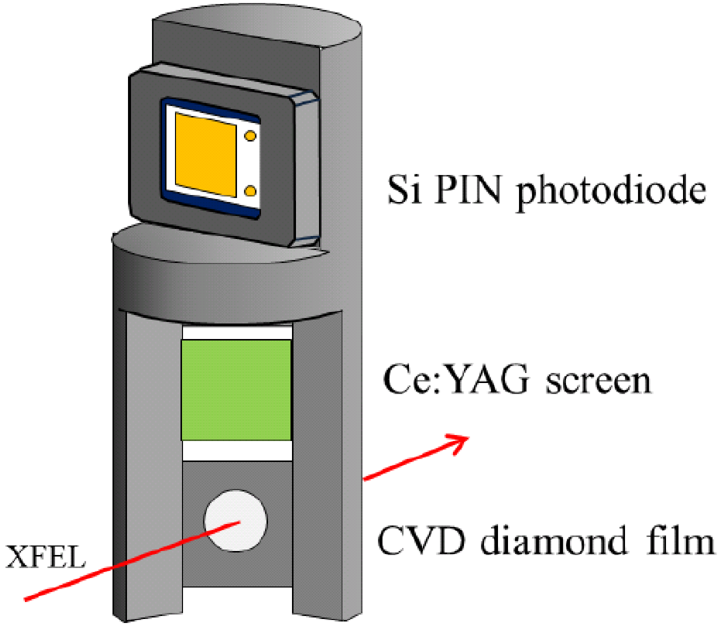


Tanaka, Saito et al, in preparation

Push to commercially available device

Spatial Profile Diagnostics (I)

Retractable screens



Ce:YAG (300 um t)

high efficiency (~ 1 uJ/pls)

destructive

CVD B-doped diamond (30 um t)

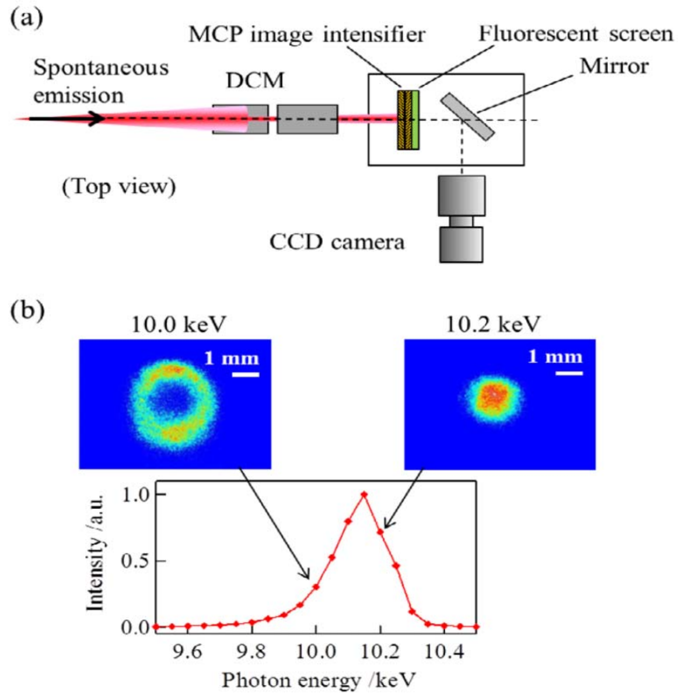
low-efficiency

semi-transparent (>97% for 10-keV)

speckle-free

-> Available as inline, routine monitors

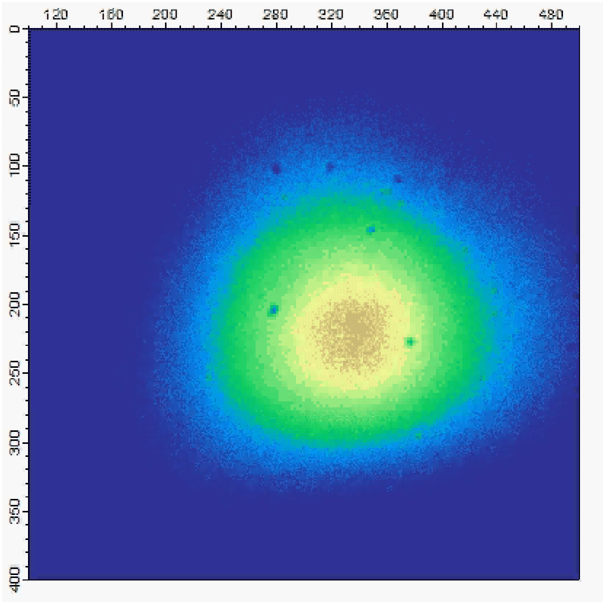
Phosphor-coupled-MCP monitor



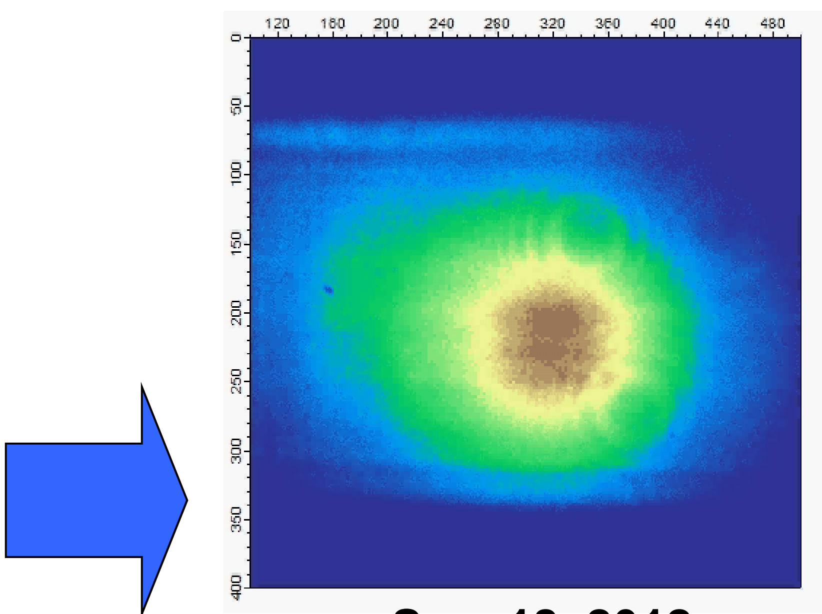
- Very high efficiency to image spontaneous radiation
- Routine use for undulator alignment in every two weeks

Spatial Profile & Pointing Stability

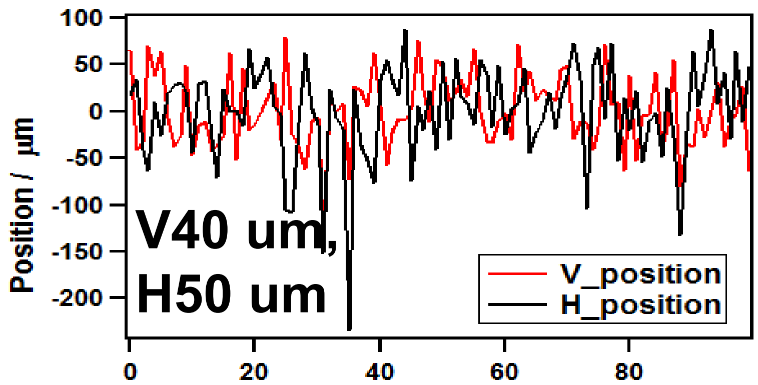
Temperature stabilization of injector section (2012 autumn)

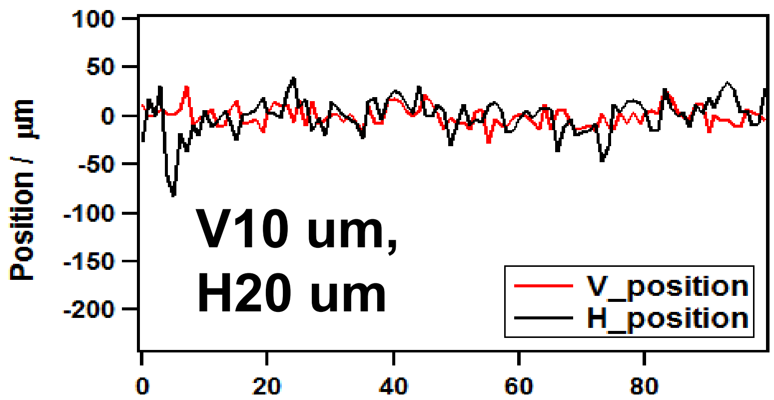


July 25, 2012



Sep. 18, 2012



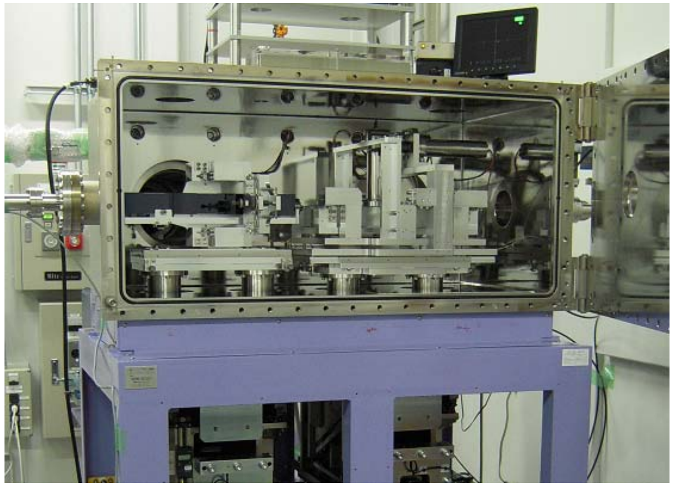


Spatial Profile Diagnostics (II)

Slit/knife-edge scanning method

Stability ? (intensity/position)

1-um Focusing at EH3



Yumoto et al Nature Photon. **7**, 43 (2013)

nature photonics | LETTERS

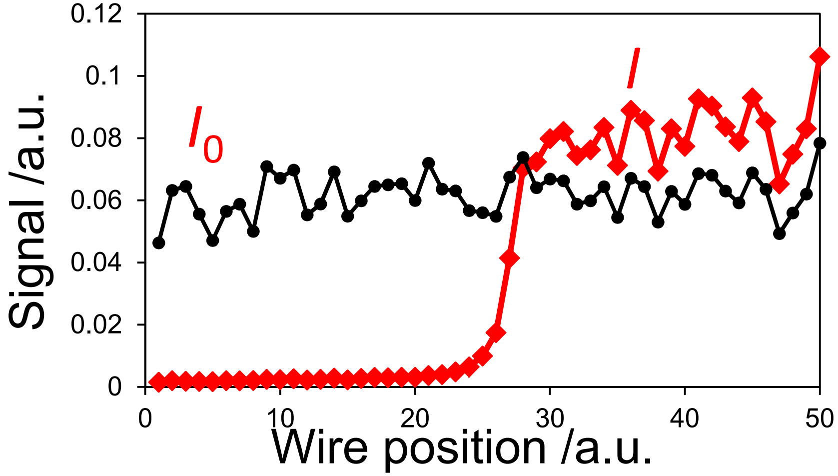
PUBLISHED ONLINE: 16 DECEMBER 2012 | DOI: 10.1038/NPHOTON.2012.306

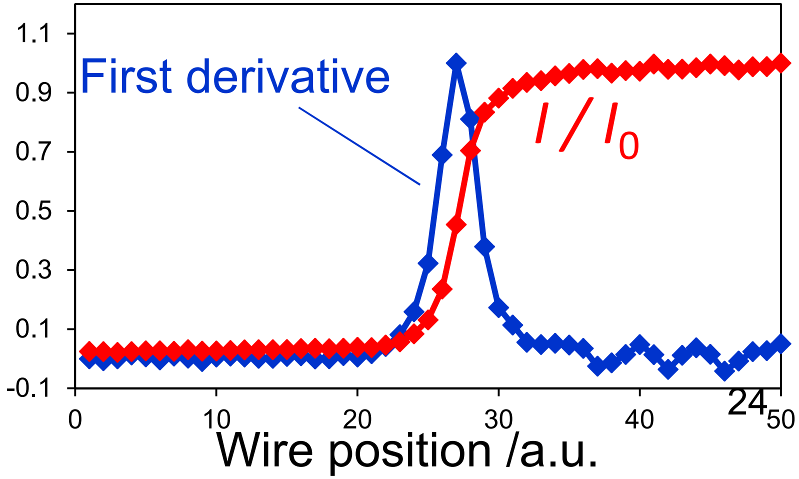
Focusing of X-ray free-electron laser pulses with reflective optics

Hirokatsu Yumoto[1]*, Hidekazu Mimura[2], Takahisa Koyama[1], Satoshi Matsuyama[3,4], Kensuke Tono[1], Tadashi Togashi[1], Yuichi Inubushi[5], Takahiro Sato[5], Takashi Tanaka[5], Takashi Kimura[6], Hikaru Yokoyama[3], Jangwoo Kim[3], Yasuhisa Sano[3], Yousuke Hachisu[7], Makina Yabashi[5], Haruhiko Ohashi[1,5], Hitoshi Ohmori[7], Tetsuya Ishikawa[5] and Kazuto Yamauchi[3,4,8]

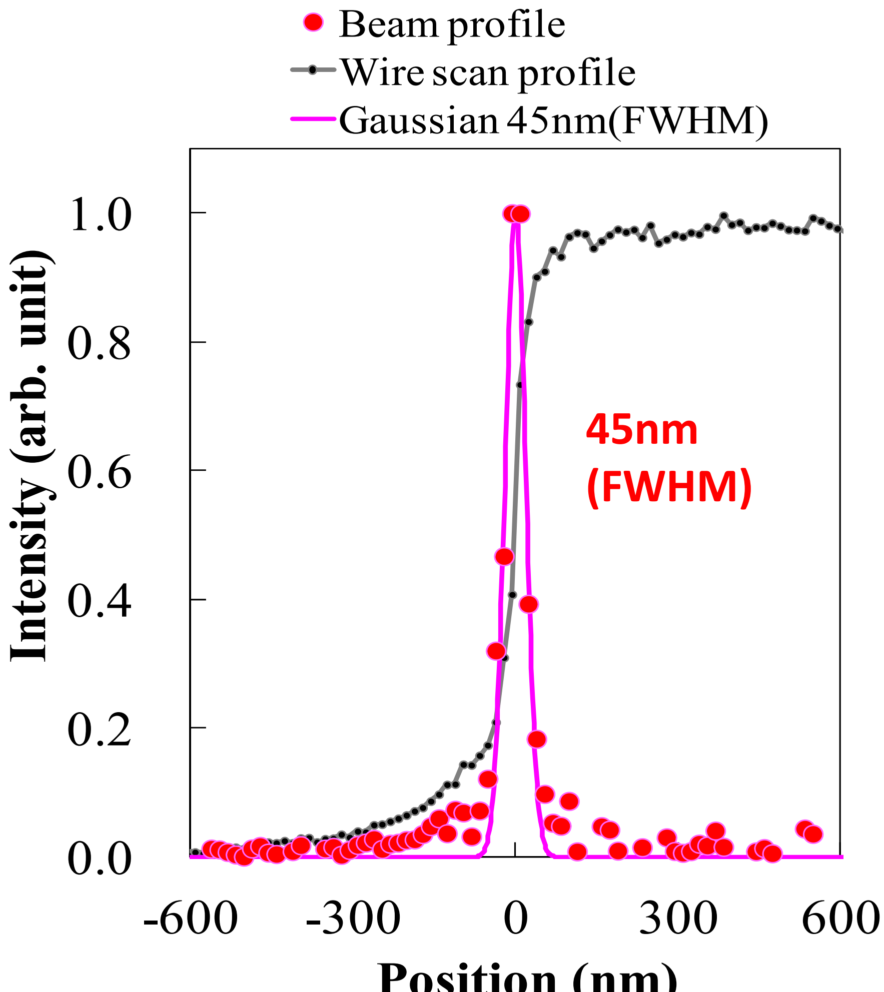
X-ray free-electron lasers[1,2] produce intense femtosecond pulses that have applications in exploring new frontiers in science. The unique characteristics of X-ray free-electron ...

To date, refractive[10], diffractive[3,11] and reflective optics[12] have been developed to focus X-rays. Of these options, total reflective optics in the Kirkpatrick–Baez (K–B) geometry[13] which combines ...

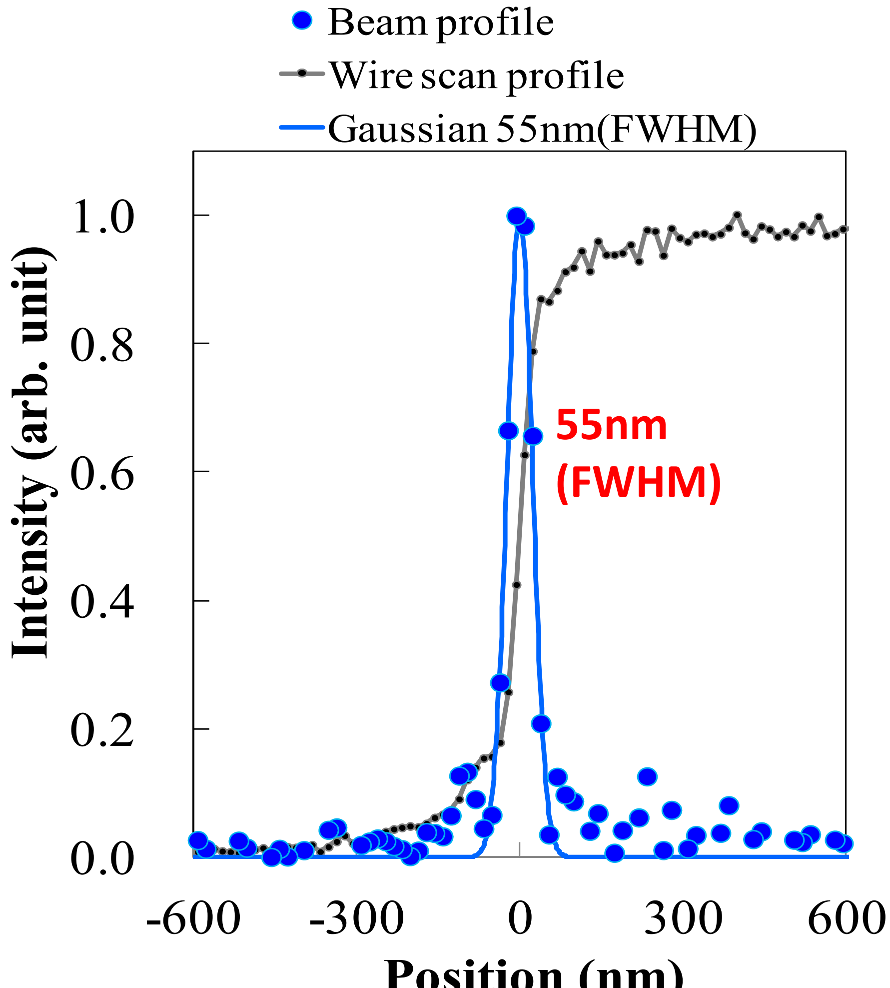




Measurement of nano-scale spot with two-stage focusing system



Vertical direction



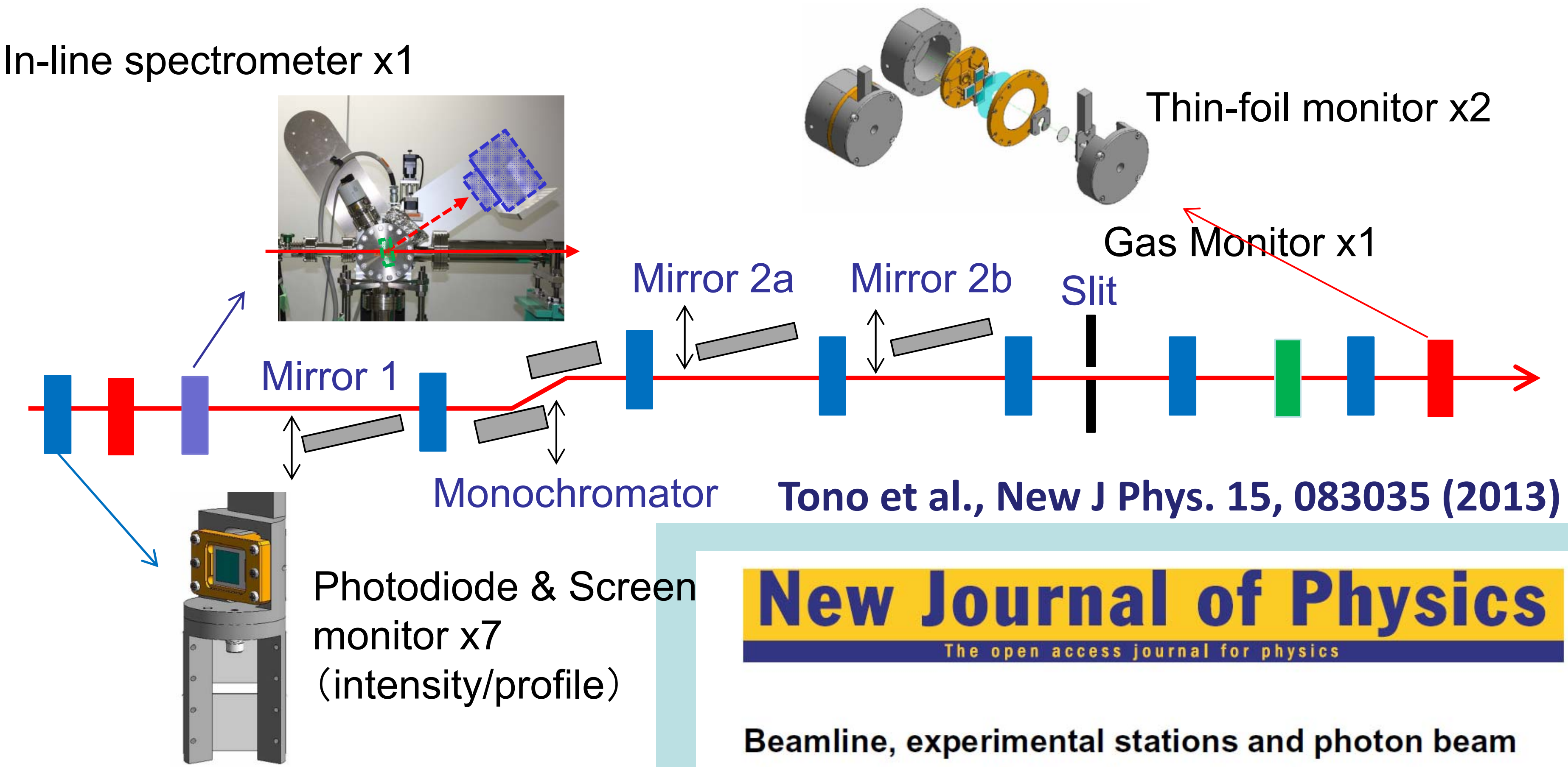
Horizontal direction

~10^{20} W/cm^2

Mimura et al, in preparation

X-ray energy: 10keV

Beamline Optics & Diagnostics



Tono et al., New J Phys. 15, 083035 (2013)

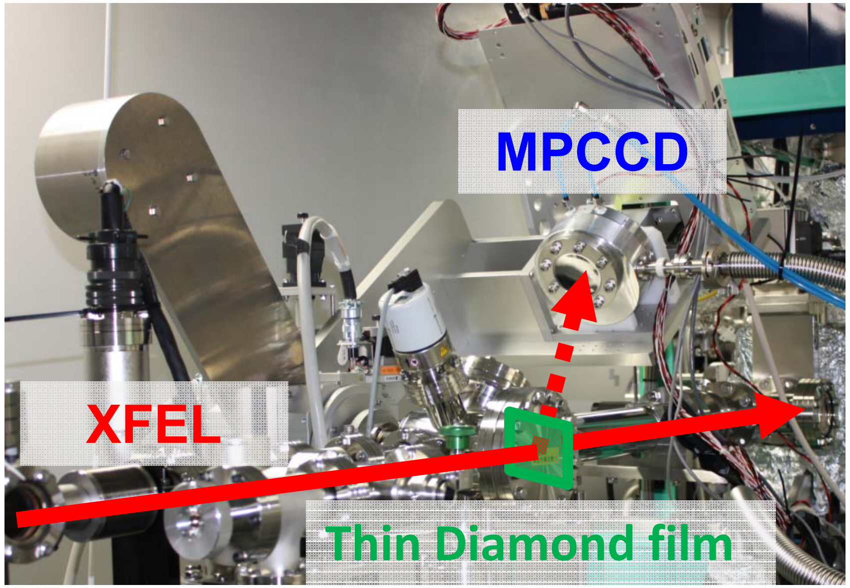
New Journal of Physics
The open access journal for physics

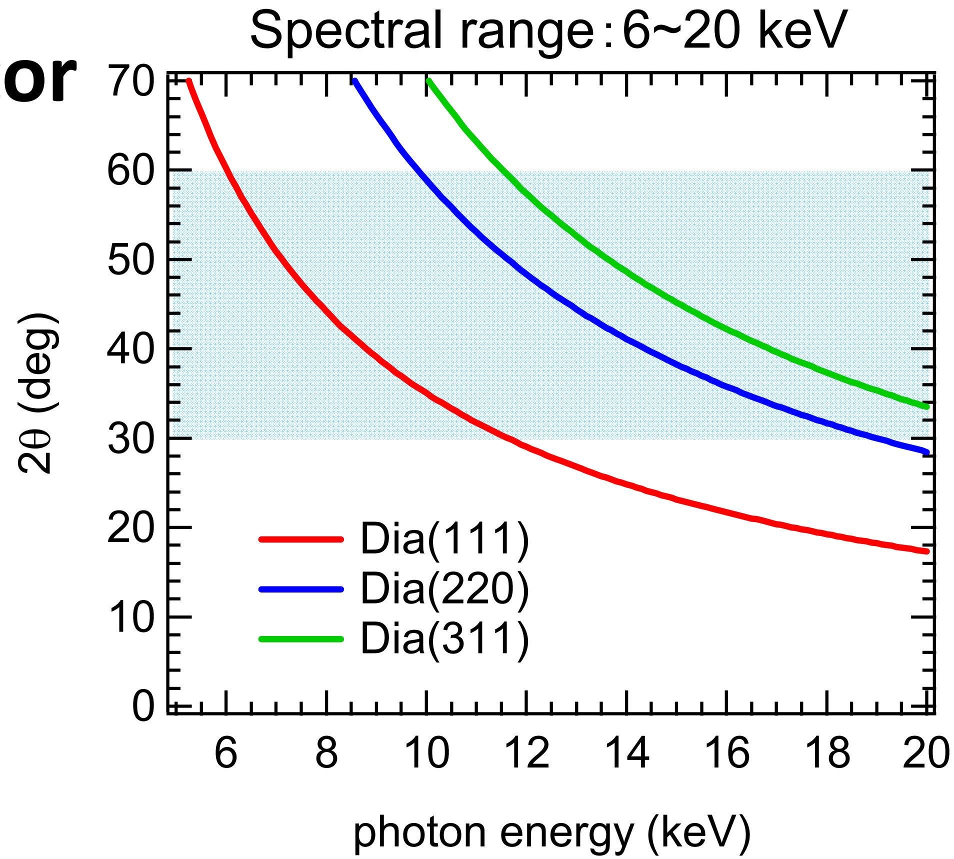
Beamline, experimental stations and photon beam diagnostics for the hard x-ray free electron laser of SACLA

K Tono[1,3], T Togashi[1], Y Inubushi[2], T Sato[2], T Katayama[1], K Ogawa[2], H Ohashi[1,2], H Kimura[1,2], S Takahashi[1,2], K Takeshita[1,2], H Tomizawa[1,2], S Goto[1,2], T Ishikawa[2] and M Yabashi[2]

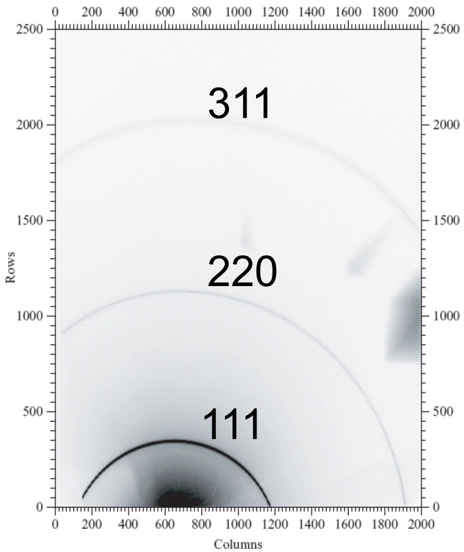
Contents

Central wavelength monitor

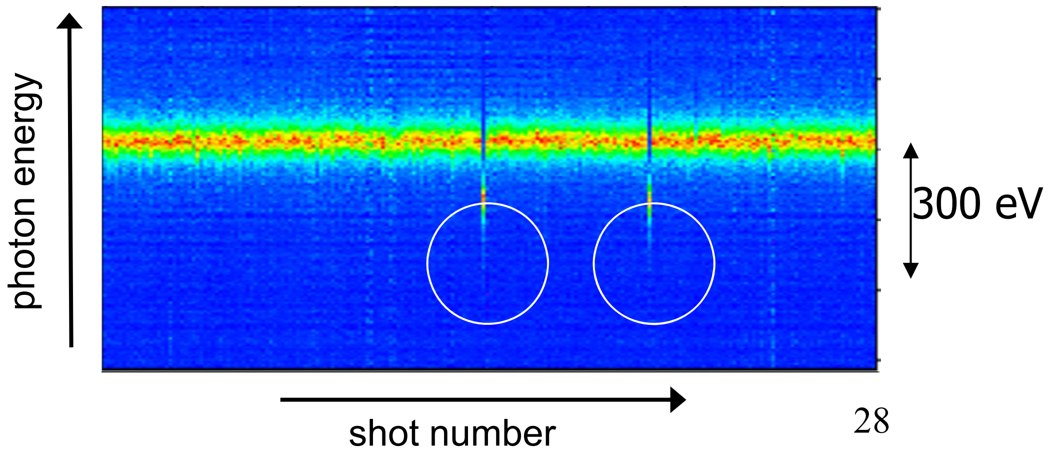




Inubushi-san

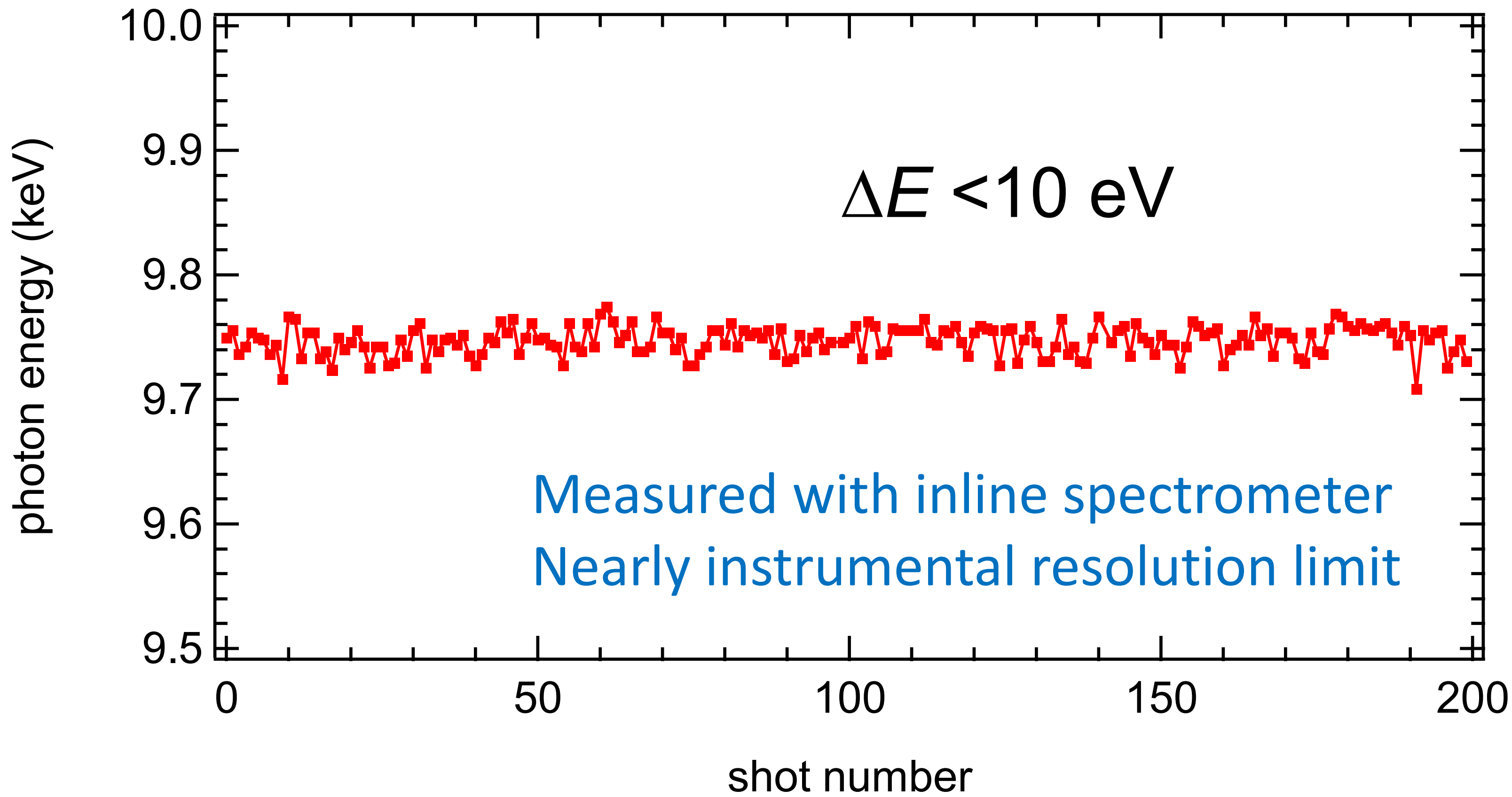


Diffraction ring from CVD diamond



High Wavelength Stability Routinely Achieved

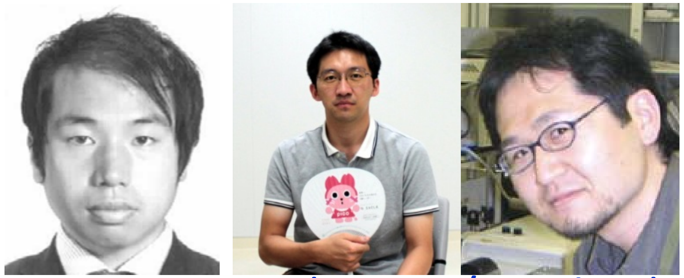
c.f. bandwidth: 0.05 keV @10 keV



Arrival Timing

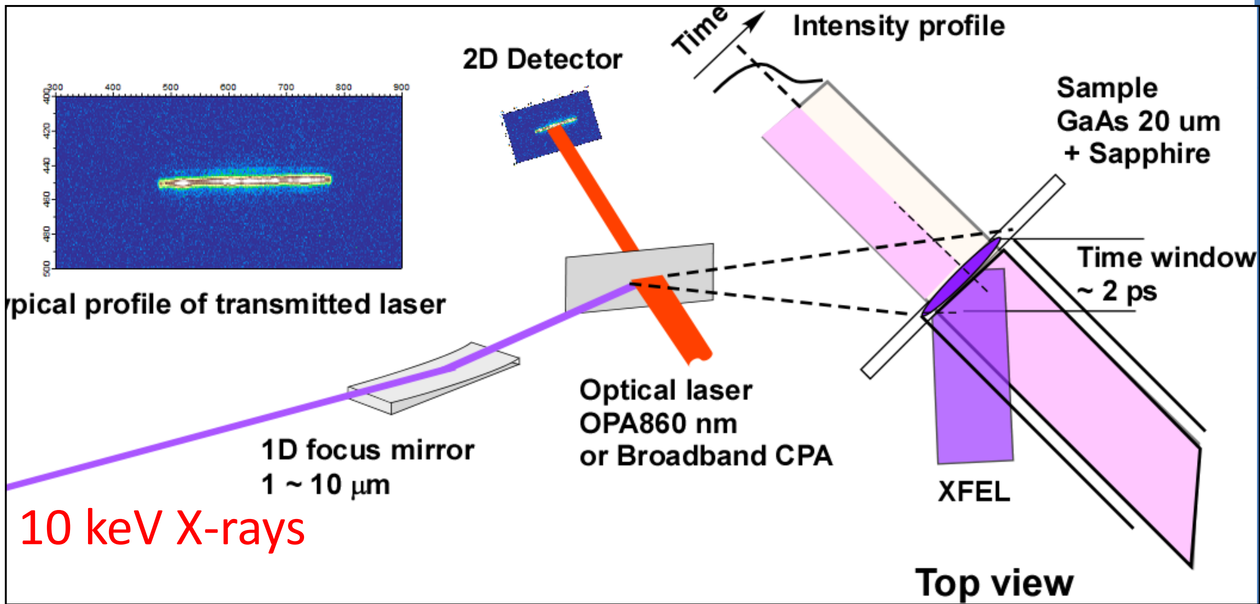
Harmand et al, Nat. Photon 2013

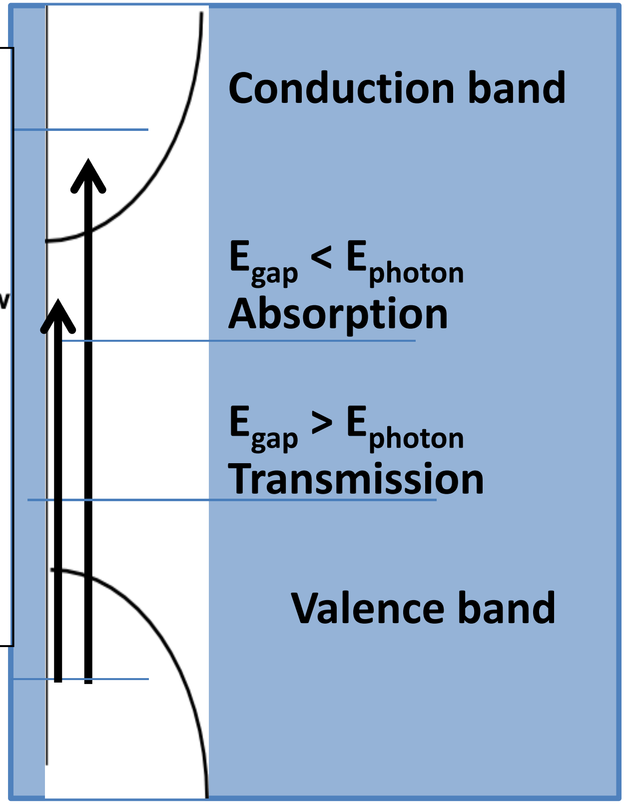
Transient transmission of optical laser induced with X-rays; Spatial decoding



Sato-san (SACLA/U Tokyo)

Ogawa-san, Togashi-san (SACLA)





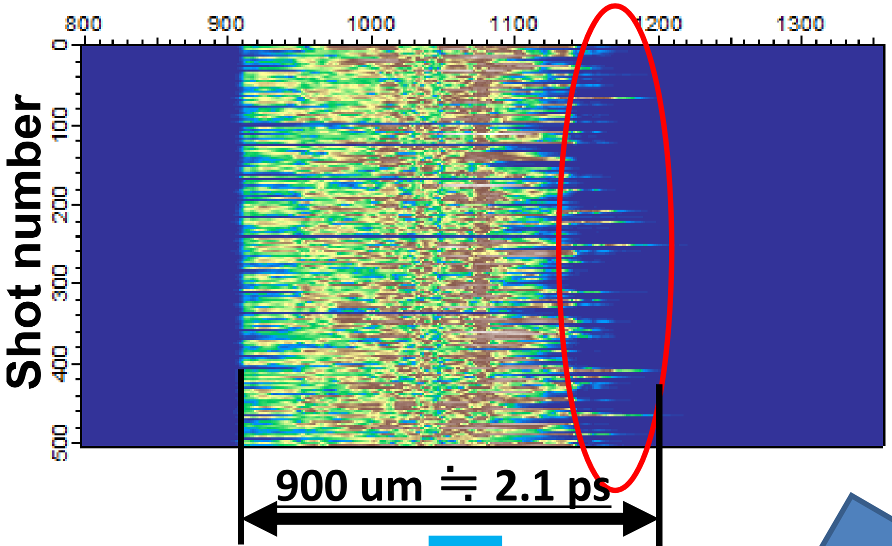
XFEL 1D focus

→ Pulse energy < 10 uJ

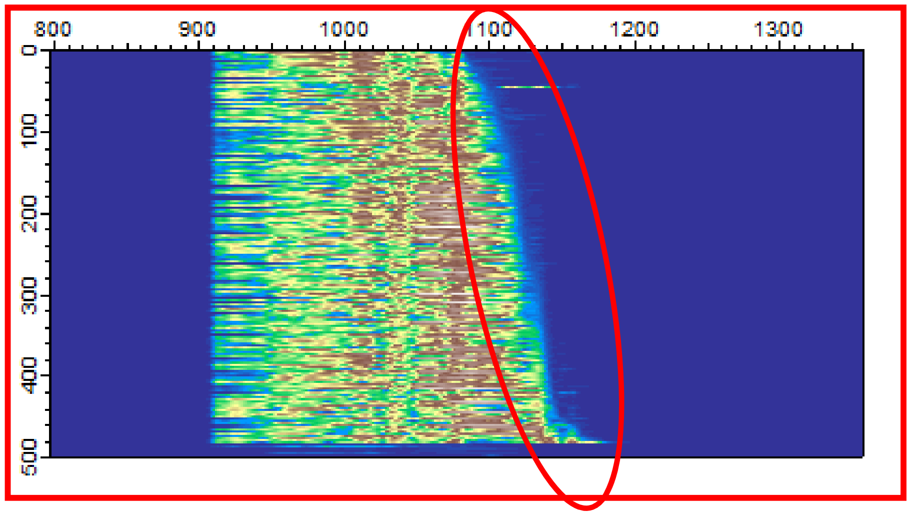
S. M. Durbin, et al., X-ray pump optical probe cross correlation study of GaAs *Nature Photonics* **6**, 111

Jitters and Resolution

Sato et al., in preparation

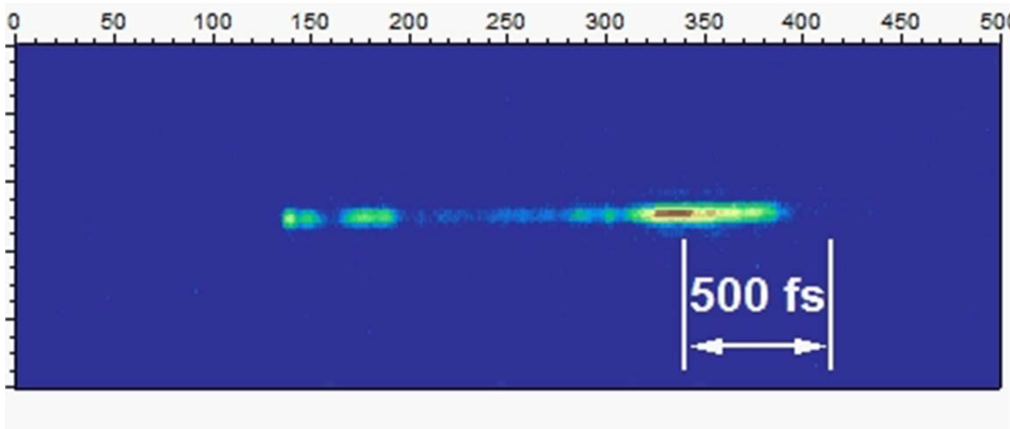


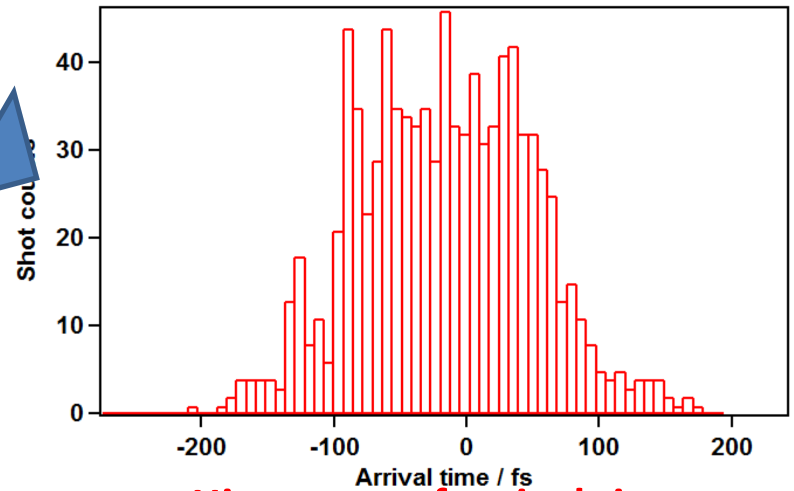
Sorting



~ 10 fs resolution

Single shot image



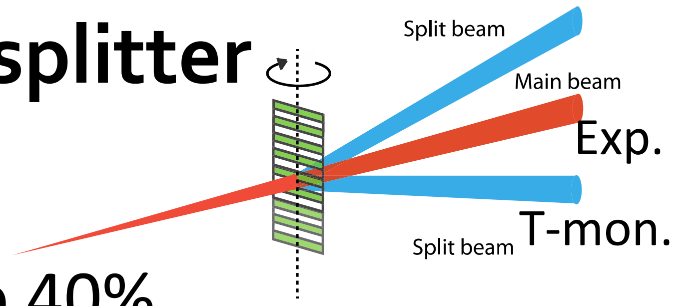


Histogram of arrival time

Timing jitter: 130 fs (rms)

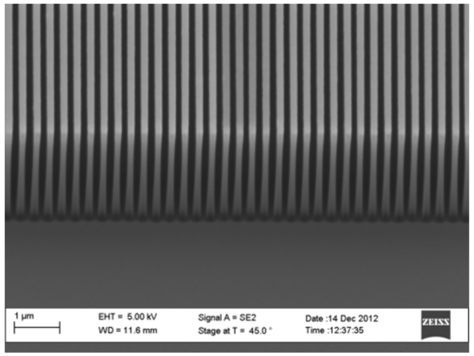
"From destructive to nondestructive"

Branching with beam splitter

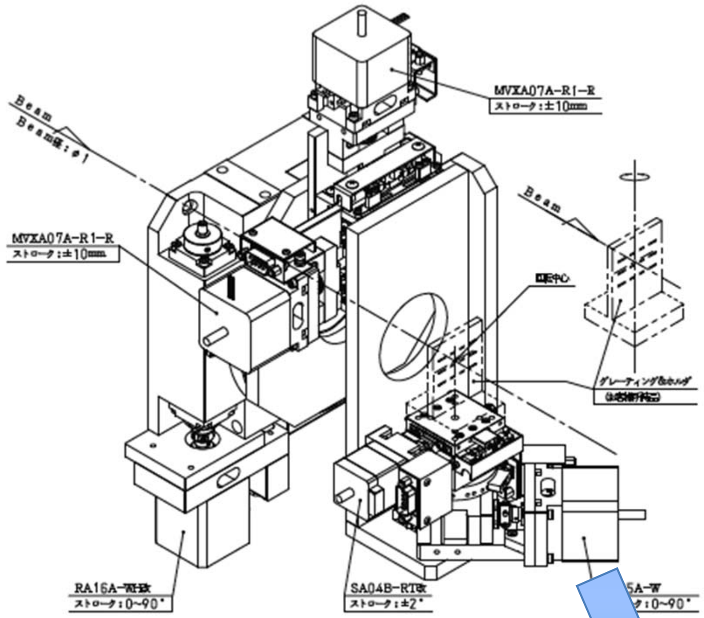


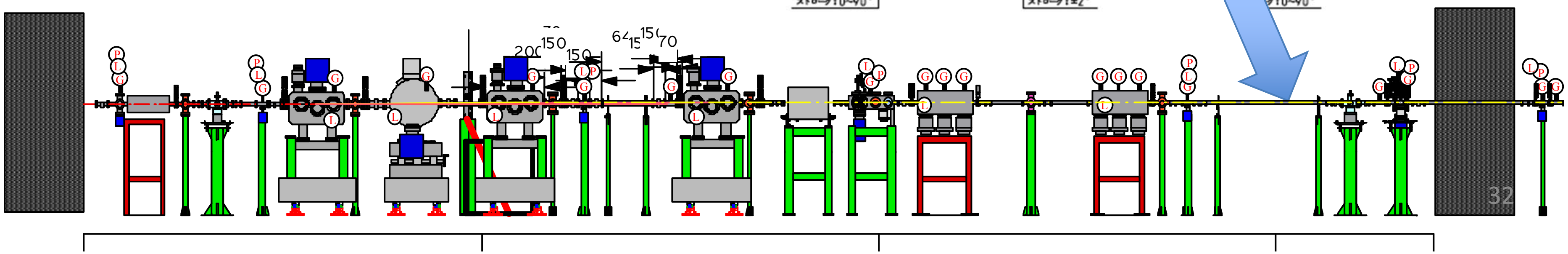
- Transmission grating
- Efficiency can be tuned from 0.1% to 40%
- Install to optics hutch as a permanent component

Si grating 300 nm p/1 um t



Collaboration with Ch. David (PSI)





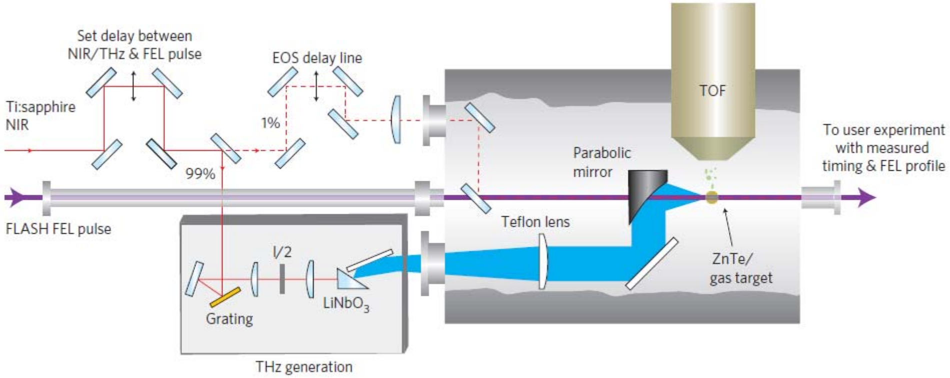
Summary of Performance

Pulse Energy	0.4 mJ @10 keV
Photon energy range	4.5 to 15 keV
Stability Intensity $\sigma_{\delta I/I}$	$\leq$ 10%
Pointing	3 ~7% of beam size
Repetition rate	20 Hz (Max. 60 Hz)
Pulse duration	**??**
Peak Power	**??**

Temporal profile/Pulse duration

THz streaking method

Grguraš et al, Nat Photon. 2012

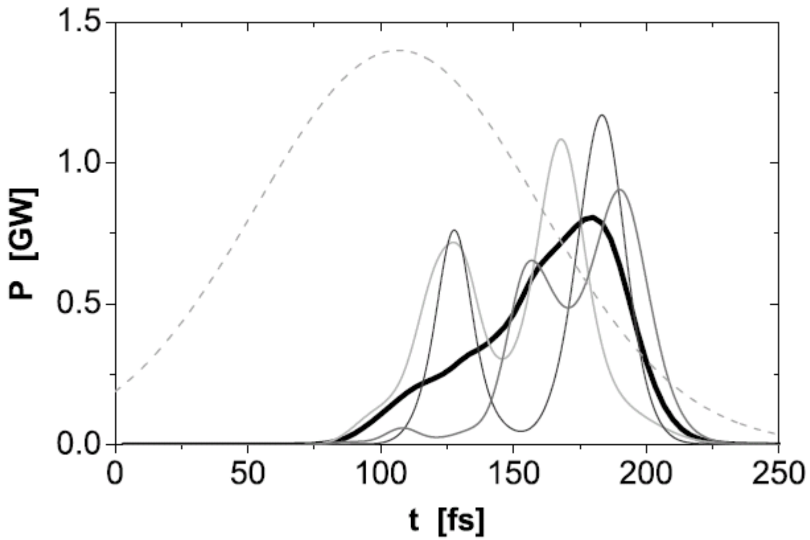


ref. T-CAV

Frequency domain

TTF-2 PRL (2002)

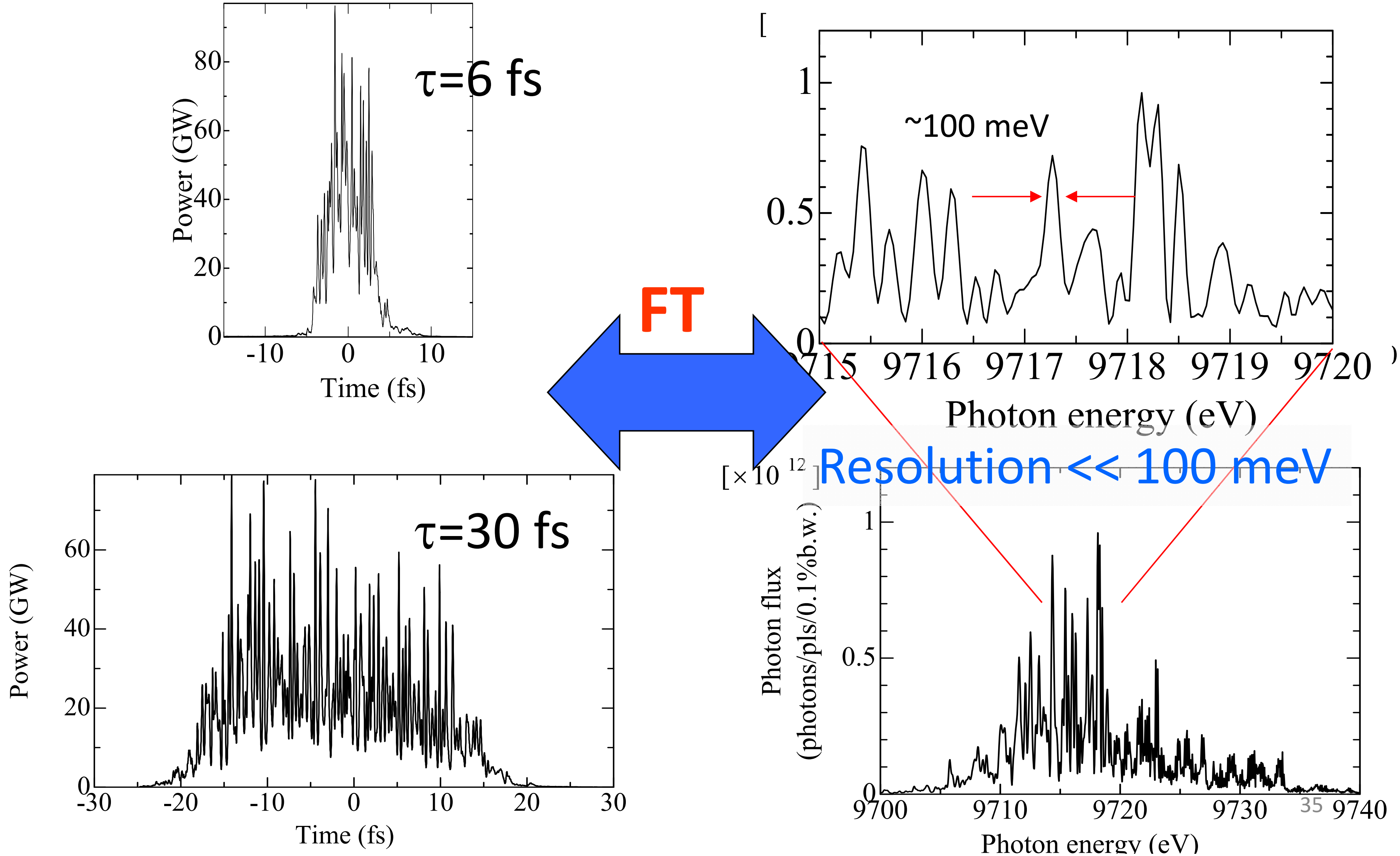
Shintake et al, Nat Photon (2008)



Temporal vs. Frequency

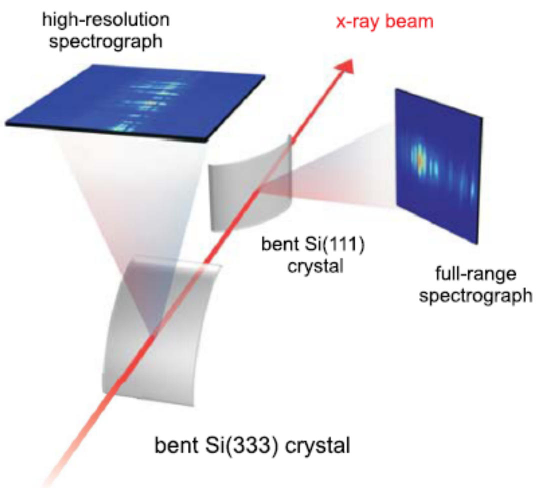
Temporal domain

Frequency domain



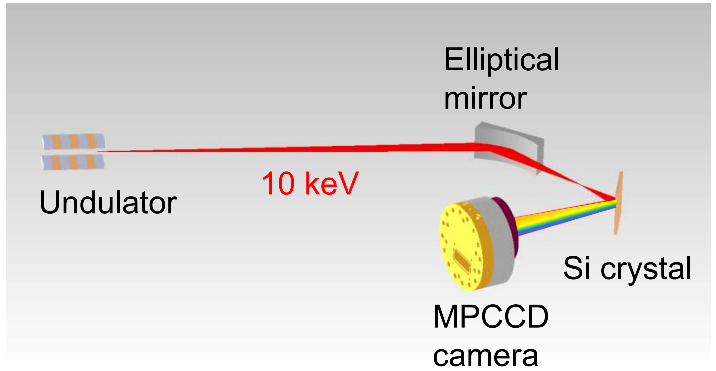
Recent developments of single-shot spectrometers

LCLS: Collimated beam + bent, thin crystal analyzer



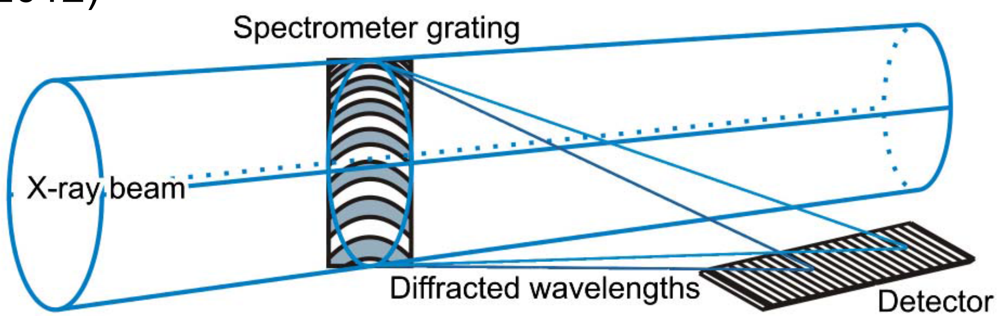
D. Zhu et al, APL **101**, 034103 (2012)

SACLA: Diverged beam (elliptical mirror) + flat, thick crystal analyzer



M. Yabashi et al, PRL **97,** 084802 (2006)
Y. Inubushi et al, PRL **109** 144801 (2012)

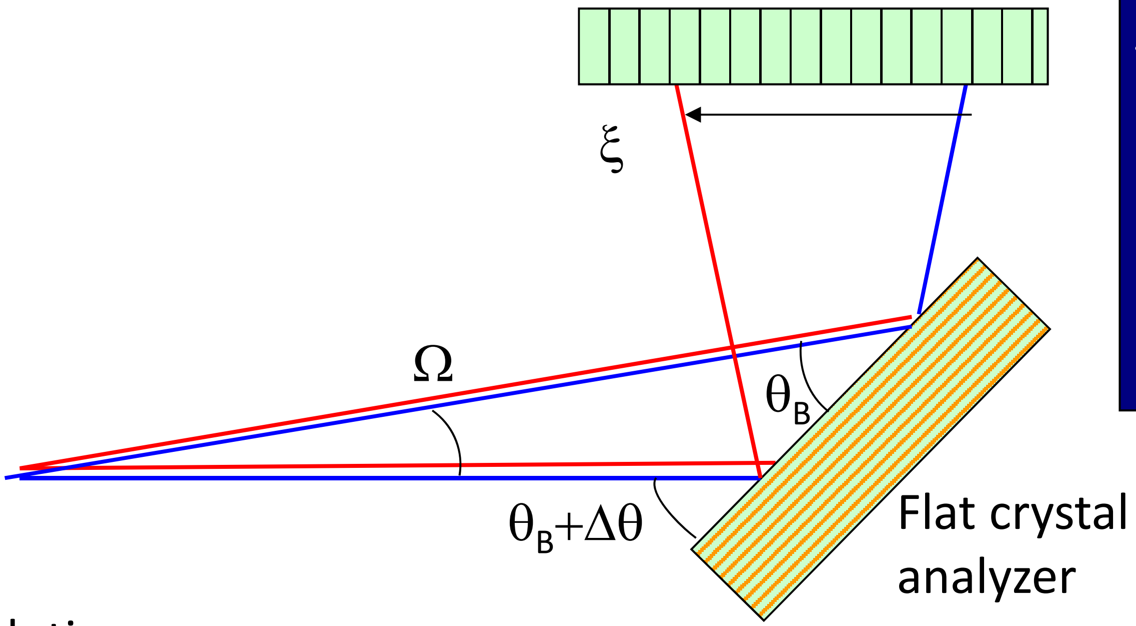
SwissFEL: Grating

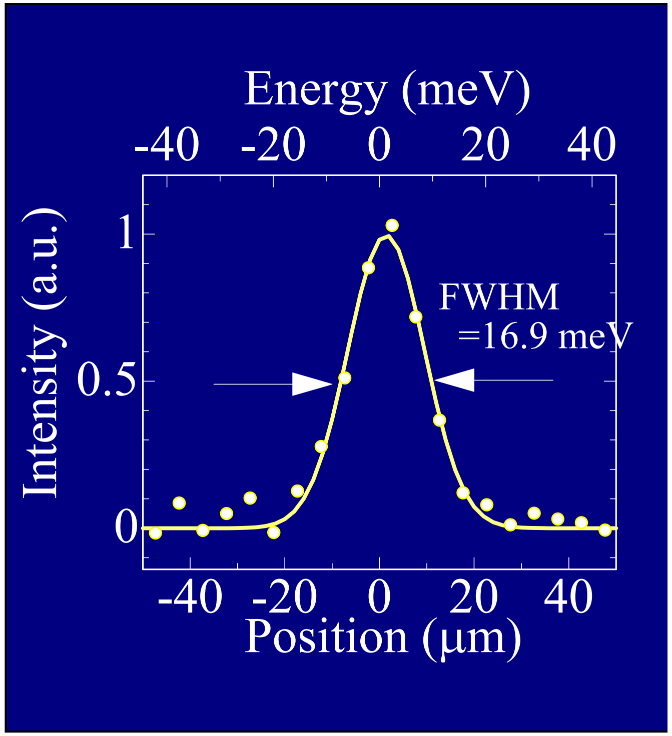


P. Karvinen et al, Opt. Lett. **37** 5073 (2012)

Principle

Divergent beam
+ Flat Crystal Analyzer
+ Position Sensitive Detector





Measured at SPring-8
M. Yabashi et al, PRL **97,** 084802 (2006)

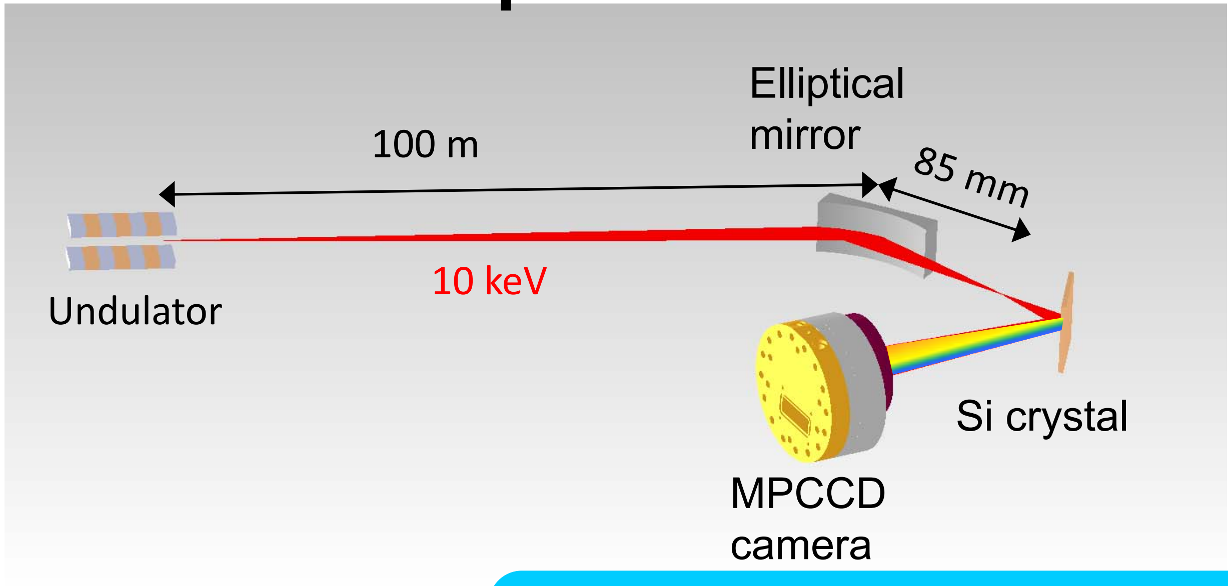
Resolution

$$\frac{\Delta E}{E} = \Delta\theta_{\min} \cot\theta_B$$

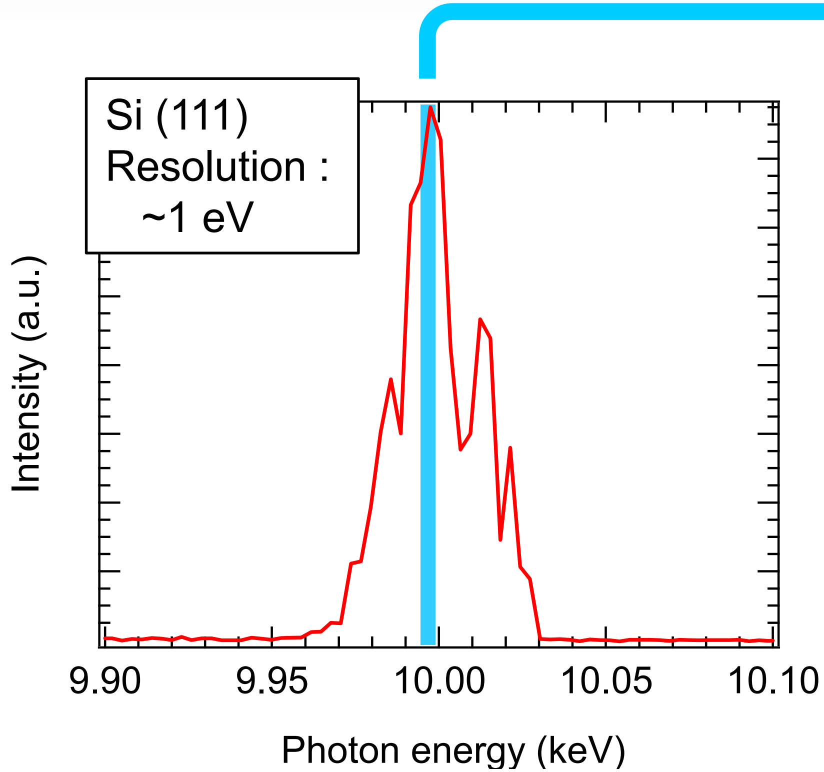
$$= \frac{\cot\theta_B \sqrt{\overbrace{\sigma_x^2}^{\text{focus size}} + \overbrace{(3.2\Lambda\cos\theta_B)^2}^{\text{extinction}} + \overbrace{s^2}^{\text{Detector pixel size}}}}{L} \cong \omega_s \cot\theta_B = \frac{4r_e}{\pi v_c}\left|F_{hkl}\right| d_{hkl}^2$$

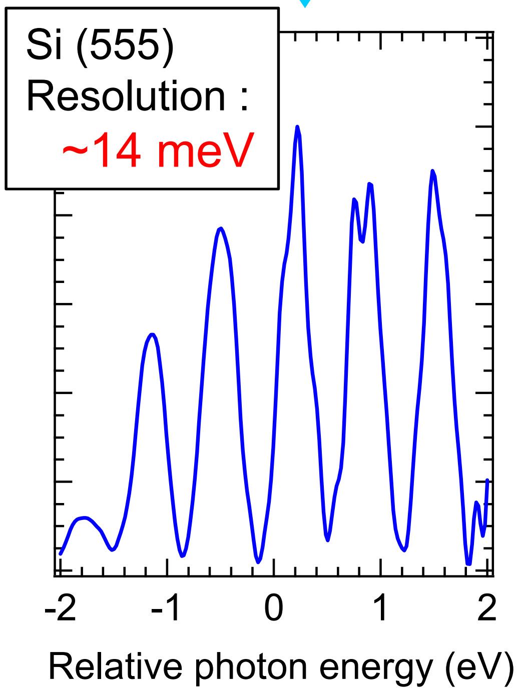
Higher-order reflection -> higher resolution

Development at SACLA

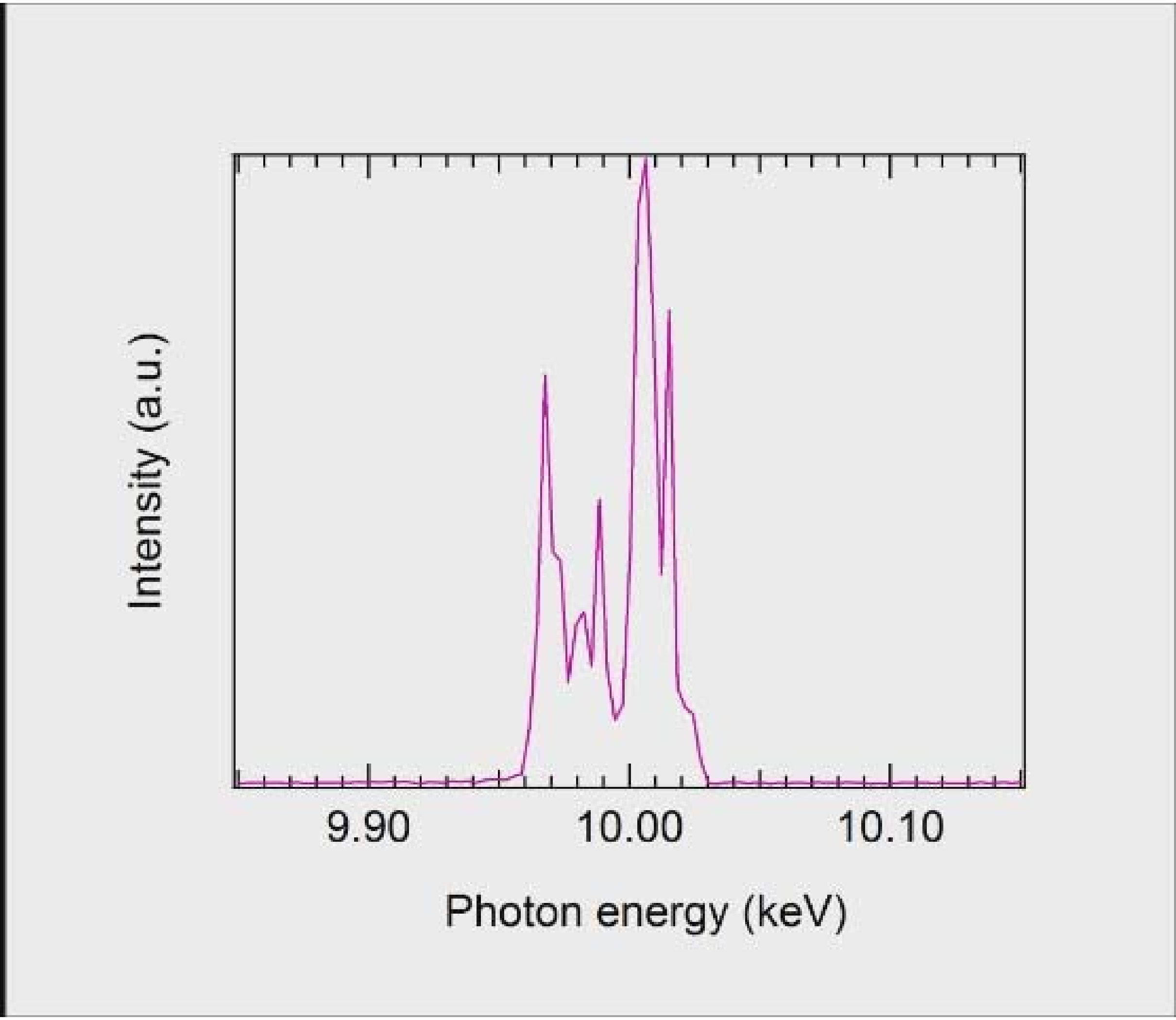


Inubushi-san (SACLA)



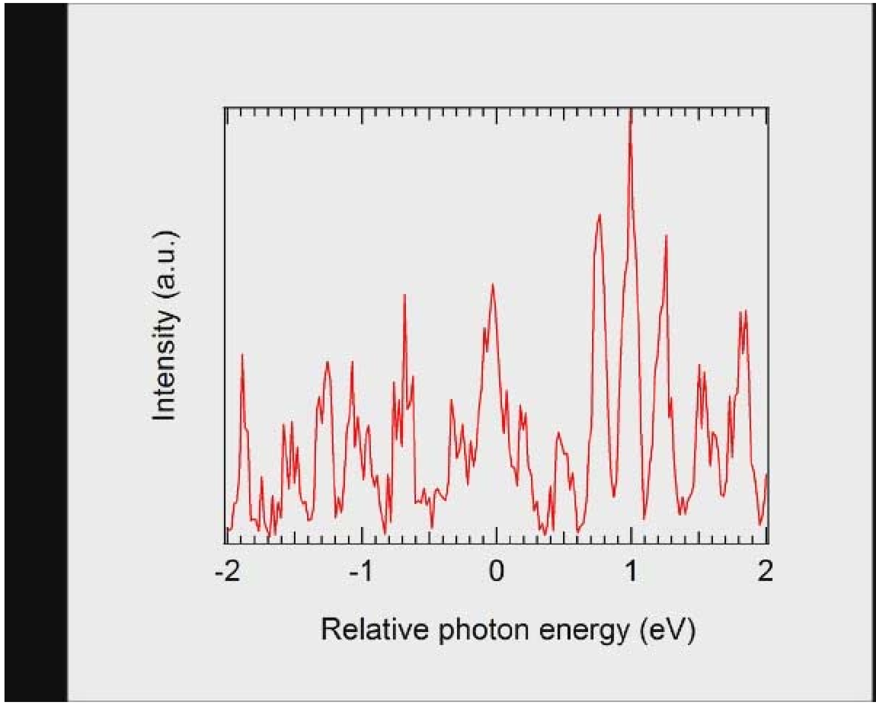


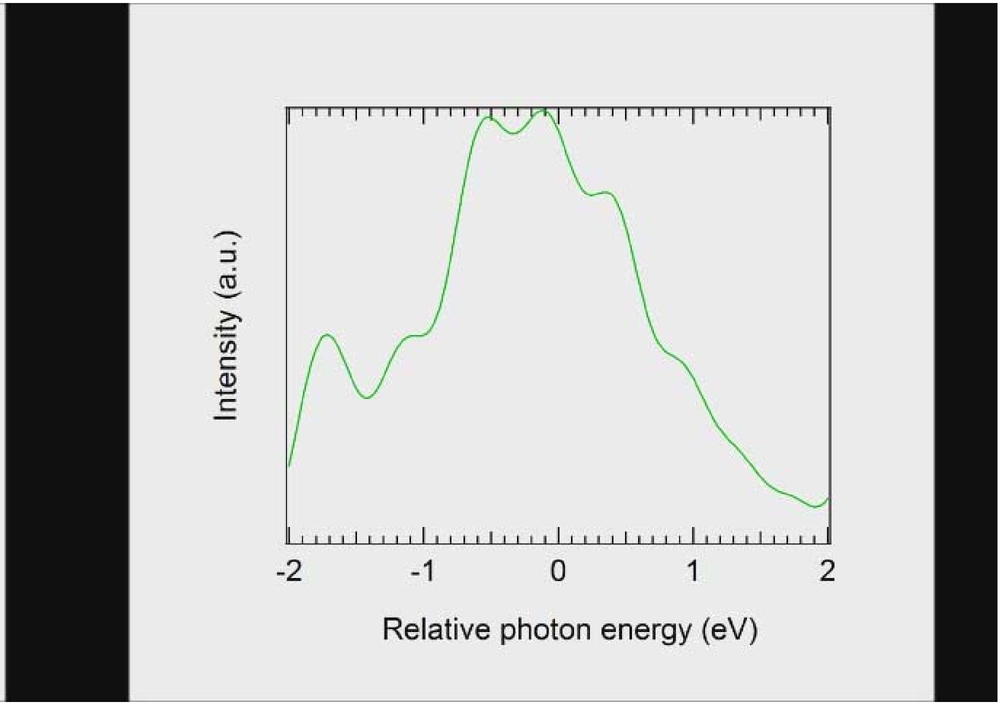
Single-shot spectra: wide range (~100 eV) with Si111

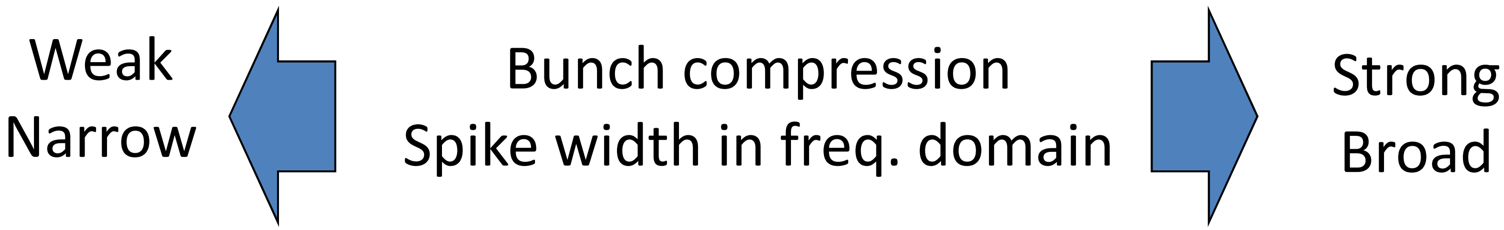


Spike profiles change in every shot due to SASE scheme
But central energy is stable

Single-shot spectra: high-resolution (14 meV) with Si 555

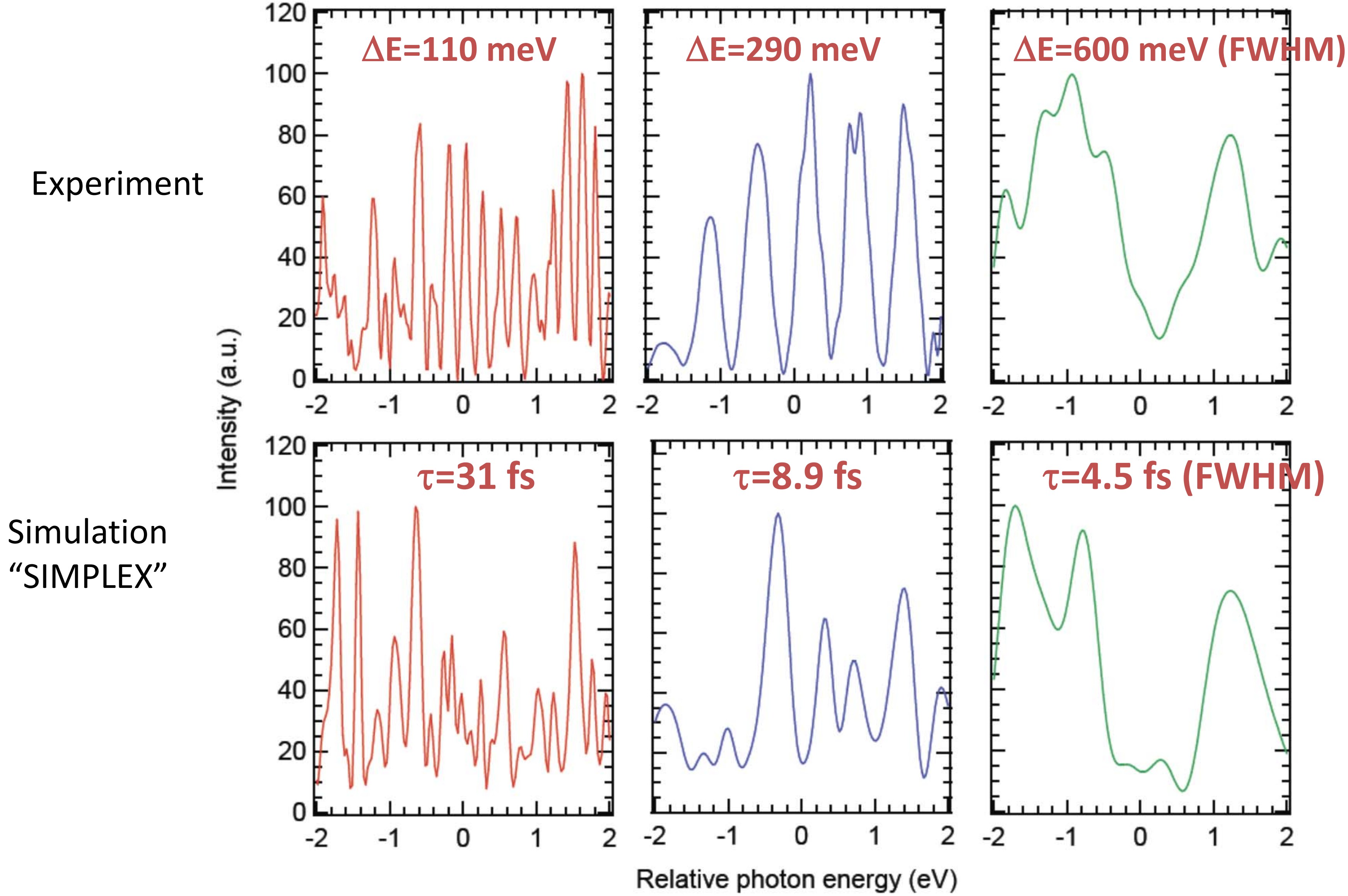






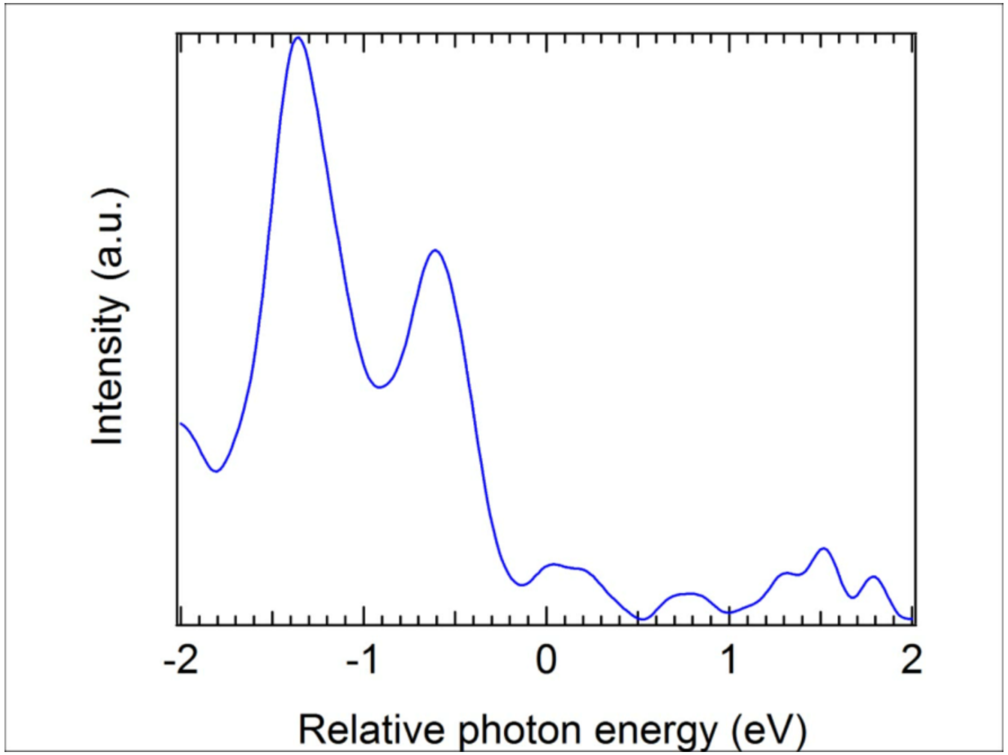
Fourier relationship between temporal and frequency

Evaluation of pulse duration using XFEL simulation



Y. Inubushi, et al, PRL. **109** 144801 (2012).

Recent operation condition (Jan 2013)



ΔE = 400±60 meV → τ ~6.5 ±1.5 fs

300 uJ/pls (@ 10 keV) → 40 GW

Summary of Performance

Pulse Energy	0.3 mJ @10 keV
Photon energy range	4.5 to 15 keV
Stability Intensity $\sigma_{\delta I/I}$	$\leq$ 10%
Pointing	3 ~7% of beam size
Repetition rate	10 Hz (Max. 60 Hz)
Pulse duration	< 10 fs
Peak Power	> 40 GW

Note: recent nonlinear X-ray experiment suggests shorter pulse duration (FWHM: 2.5-2.8 fs, Tamasaku et al, PRL 2013)

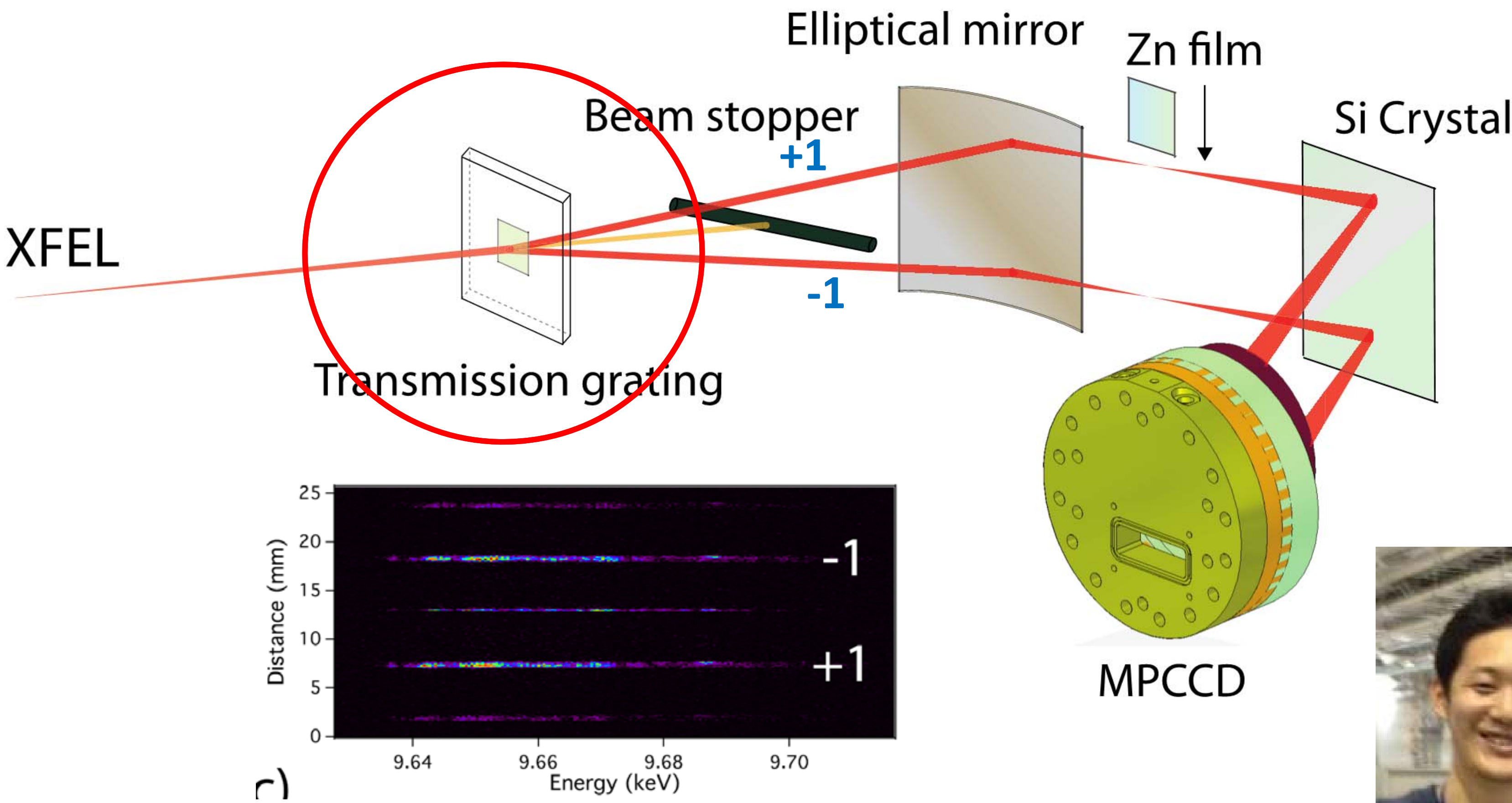
Continue to develop new methods

PRL **111,** 043001 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

Double Core-Hole Creation by Sequential Attosecond Photoionization

Kenji Tamasaku,[1,*] Mitsuru Nagasono,[1,†] Hiroshi Iwayama,[2] Eiji Shigemasa,[2] Yuichi Inubushi,[1] Takashi Tanaka,[1] Kensuke Tono,[3] Tadashi Togashi,[3] Takahiro Sato,[1] Tetsuo Katayama,[3] Takashi Kameshima,[3] Takaki Hatsui,[1] Makina Yabashi,[1] and Tetsuya Ishikawa[1]

Application (II): Dispersive Absorption Spectroscopy

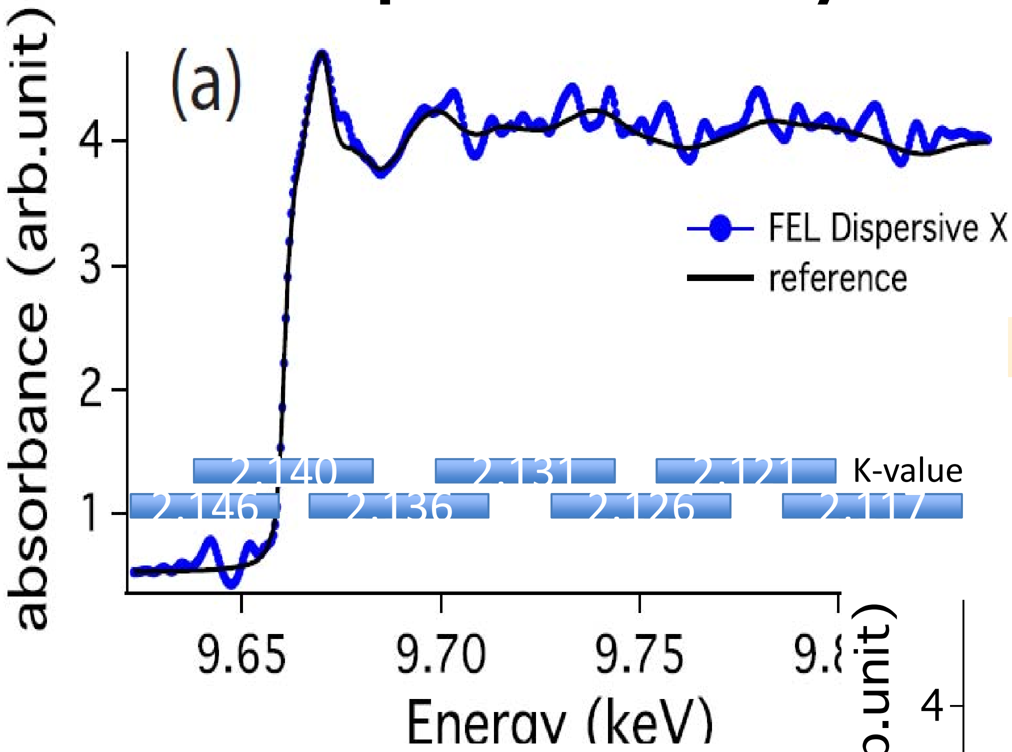


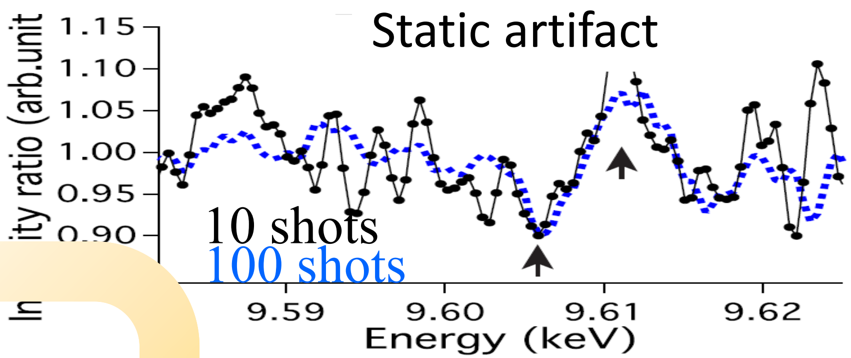
Normalization of SASE spikes by comparing two spectra from +1 and -1 order

Katayama-san (SACLA)

Collaborated with Profs. Toshinori Suzuki (Kyoto U), Kazuhiko Misawa (TUAT) Kiyotaka Asakura (Hokkaido U)

Dispersive X-ray absorption spectrum

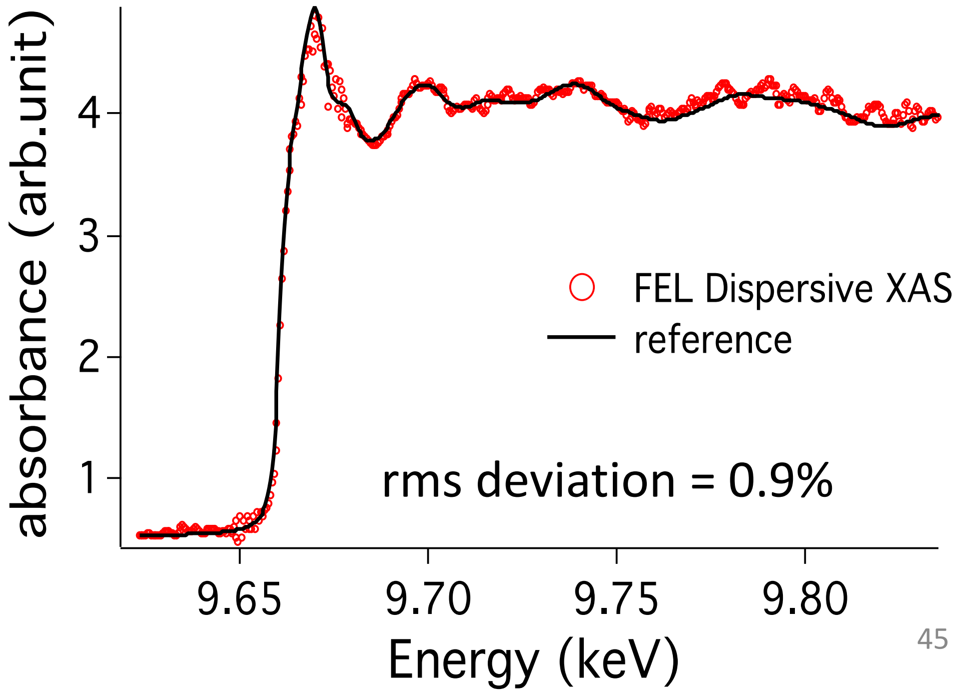




- Zn thickness : 20µm
- 200 shots (one K value)
- Observable range 30 ~ 40 eV (one K value)
- resolution ~0.4 eV

200 shots (20 s) for measuring XAS with good S/N level

Katayama et al, APL, in press



Summary

- Photon diagnostics are practically working for reliable and stable operation of XFEL machine
- Advanced diagnostics promote to develop user experimental methods
- Close collaboration among machine, beamline, and control-interface people is essential

- Absolute pulse energy: easily measured with RT calorimeter
- Spatial profile: screen-based and edge-scan based methods are available, single-shot high-resolution method is demanded
- Wavefront: grating interferometer shows excellent performance
- Spectrum: high resolution below 20 meV with crystal spectrometer, useful for seeded operation
- Arrival timing: below 10 fs is possible
- Pulse duration: still need to develop, especially below 10-fs region

  \- Spectral spikes, THz streaking, auto/cross correlation w XNL

- Still a lot of exciting challenges. Your valuable inputs, proposals, and collaboration are highly appreciated

Acknowledgement

All SACLA/SPring-8 Members

Especially,

Kensuke Tono, Tadashi Togashi, Yuichi Inubushi, Tetsuo Katayama, Kanade Ogawa, Takaki Hatsui, Yasumasa Joti, Togo Kudo, Takashi Kameshima, Yoichi Kirihara, Shun Ono, Hiroaki Kimura, Hiromitsu Tomizawa, Haruhiko Ohashi, Hirokatsu Yumoto, Takahisa Koyama, Shunji Goto, Kenji Tamasaku, Mitsuru Nagasono, Kazuaki Togawa, Takashi Tanaka, Toru Hara, Hitoshi Tanaka, Ryotaro Tanaka, Mitsuhiro Yamaga, Toru Ohata, Yukito Furukawa, Takashi Sugimoto, Hideo Kitamura, & Tetsuya Ishikawa

Yoshiro Fujiwara & Engineering Team

Osaka University

Yasuhisa Sano, Satoshi Matsuyama, Taito Osaka,

Univ. of Tokyo

Hidekazu Mimura, Takahiro Sato, Ichiro Inoue

Thank you for your attention

END