



Frontiers of science at SACLA

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Japan Synchrotron Radiation Research Institute



SPring-8

SACLA



Contents

Brief introduction of SPring-8

Current status of SACLA

Generation of intense XFEL pulses

Applications of intense XFEL pulses

Combination of XFEL and high-power laser

Summary

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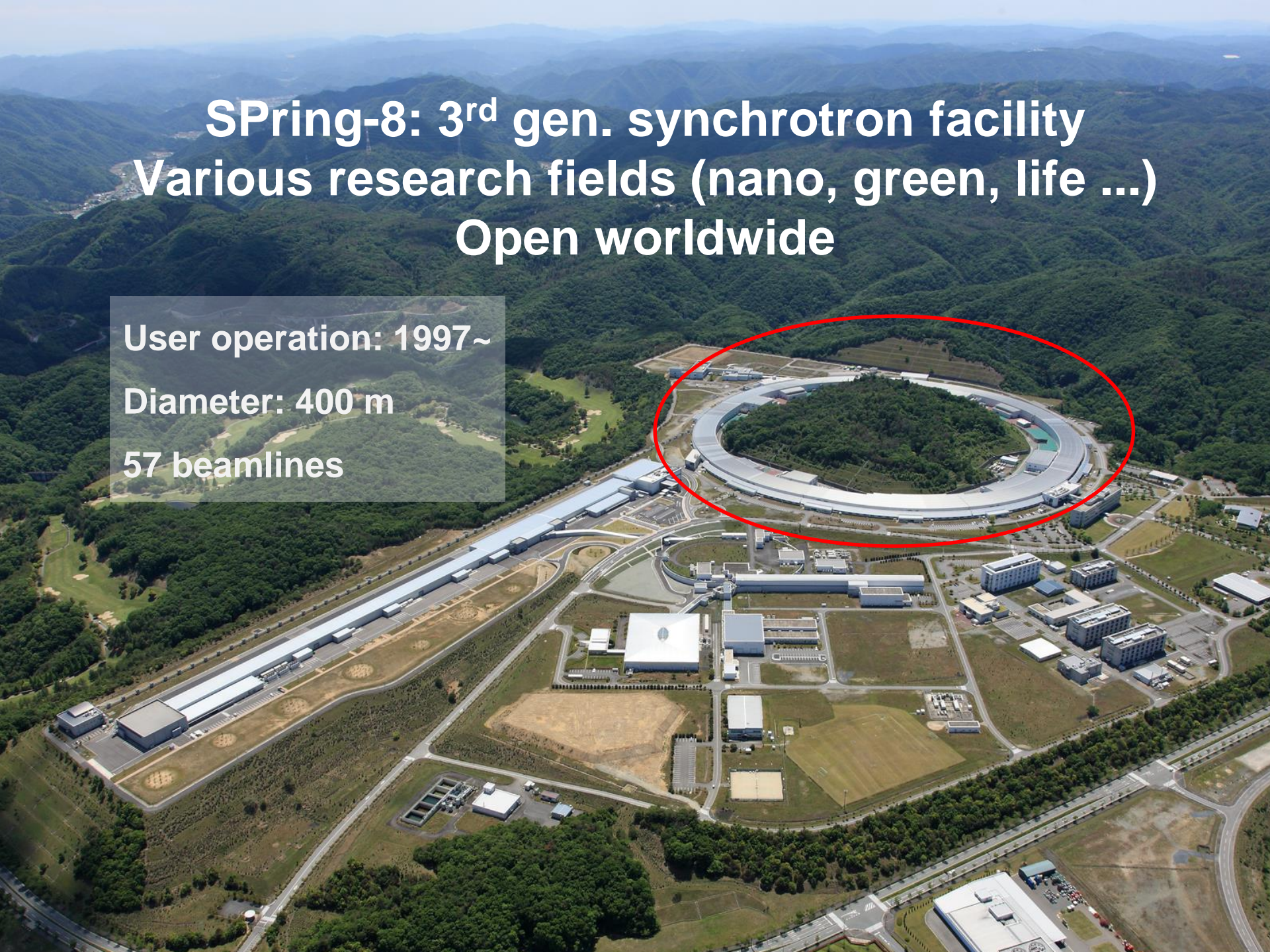
SPring-8: 3rd gen. synchrotron facility

Various research fields (nano, green, life ...)
Open worldwide

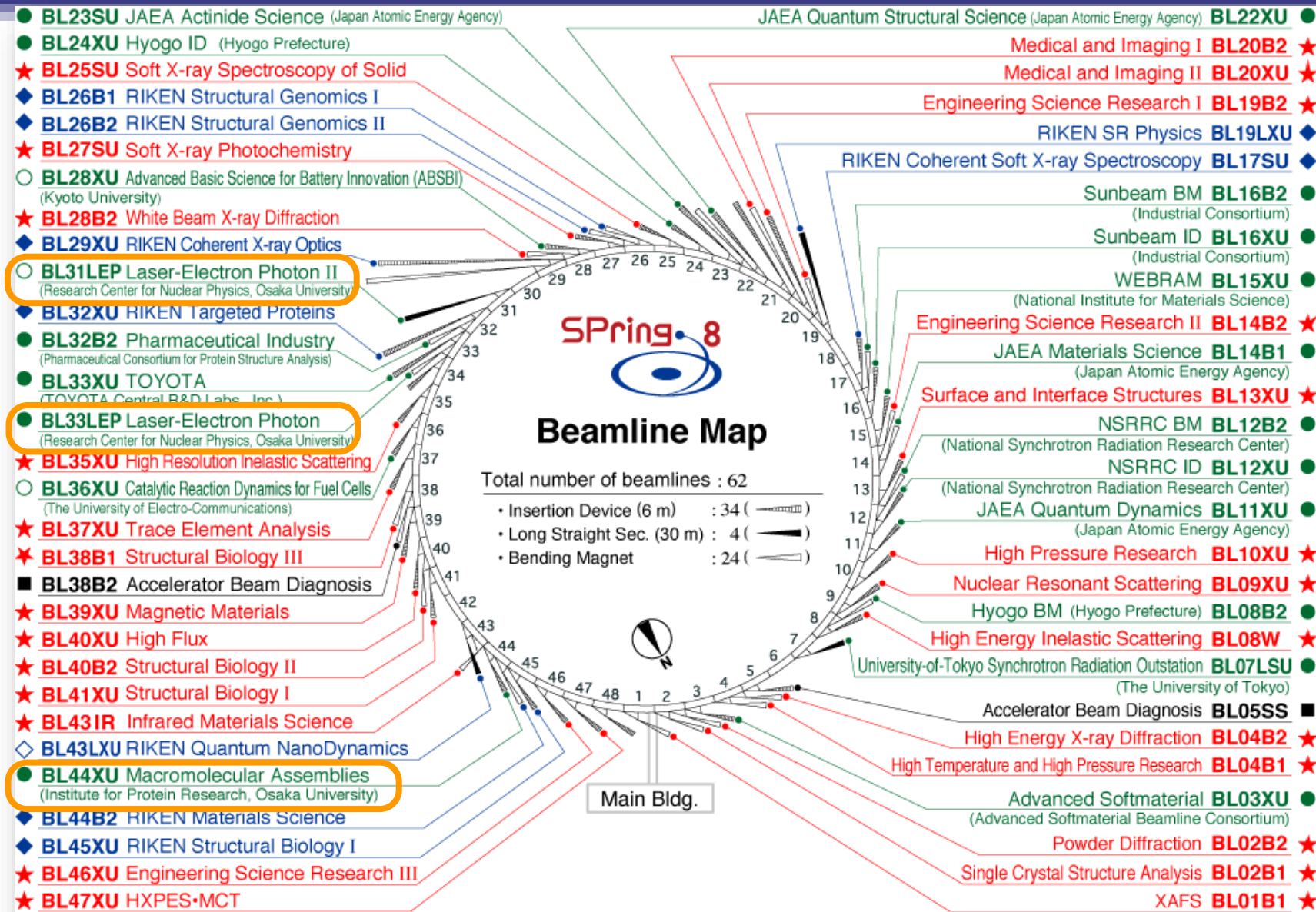
User operation: 1997~

Diameter: 400 m

57 beamlines

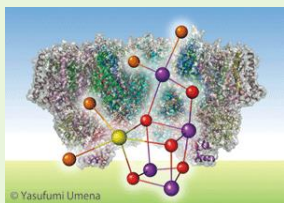


Beamline map



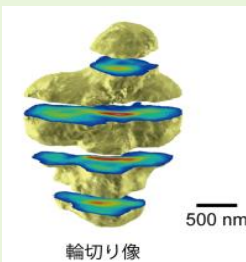
Application fields and achievements of SPring-8

Development of X-ray microscope enabling intracellular 3D imaging



© Yasufumi Umena

Structural elucidation of core protein complex in photosynthesis



輪切り像

Life science



Development of fuel-efficient tires using 3D measurement technique

Material science
Industrial applications

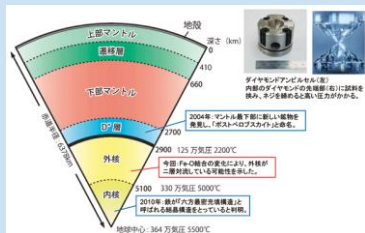
Structural Analysis of Human Hair for development of functional shampoo

Elucidation of anti-carries mechanism of chewing gum



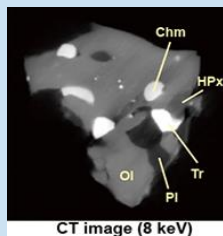
SPring-8

Earth-Planetary science



Earth's internal environment reproduced
Two-layer convection in outer liquid core of earth suggested

Analysis of microparticles brought from Asteroid Itokawa by Hayabusa



CT image (8 keV)

Archeology

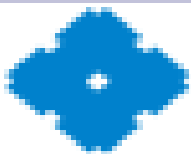


Material investigation of Sankakubuchi Shinjykyo (ancient mirror) by fluorescent X-ray analysis



Materials identified using pieces from old wooden surface

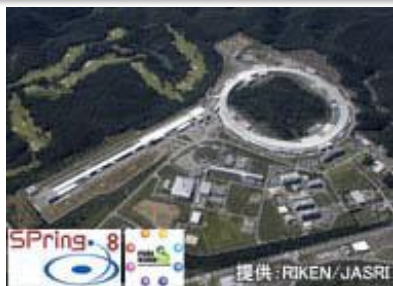
Industrial applications: Molecular Design for Energy Saving Tire



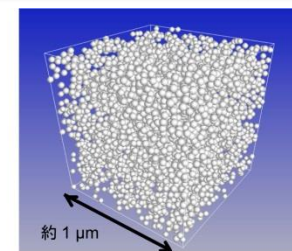
Sumitomo Rubber
Industries Ltd.



Sophisticated Analysis
at FSBL, SPring-8



Multi-Scale Simulation of
Rubber Molecule Dynamics
by Super Computer



President Ikeda presents new energy saving tire. 1st Dec. 2011

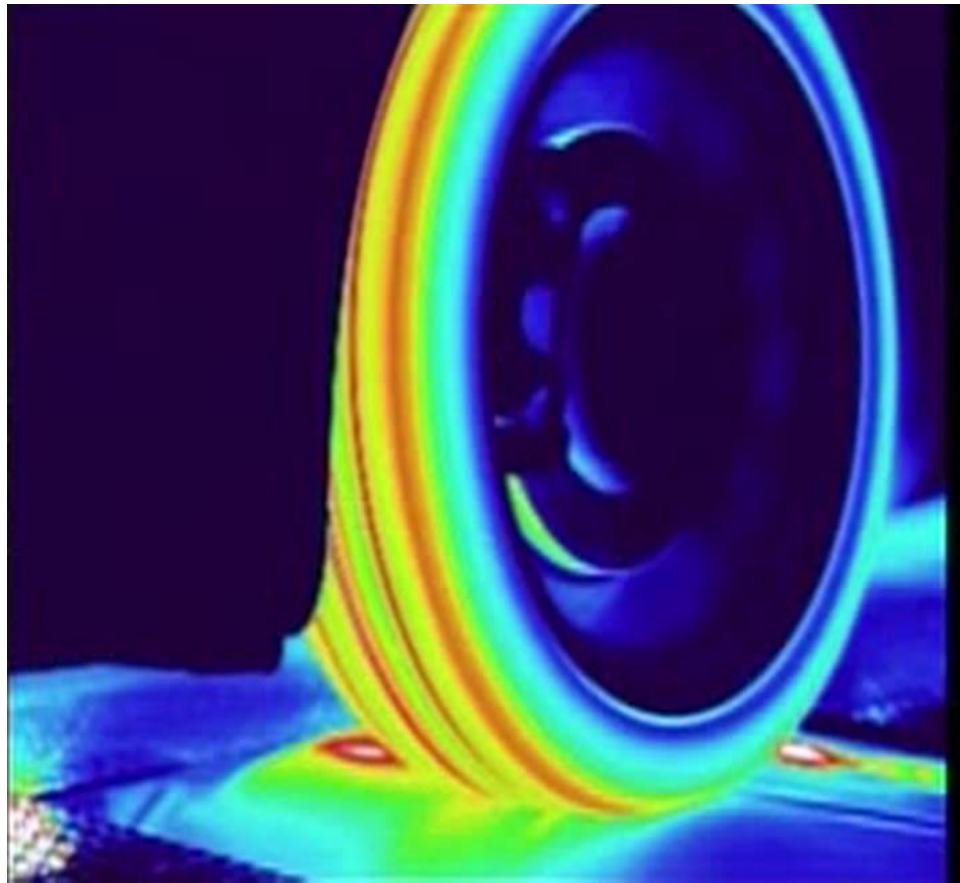


Achieving Improvement
6%: fuel efficiency
39 %: traction performance!

“EnerSave” Premium Performance

Existing Tire

エナセーブ
PREMIUM



Lower Energy Loss

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SACLA

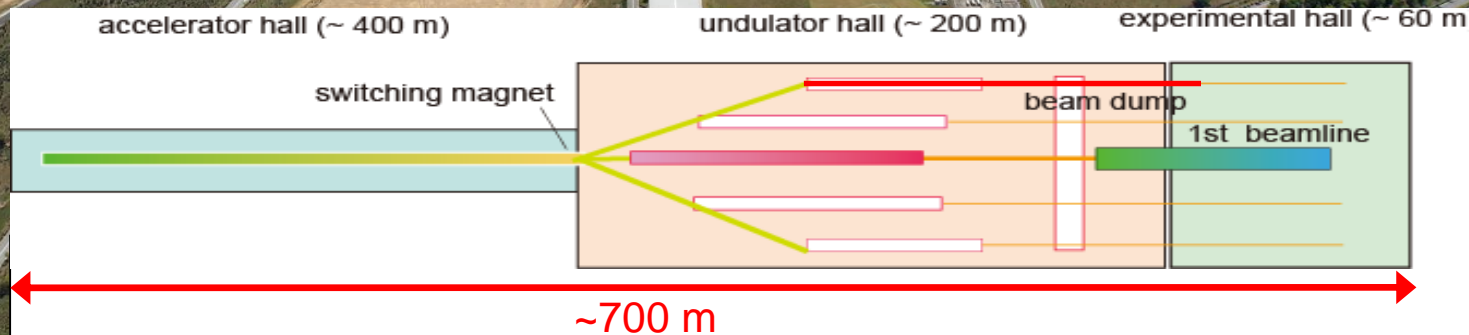
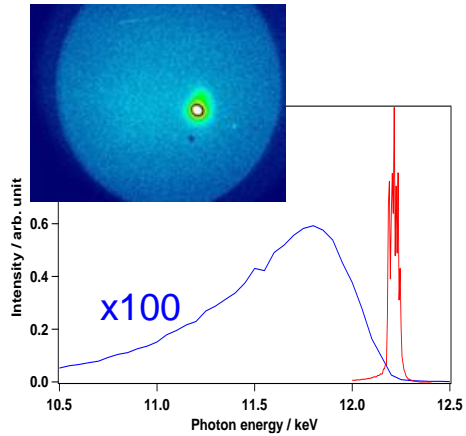
SPring-8 **A**ngstrom **C**ompact free electron **L**aser

First compact XFEL

Construction: 2006~2010

User operation: March 2012~

June, 2011
First Lasing



XFELs in the world

European XFEL



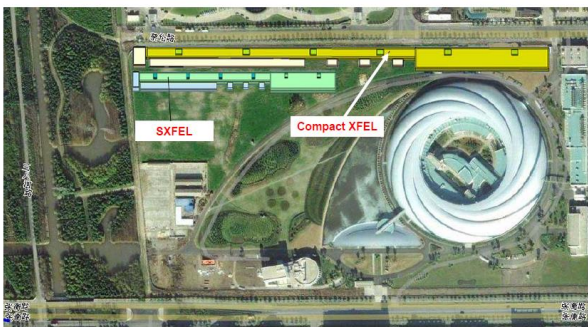
Characteristics of PAL XFEL



LCLS



Layout of Shanghai XFELs



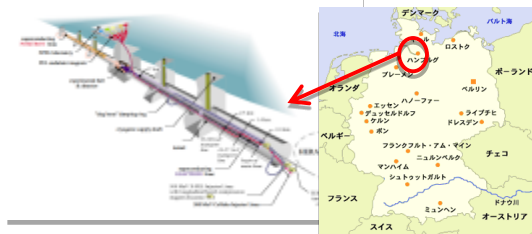
SACLA



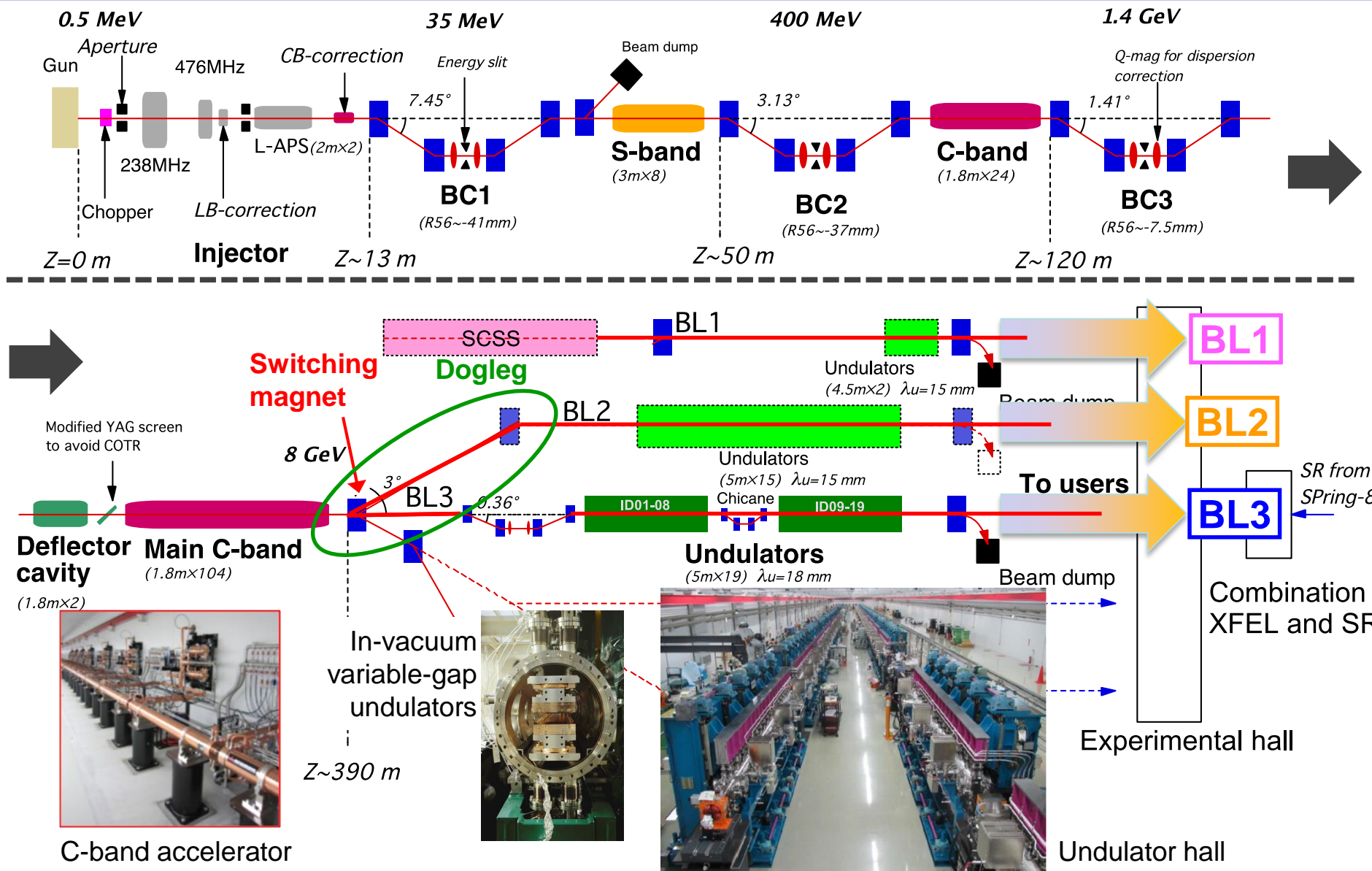
【注1】「●」は予定を要す。なお、拡大図に添付する図1(施設)については、本図では省略の図及び資料を省略している。
 【注2】図中の施設については、「世界のXFEL」(外務省ホームページ)の掲載(2007年11月現在)に準拠し、最新を念頭に適宜改定を要している。

Comparison

	European XFEL	SACLA	LCLS
Length	3.3 km	700 m	~ 2 km
Beam energy	17 GeV	8 GeV	14 GeV
Wave length	0.085 nm	0.06 nm	0.12 nm
Cost	900M Euro	370 M\$	600 M\$
Operation	2017	2011	2009
	Superconducting technology High rep rate High pulse energy	First compact XFEL Short wavelength (sub-Å) Short-pulse operation (~ 10 fs)	First XFEL facility using existing linac High pulse energy

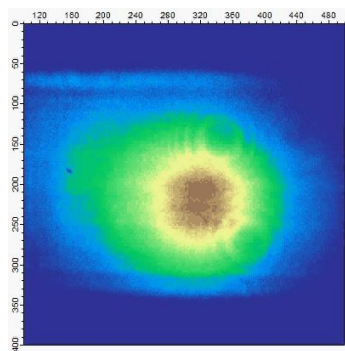


SACLA accelerator and beamlines (2017~)



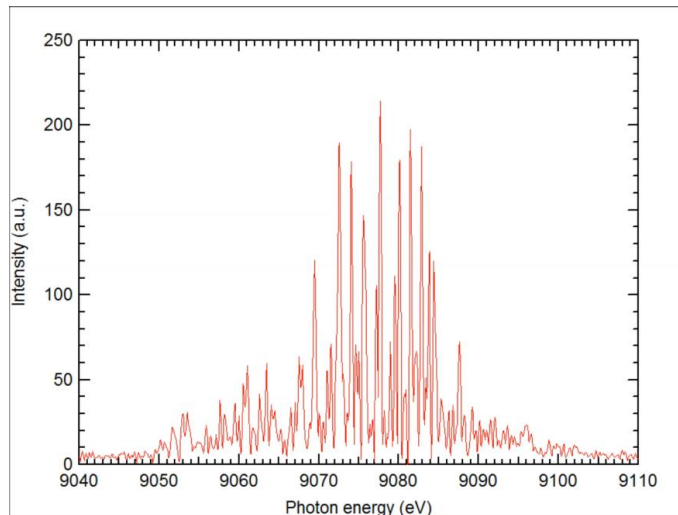
Performance

	BL3	BL2	BL1
Photon energy	4~15 keV	4~15 keV	40 ~ 150 eV
Bandwidth($\Delta E/E$)	$< 5 \times 10^{-3}$	$< 5 \times 10^{-3}$	~ 0.01
Pulse energy	$\sim 500 \mu\text{J}$ @10keV	$\sim 400 \mu\text{J}$ @10keV	$\sim 90 \mu\text{J}$ @ 100 eV
Photon number (/pulse)	$> 10^{11}$ @ 10 keV	$> 10^{11}$ @ 10 keV	$> 10^{12}$ @ 100 eV
Pulse duration	< 10 fs	< 10 fs	< 1 ps
Peak power	$> 50\text{GW}$	$> 40\text{GW}$	> 100 MW
Repetition rate	30Hz (60Hz: Single beamline operation)	30Hz	60Hz



Profile

FWHM: $\sim 300 \mu\text{m}$
10 keV (BL3)



Spectrum

9 keV (BL3)

Y. Inubushi, *et al.*,
PRL **109**, 144801 (2012)
Appl. Sci. **7**, 584 (2017)

Experimental hall

BL3: Hard X-ray FEL (March 2012~)

BL2: Hard X-ray FEL (April 2015~)

BL1: Soft X-ray FEL (July 2016~)

OH: Optics, Monitors

**EH1: Diagnostics:
Spectrum, Timing**

EH2: Pump&Probe

**EH3: 1- μ m focusing:
Imaging, Crystallography**

**EH4c: 1- μ m focusing:
Pump&Probe,
Nonlinear optics**

**Synchronized
optical laser**

**SACLA-SPring-8
Experimental Facility**

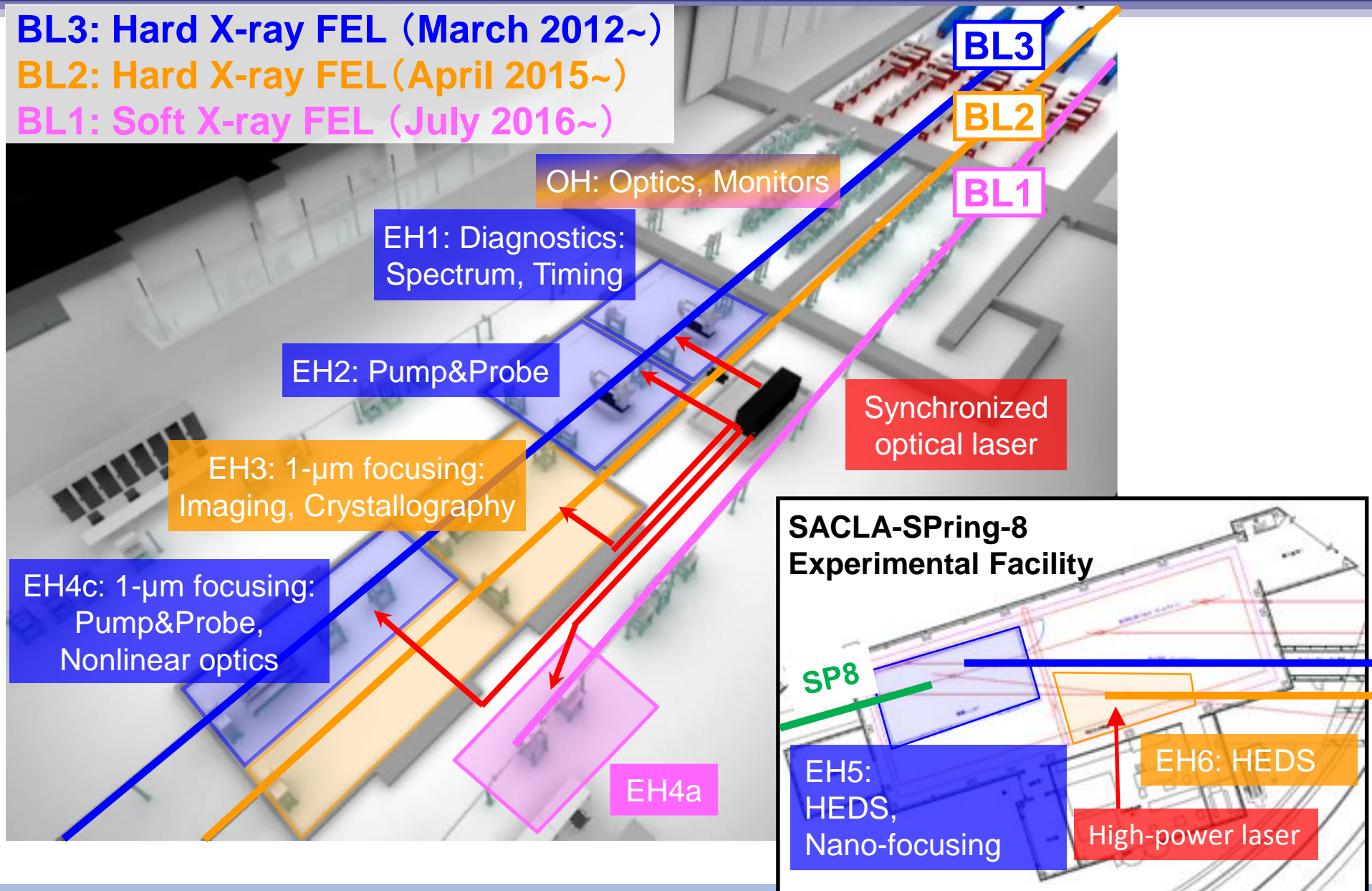
SP8

**EH5:
HEDS,
Nano-focusing**

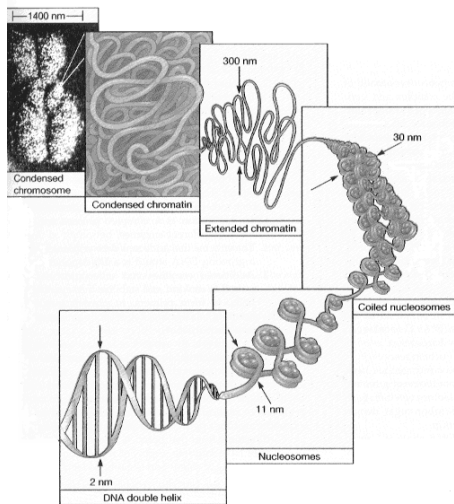
EH6: HEDS

High-power laser

EH4a

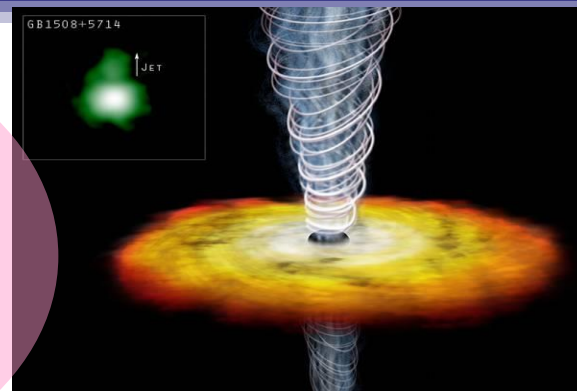


XFEL sciences



Imaging Biology

Brilliance
($\times 10^9$)

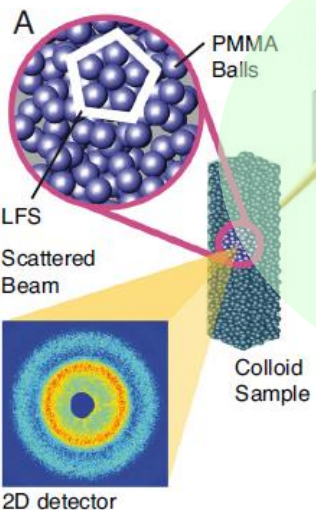


NL & Quantum X-ray Science
High Energy Density Science
AMO science

XFEL

Protein Crystallography
Ultrafast Materials Science

Coherent
(~100% in transverse)



Ultrafast X-Ray Diffraction

Ultrafast (~10 fs)

The diagram illustrates the timing of X-ray and light pulses. It shows three sequential pulses: X-Ray Pulse, Light Pulse, and X-Ray Pulse. The resulting diffraction patterns are shown as a series of frames.

Movie of Atomic Movement

The movie shows three frames of atomic movement, represented by a grid of atoms that changes shape over time.

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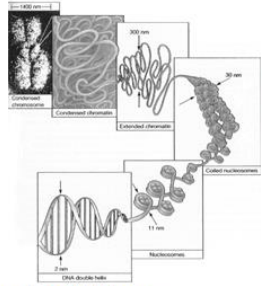
Generation of intense XFEL pulses

Application of intense XFEL pulses

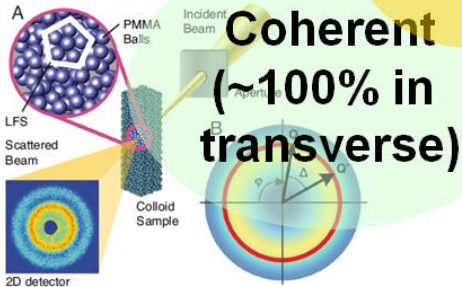
Combination of XFEL and high-power laser

Summary

Intense XFEL pulses has opened new sciences



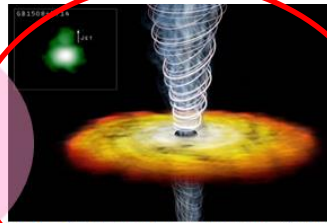
Imaging Biology



Coherent
(~100% in transverse)

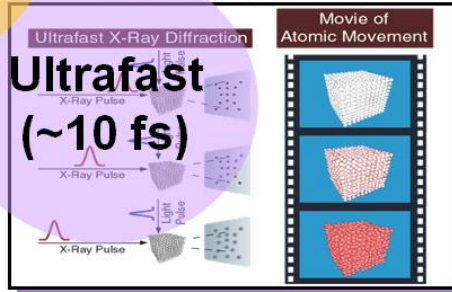
Brilliance
(X10⁹)

XFEL



NL & Quantum X-ray Science
High Energy Density Science
AMO science

Protein Crystallography
Ultrafast Materials Science



Ultrafast
(~10 fs)

Application of intense X-ray source as a pumping source

This is a new experimental scheme, which has opened by XFEL.

Intensity

$$I = \frac{E}{\tau \cdot S} \quad (\text{W/cm}^2)$$

Pulse energy

Pulse duration

Area of XFEL beam

Development of single-shot spectrometer and the application for temporal characterization

Fully-resolved whole single-shot XFEL spectrum is applicable to temporal characterization

Frequency domain \longleftrightarrow FT \longleftrightarrow Temporal domain

Pulse duration \leftarrow **Spike width**

Spectral resolution: < 100 meV

$$\frac{dE}{E} = \frac{\sqrt{(p/L)^2 + \omega^2}}{\tan \theta_B}$$

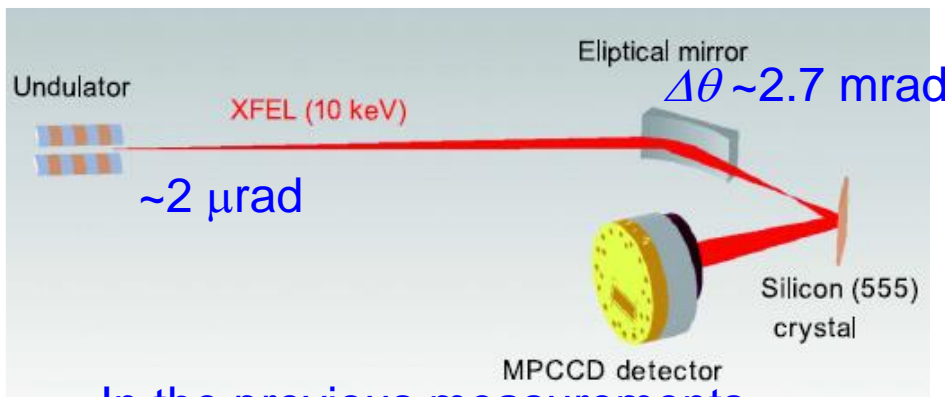
p : Pixel size
 L : Distance from source to detector
 ω : Darwin width
 θ_B : Bragg angle

Longitudinal mode number

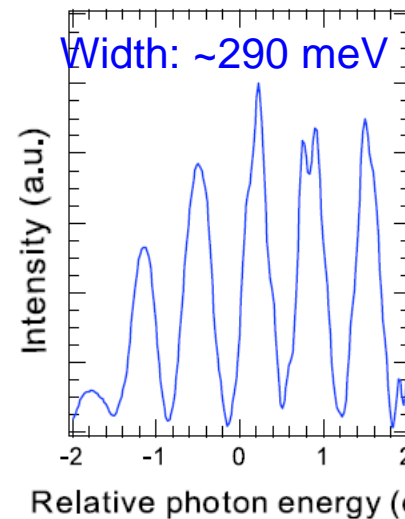
\leftarrow **Number of spikes**

Observation range: > 50 eV

$$\frac{\Delta E}{E} = \frac{\Delta \theta}{\tan \theta_B} \quad \Delta \theta: \text{angular divergence on analyzer crystal}$$



In the previous measurements, $\Delta \theta$ is too small to cover whole spectrum.

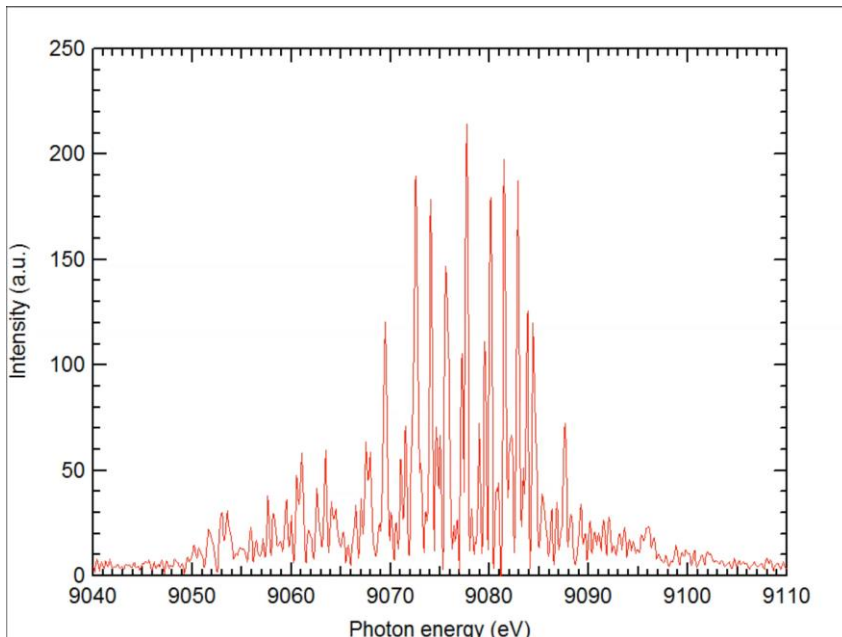
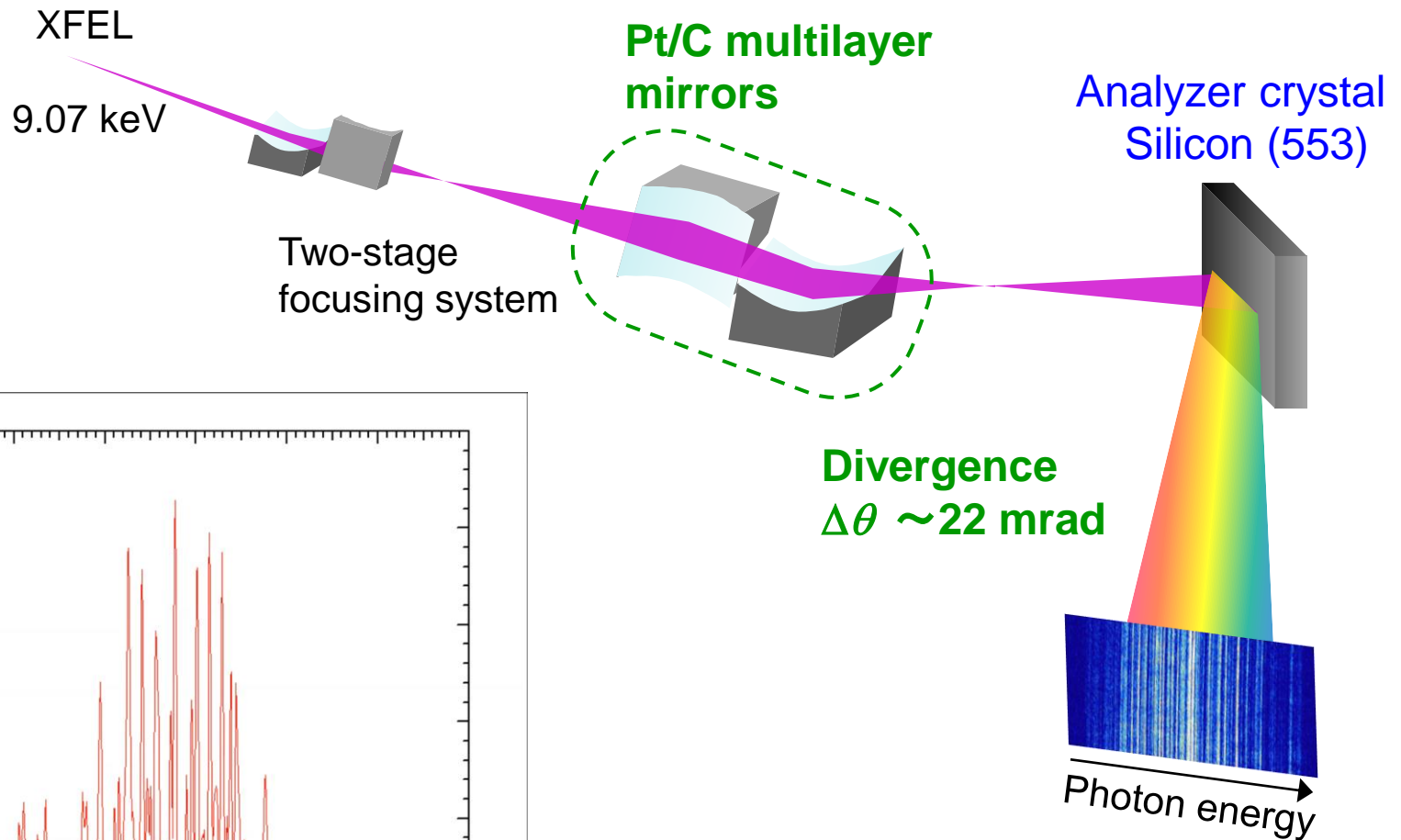


Resolution: ~ 15 meV

Range: ~ 4eV

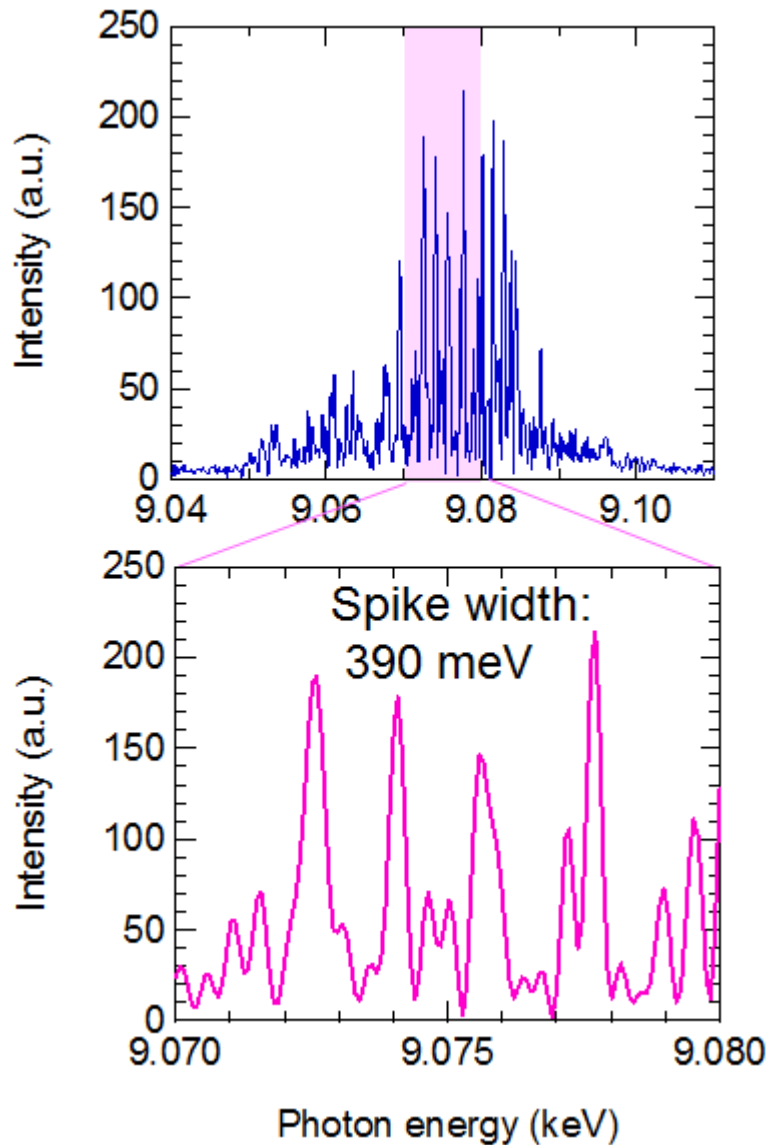
Y. Inubushi, *et al*, PRL. **109** 144801 (2012).

Single-shot spectrometer with multilayer mirror

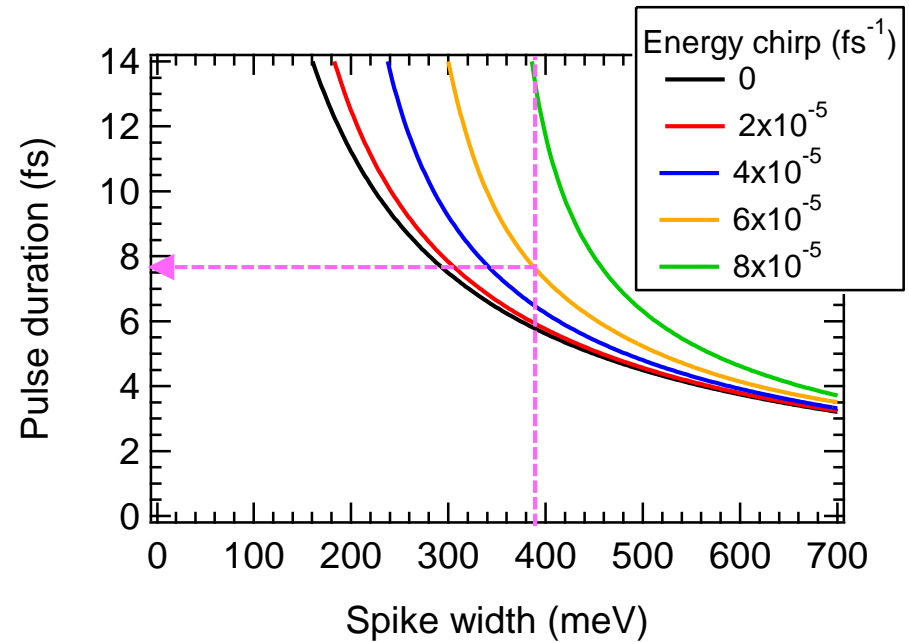


Spectral resolution: ~ 80 meV
Observation range: ~ 60 eV

Pulse duration and longitudinal mode number



Determination of pulse duration

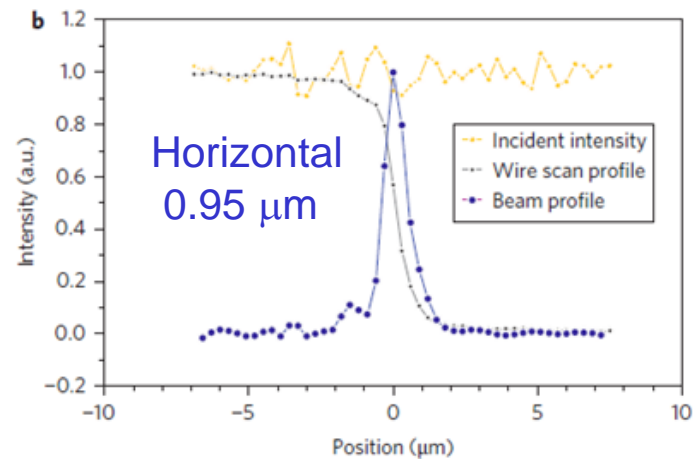
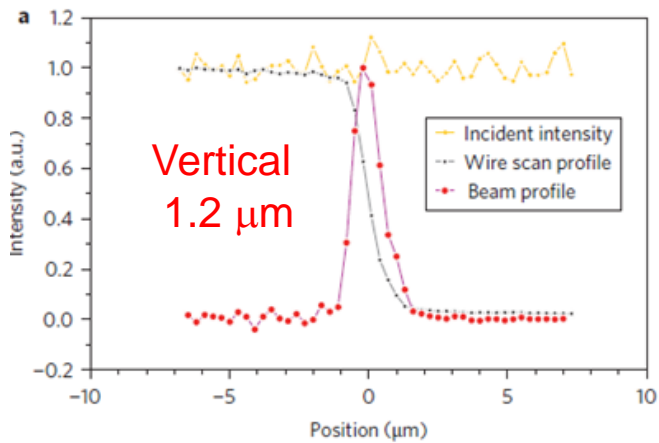
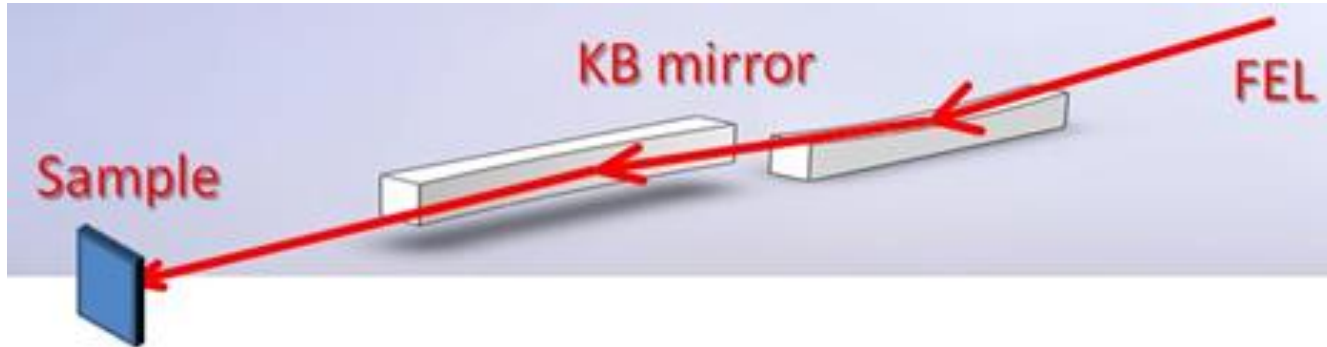


Pulse duration: ~ 8 fs

(assuming energy chirp of $6 \times 10^{-5} \text{ fs}^{-1}$)

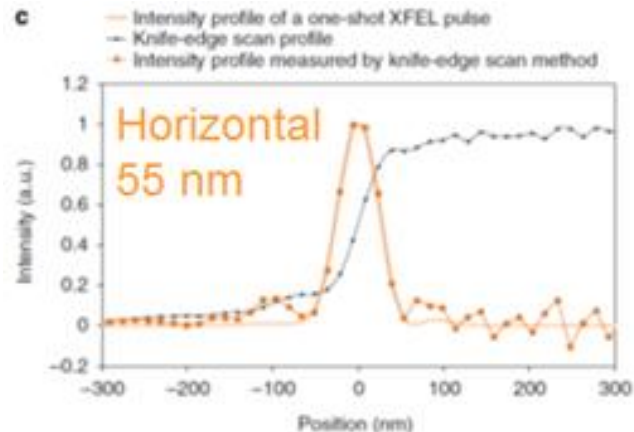
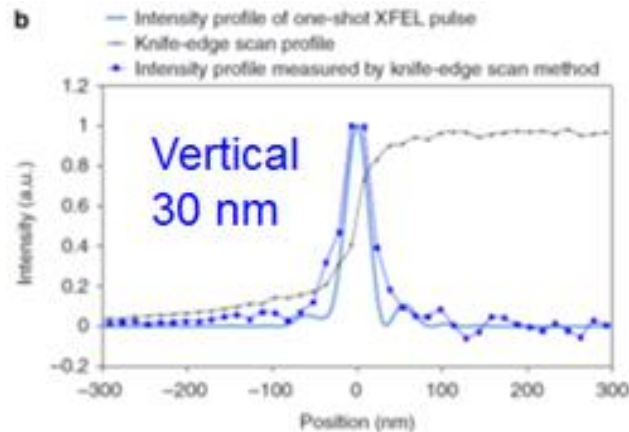
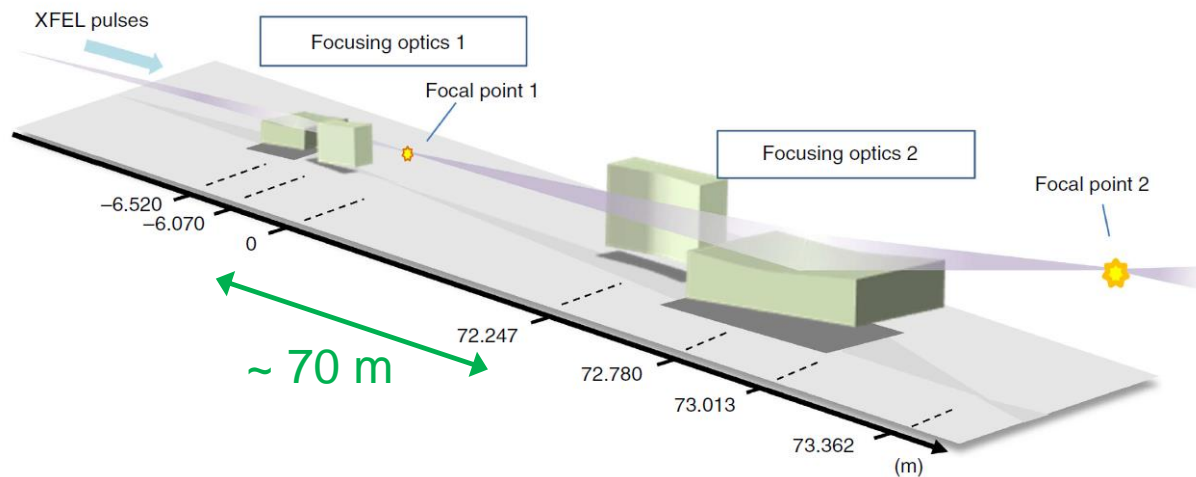
Longitudinal mode number: ~ 60

1- μm focusing system



$\sim 10^{18}$ W/cm²

2-stage focusing system



$\sim 10^{20}$ W/cm²

Parameters of XFEL pulse

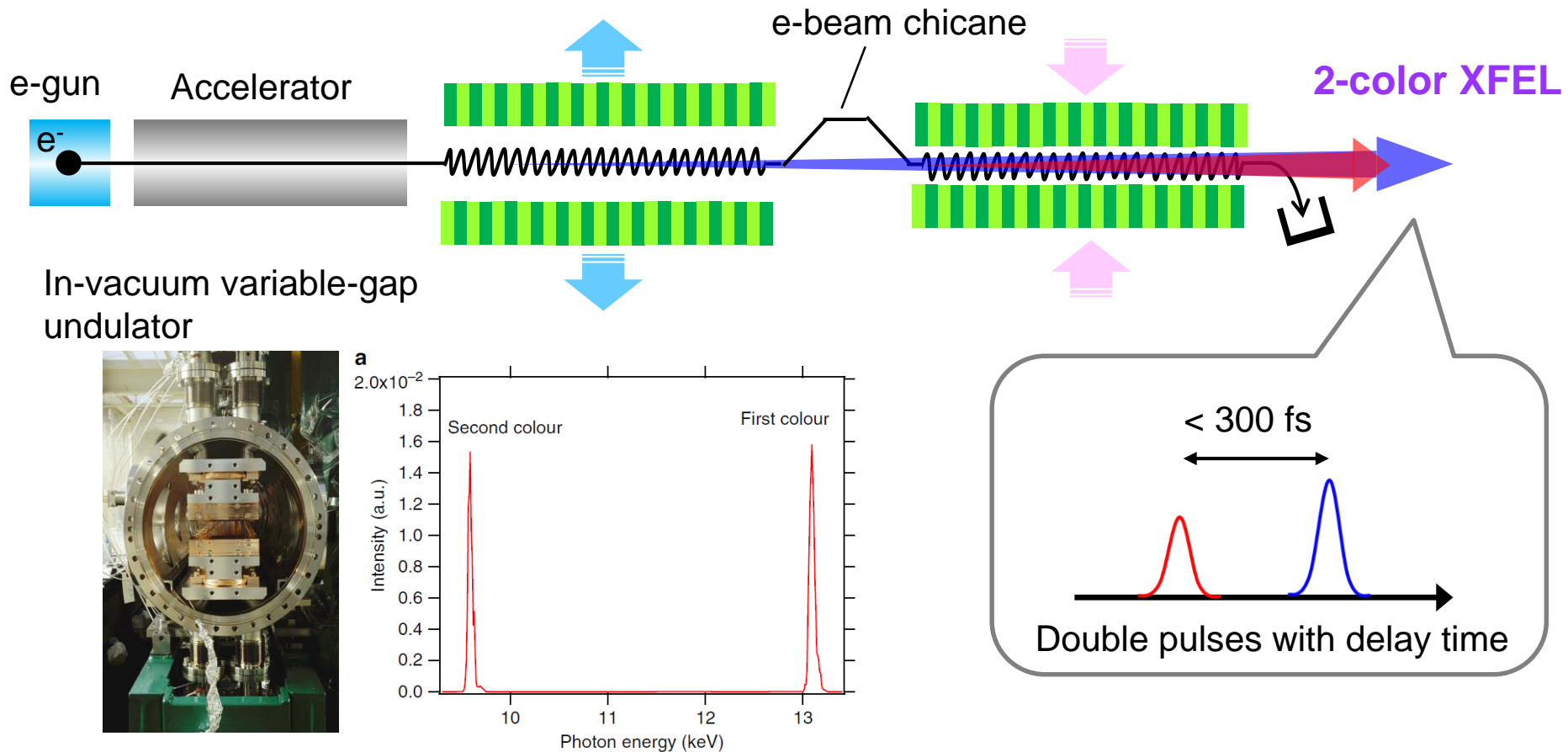
Pulse energy:	500 μJ @10keV (Throughput depends on optics)
Pulse duration:	~ 8 fs
Bandwidth:	~ 40 eV
Peak power:	~ 50 GW
Intensity:	$\sim 10^{14}$ W/cm ² (300 $\mu\text{m}\phi$, raw beam) $\sim 10^{18}$ W/cm ² (1 $\mu\text{m}\phi$) $\sim 10^{20}$ W/cm ² (50 nm ϕ)

2-color double-pulse XFEL

Applicable to XFEL pump - probe

- 2-color XFEL with the energy separation up to 30 %
- Setting of delay time between two pulses

T. Hara, *et al.*,
Nature Commun. **4**, 2919
(2013)



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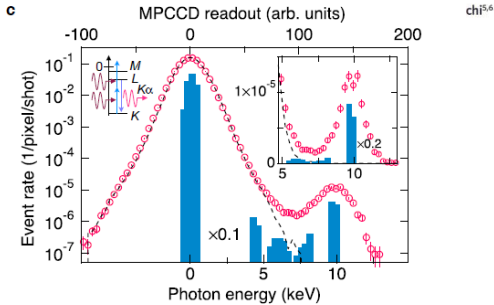
Applications of intense XFEL pulses

X-ray two-photon absorption

nature photonics LETTERS
PUBLISHED ONLINE: 16 FEBRUARY 2014 | DOI: 10.1038/NPHOTON.2014.10

X-ray two-photon absorption competing against single and sequential multiphoton processes

Kenji Hiroki and Ti



Tamasaku et al.,
Nature Photon 8
313 (2014)

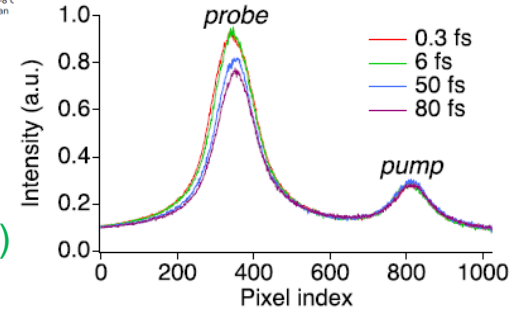
Femtosecond damages

Observation of femtosecond X-ray interactions with matter using an X-ray-X-ray pump-probe scheme

PNAS
Ichiro Inoue^{a,b,1}, Yuichi Inubushi^{b,c}, Takahiro Sato^{b,2}, Kensuke Tono^{b,c}, Tetsuo Katayama^{b,c}, Takashi Kameshima^{b,c}, Kanade Ogawa^{b,3}, Tadashi Togashi^{b,c}, Shigeki Owada^b, Yoshiyuki Amemiya^a, Takashi Tanaka^b, Toru Hara^a, and Makina Yabashi^{b,c,1}

¹Department of Advanced Materials Science, Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan; ²RIKEN Spring-8 CTR, Hyogo 679-5198, Japan; ³Sayo, Japan

Inoue et al.,
PNAS 113 1497 (2016)



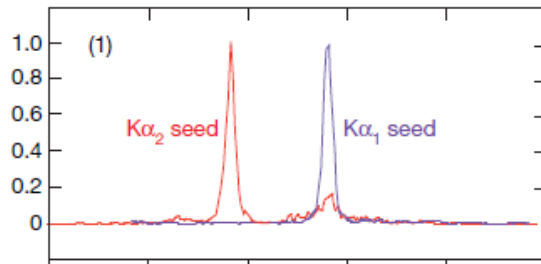
LETTER

doi:10.1038/nature14894

Atomic inner-shell laser at 1.5-ångström wavelength pumped by an X-ray free-electron laser

Hitoki Yoneda^{1,2}, Yuichi Inubushi^{2,3}, Kazunori Nagamine¹, Yurina Michine¹, Haruhiko Ohashi^{2,3}, Hirokatsu Yumoto², Kazuto Yamauchi^{2,4}, Hidekazu Mimura^{2,5}, Hikaru Kitamura², Tetsuo Katayama², Tetsuya Ishikawa² & Makina Yabashi²

Yoneda et al.,
Nature 524 446
(2015)



XFEL-pumped K α laser



Contents lists available at ScienceDirect

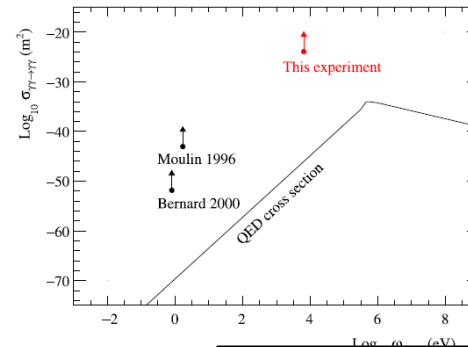
Physics Letters B

www.elsevier.com/locate/physletb



Search for photon-photon elastic scattering in the X-ray region

T. Inada^{a,*}, T. Yamaji^{a,*}, S. Adachi^a, T. Namba^b, S. Asai^a, T. Kobayashi^b, K. Tamasaku^c, Y. Tanaka^c, Y. Inubushi^c, K. Sawada^c, M. Yabashi^c, T. Ishikawa^c



Prof. Asai (U Tokyo)

Inada, Namba et al.,
Phys Lett B
732, 356-359 (2014)

Photon-photon scattering

Interaction of intense XFEL pulses with matter

- Low ponderomotive force ($\propto \sqrt{\lambda^2}$) due to short wavelength
- **Penetration to matters (Cut-off density: $\sim 10^{29} \text{ cm}^{-3}$)**
- **Ionization and excitation of inner-shell electrons due to high photon energy**

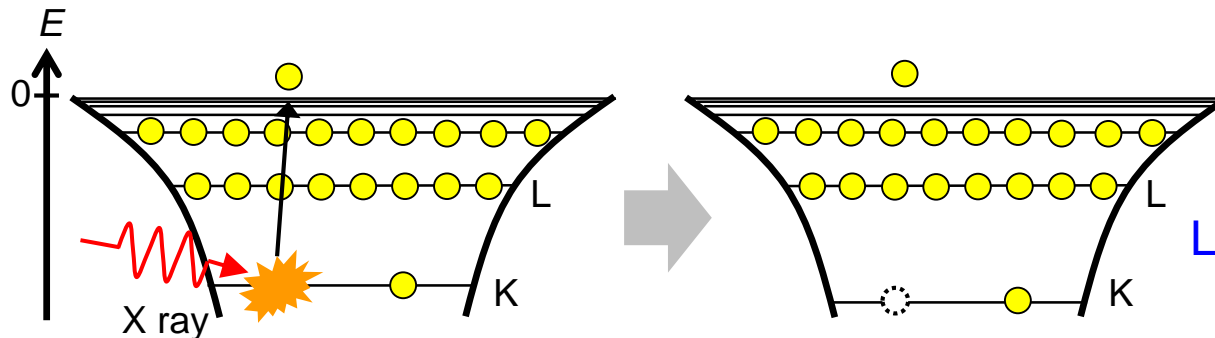
XFEL photon energy

4~15keV



corresponding to transition energy of inner-shell electrons

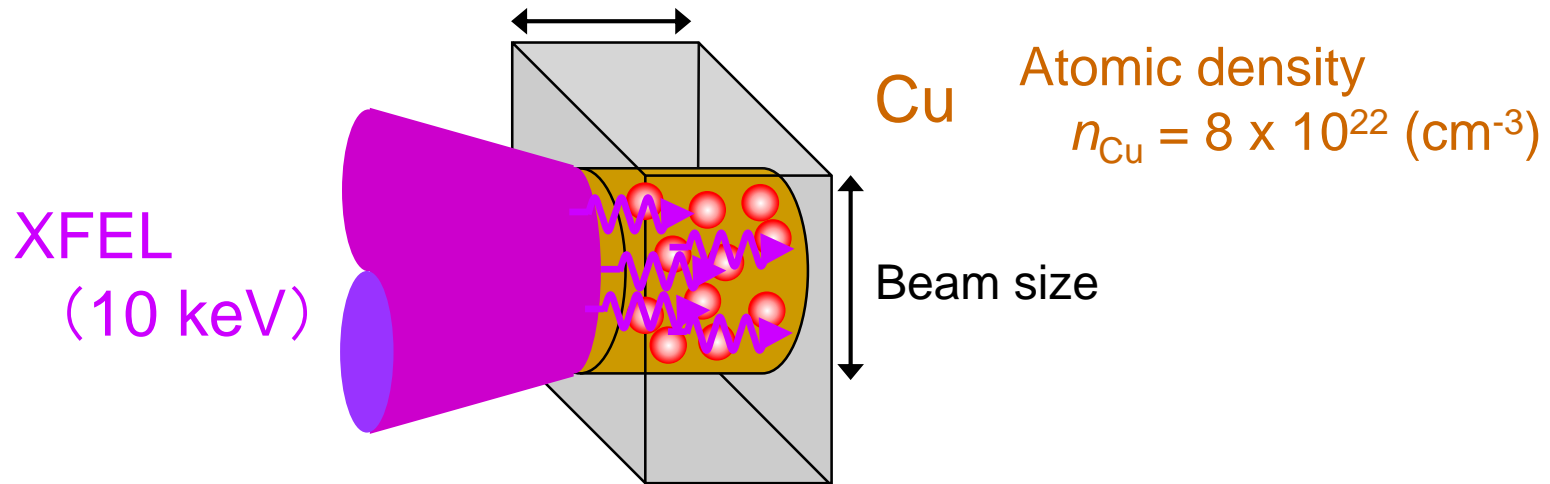
1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe



Lifetime: asec~ fsec

XFEL photon density (10keV, Cu sample)

Attenuation length ($\sim 5 \mu\text{m}$ @ 10keV)



XFEL beam size	Intensity (W/cm^2)	Absorbed photon density (cm^{-3})
Un-focus ($300 \mu\text{m} \phi$)	$\sim 10^{14}$	$\sim 10^{17}$ ($\ll n_{\text{Cu}}$)
1- μm focus	$\sim 10^{18}$	$\sim 10^{22}$ ($< n_{\text{Cu}}$)
100-nm focus	$\sim 10^{20}$	$\sim 10^{23}$ ($> n_{\text{Cu}}$)

Cross section of K-shell \gg Lshell
 Almost all atoms become "core-hole atoms".

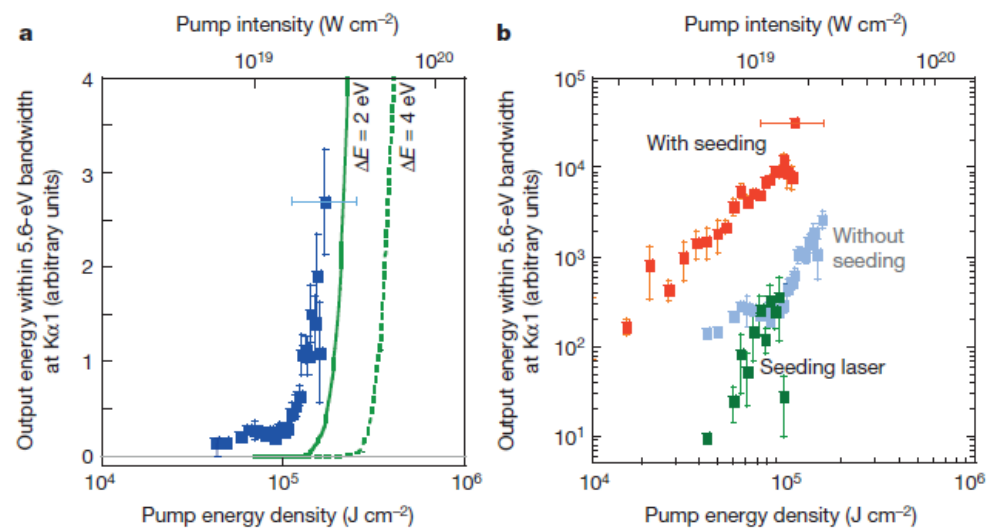
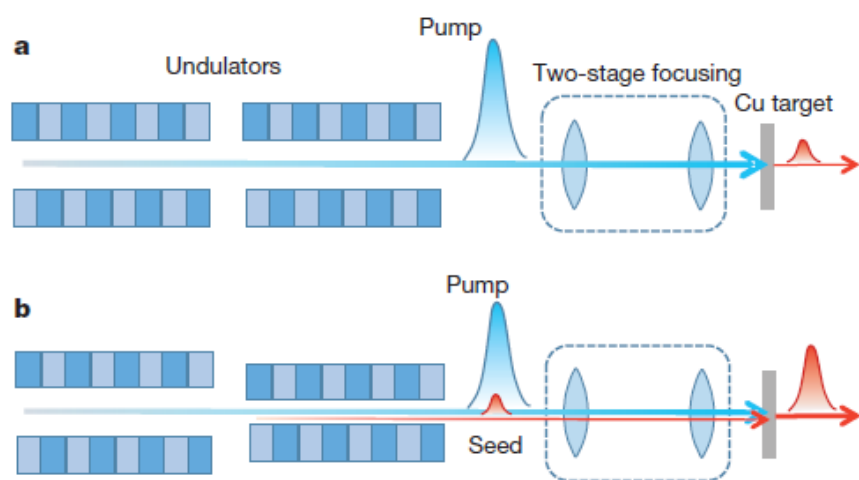
$K\alpha$ laser pumped by intense XFEL pulse

LETTER

446 | NATURE | VOL 524 | 27 AUGUST 2015

Atomic inner-shell laser at 1.5-ångström wavelength pumped by an X-ray free-electron laser

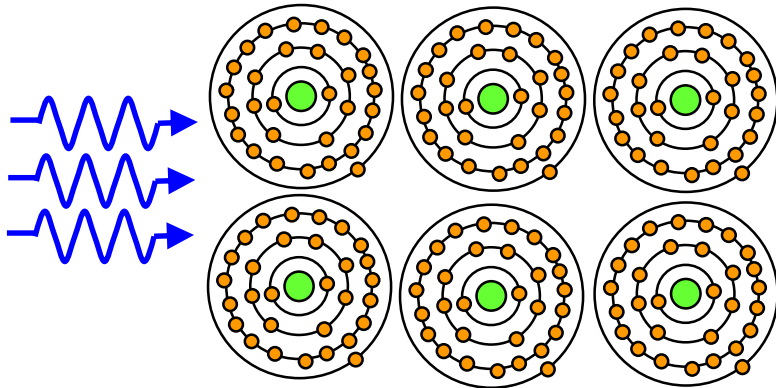
Hitoki Yoneda^{1,2}, Yuichi Inubushi^{2,3}, Kazunori Nagamine¹, Yurina Michine¹, Haruhiko Ohashi^{2,3}, Hirokatsu Yumoto³, Kazuto Yamauchi^{2,4}, Hidekazu Mimura^{2,5}, Hikaru Kitamura⁶, Tetsuo Katayama³, Tetsuya Ishikawa² & Makina Yabashi²



$K\alpha$ laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.

Weak X rays



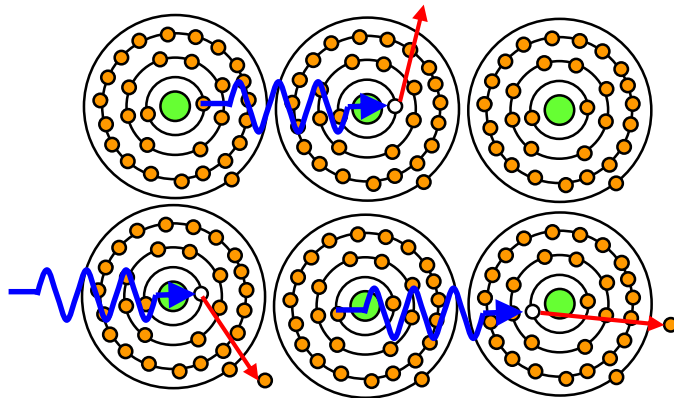
Incidence of X rays

Intense XFEL

$K\alpha$ laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.

Weak X rays



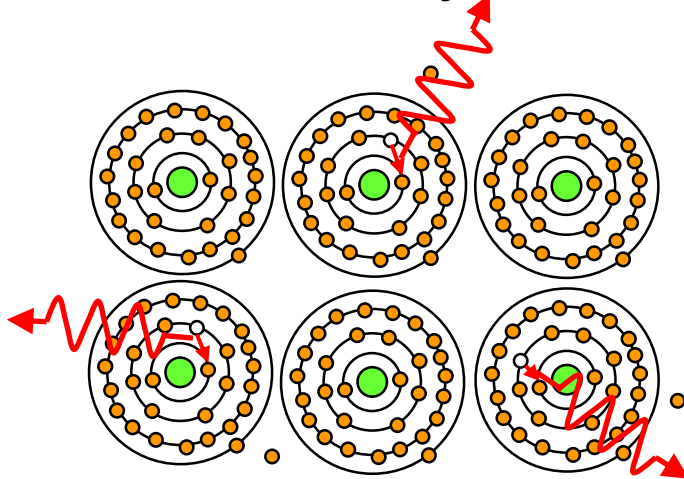
Creation of core-hole atoms

Intense XFEL

$K\alpha$ laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.

Weak X rays

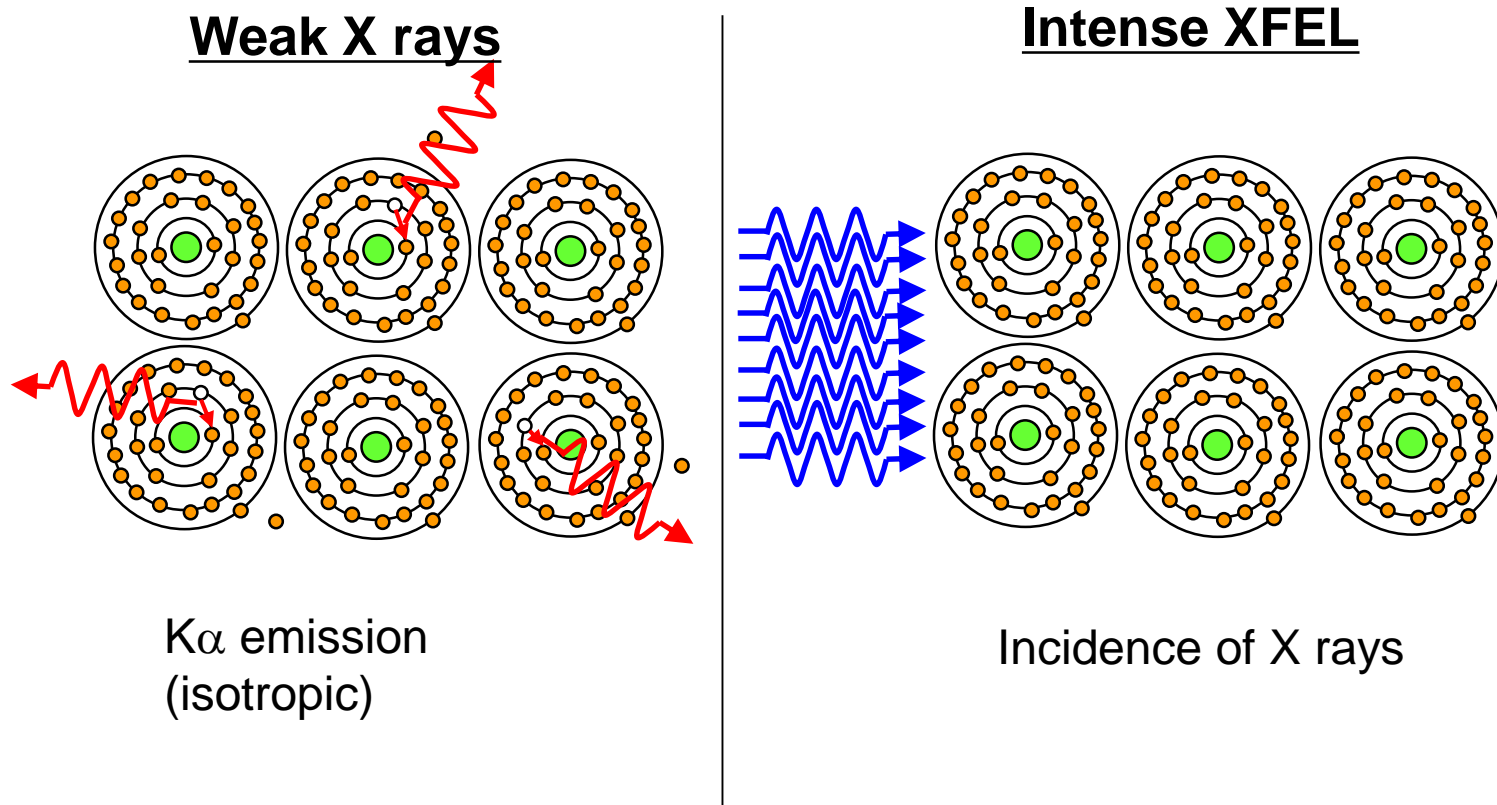


$K\alpha$ emission
(isotropic)

Intense XFEL

$K\alpha$ laser pumped by intensifier

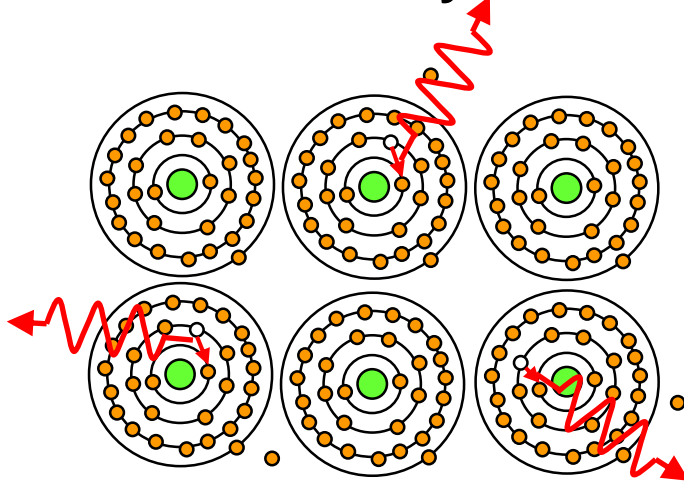
Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.



$K\alpha$ laser pumped by intensifier

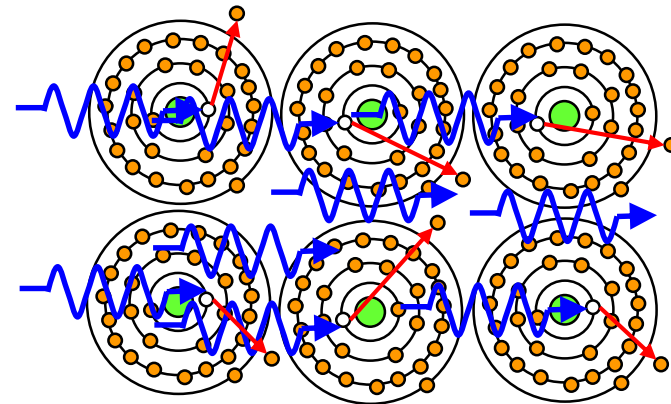
Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.

Weak X rays



$K\alpha$ emission
(isotropic)

Intense XFEL



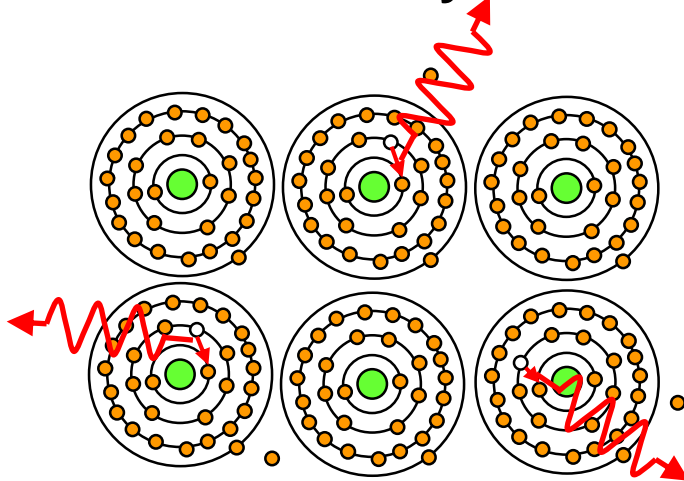
Creation of core-hole atoms

⇒ Population inversion

$K\alpha$ laser pumped by intense XFEL

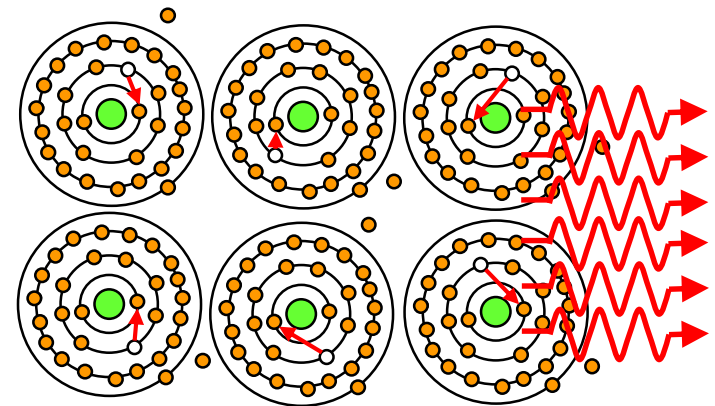
Intense XFEL create a lot of core-hole atoms.
Then, $K\alpha$ emission becomes laser via stimulated emission process.

Weak X rays



$K\alpha$ emission
(isotropic)

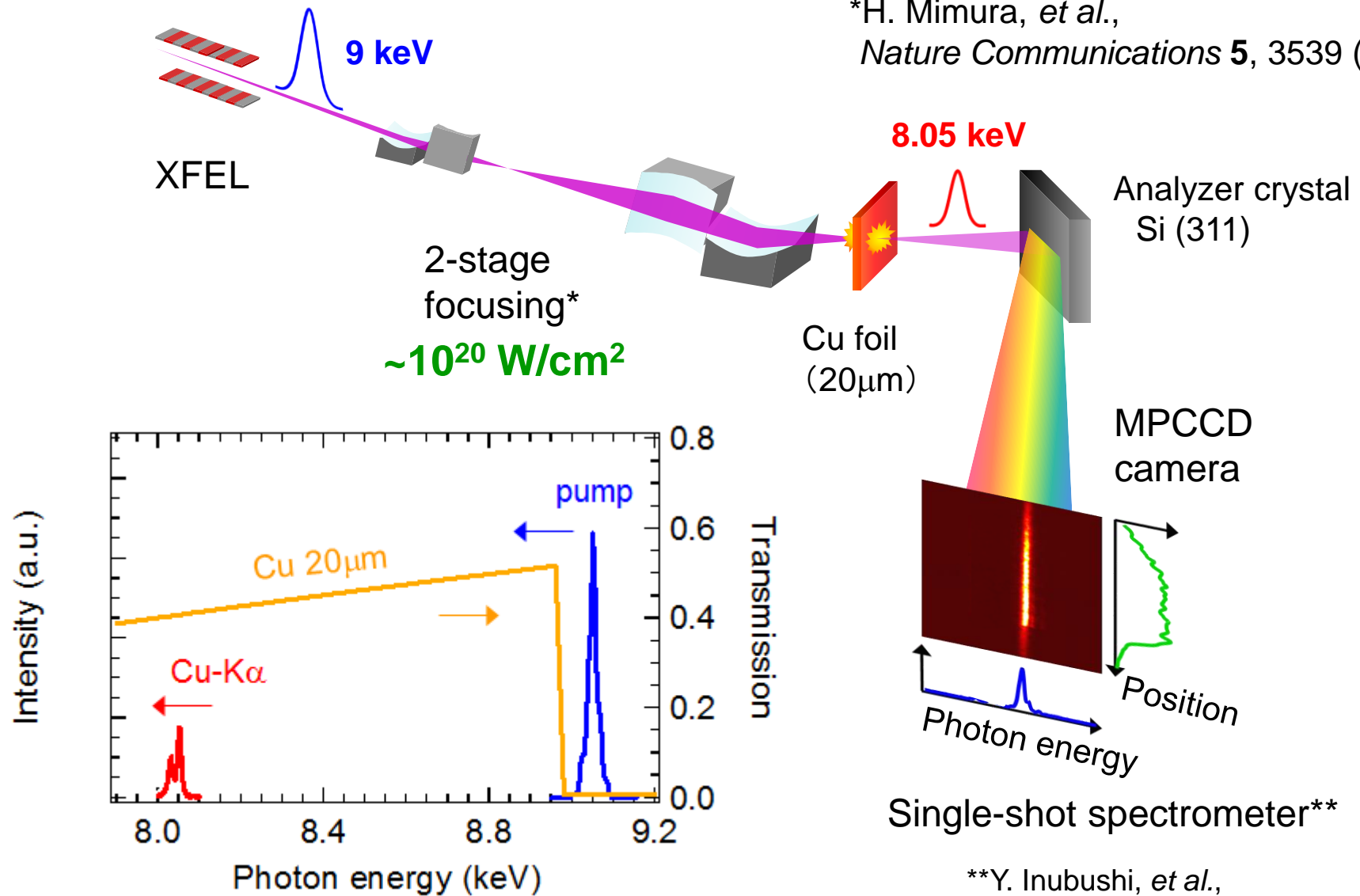
Intense XFEL



$K\alpha$ laser
via stimulated emission process

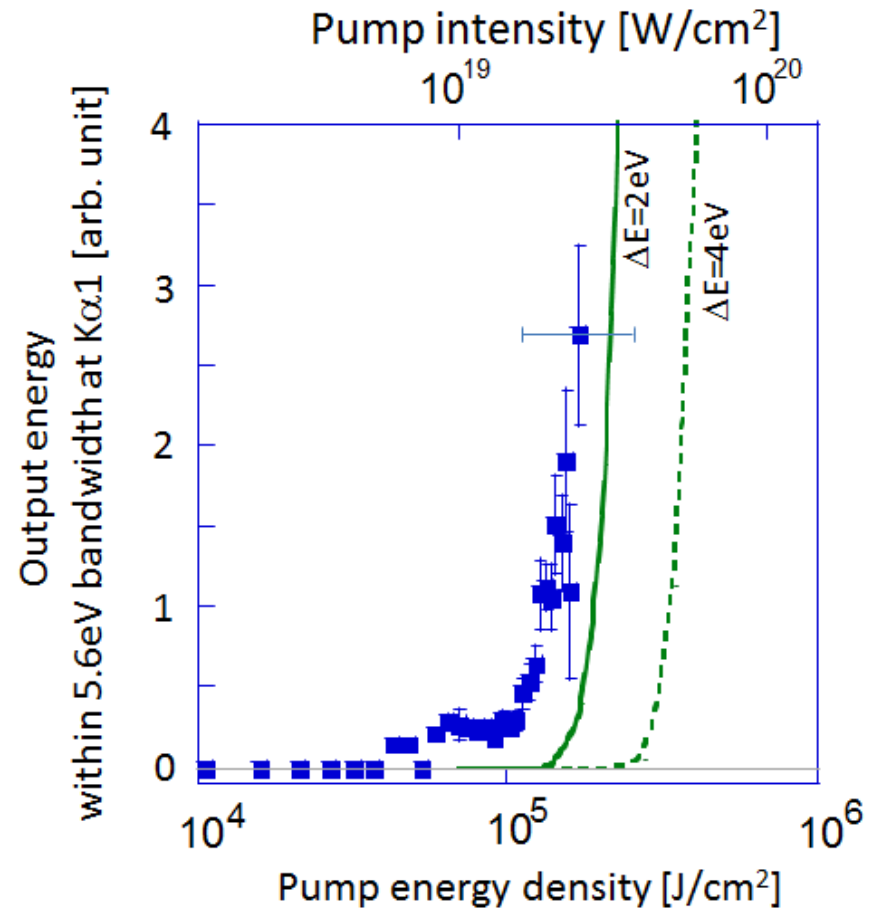
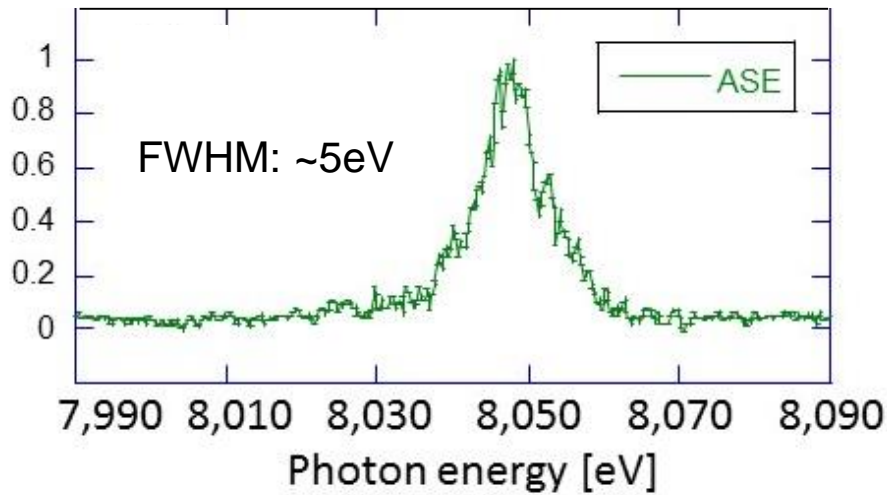
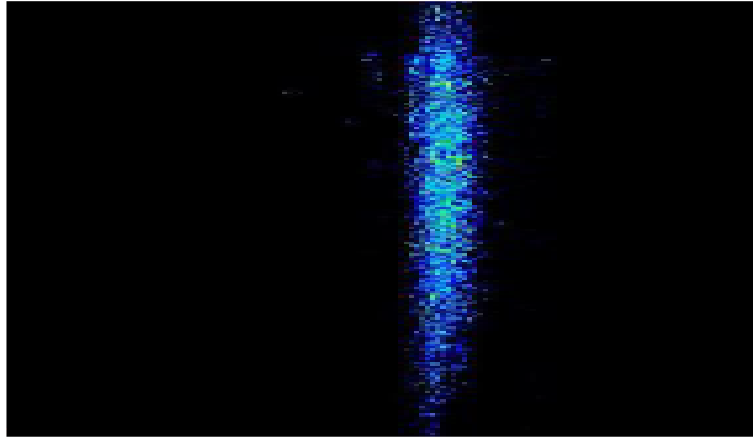
K α laser pumped by intense XFEL

*H. Mimura, *et al.*,
Nature Communications **5**, 3539 (2014).



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

$K\alpha$ laser pumped by intense XFEL

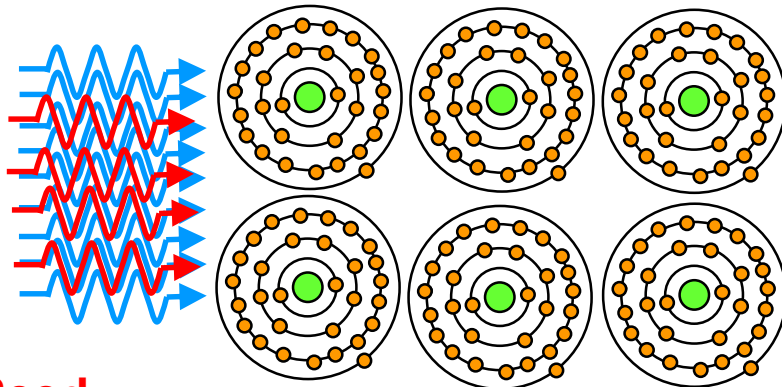


First hard x-ray laser using atomic level

Seeding in hard x-ray region

Pump

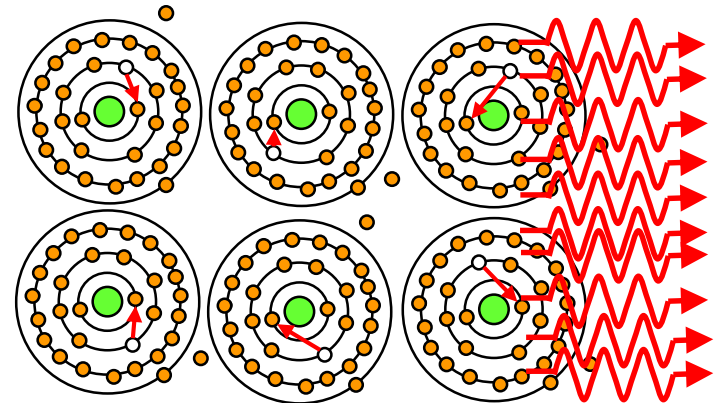
creation of core-hole atoms (9keV)



Seed

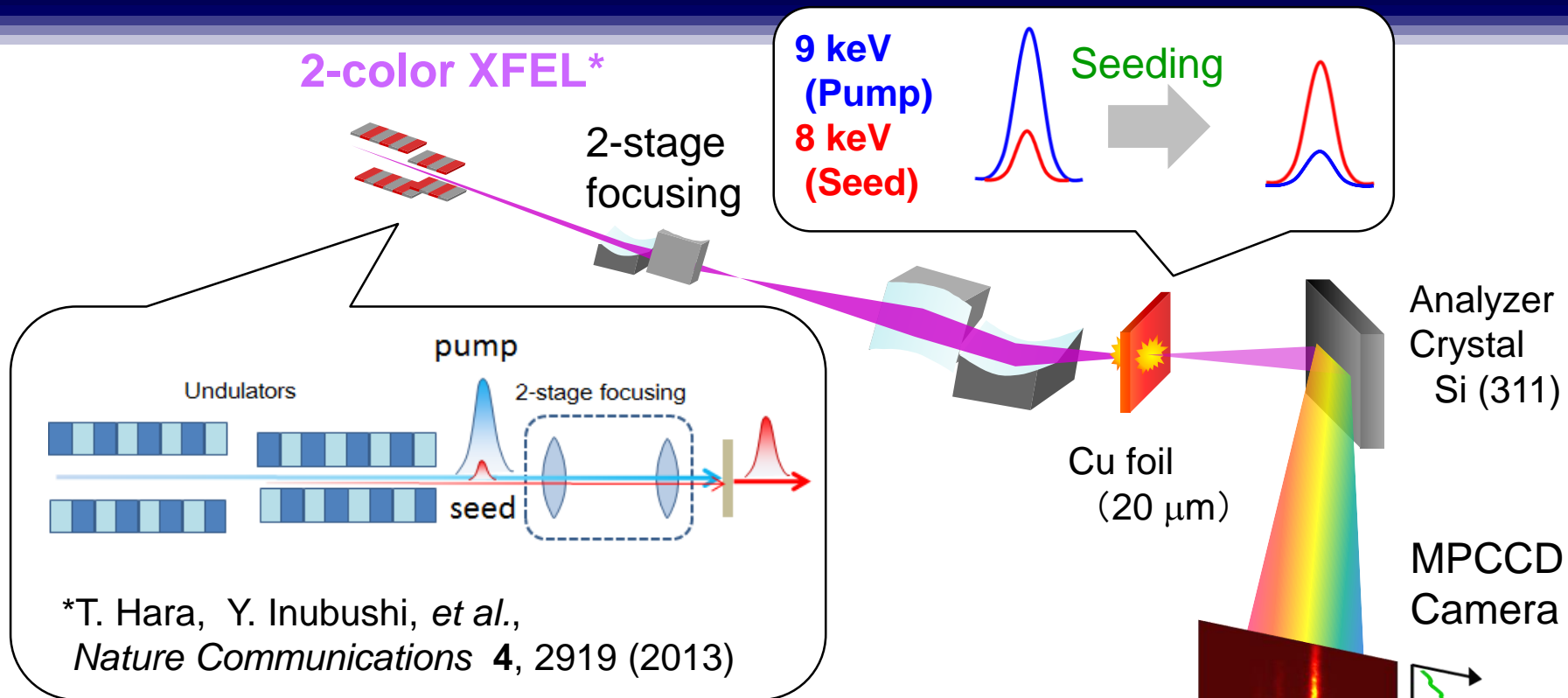
Same photon energy of $K\alpha$ (8keV)

Incidence of two-color XFEL

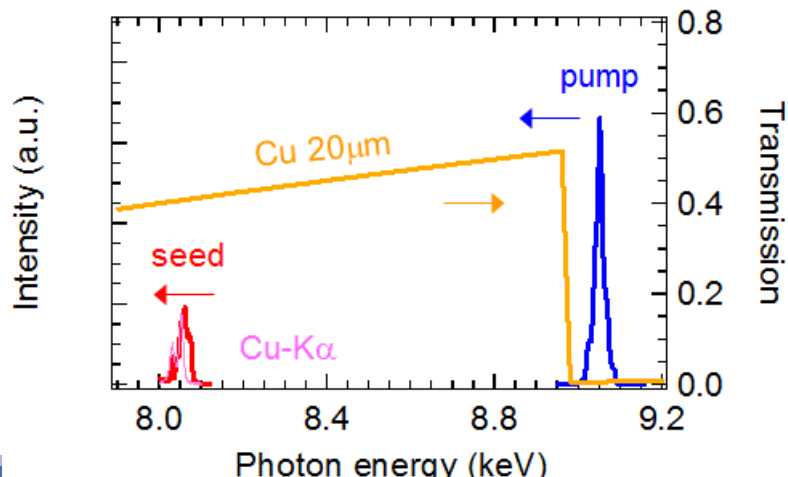


Amplification of seed pulse

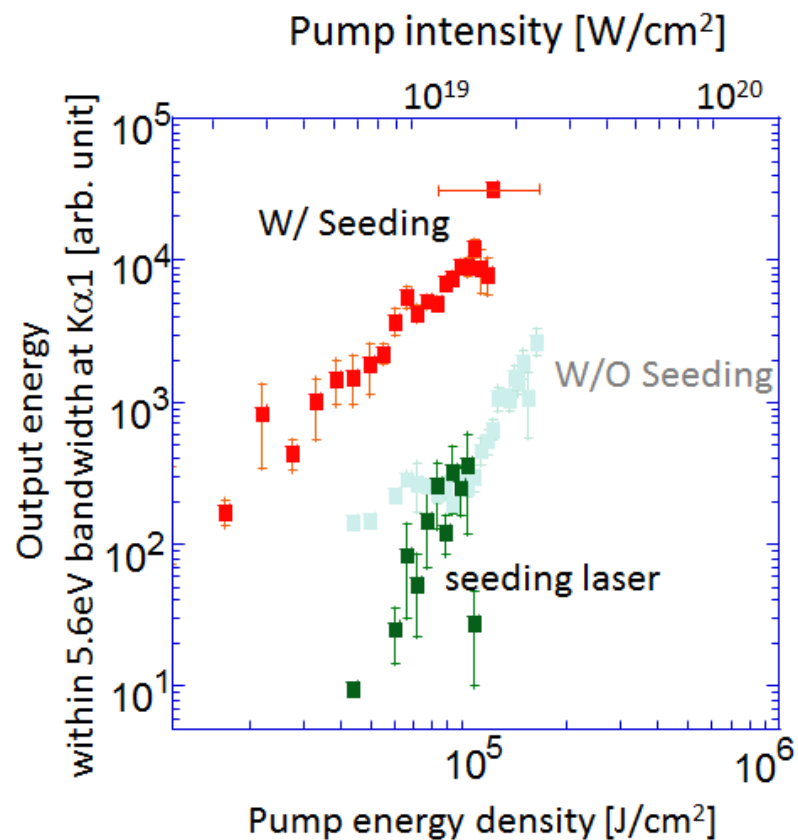
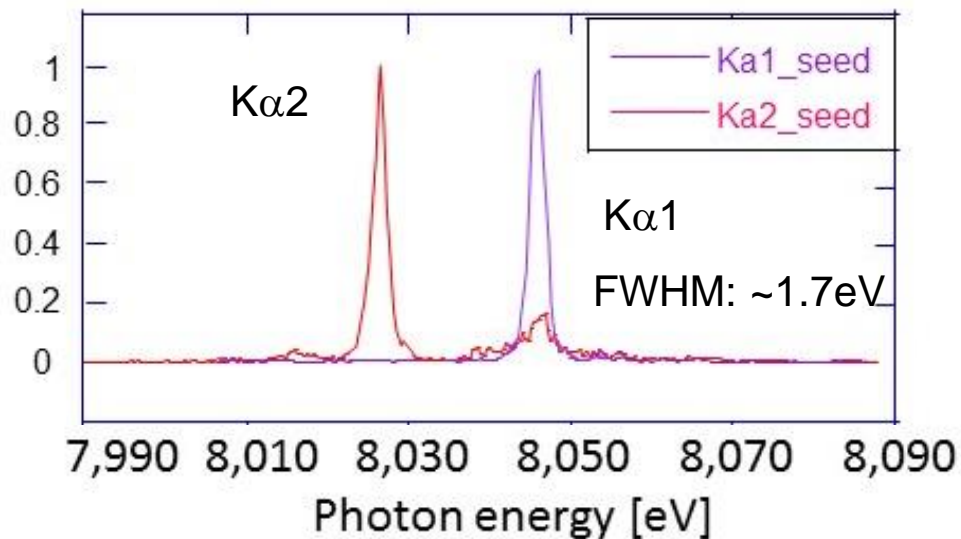
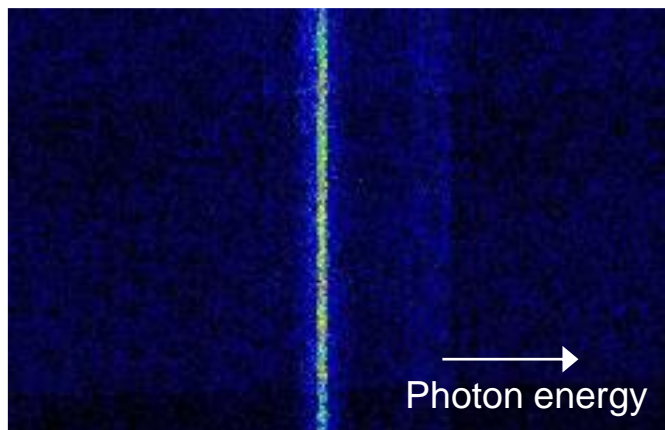
Hard x-ray seeding using 2-color XFEL



*T. Hara, Y. Inubushi, *et al.*,
Nature Communications **4**, 2919 (2013)

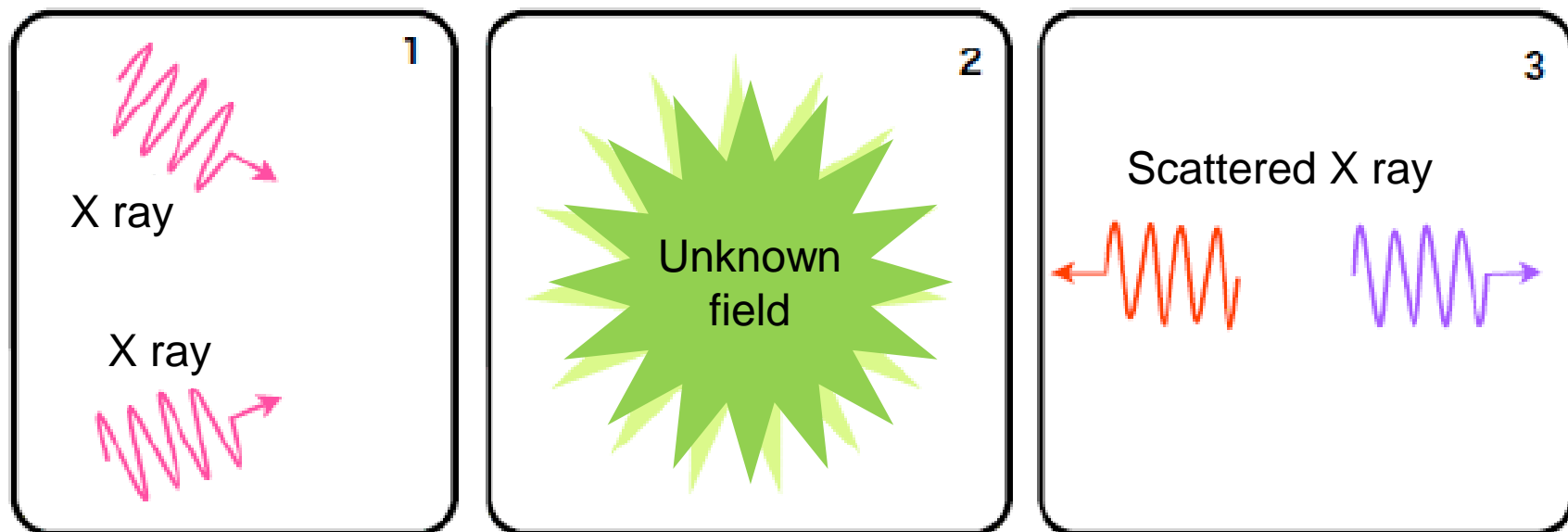


Hard x-ray seeding using 2-color XFEL



First hard x-ray seeding

Photon-Photon scattering

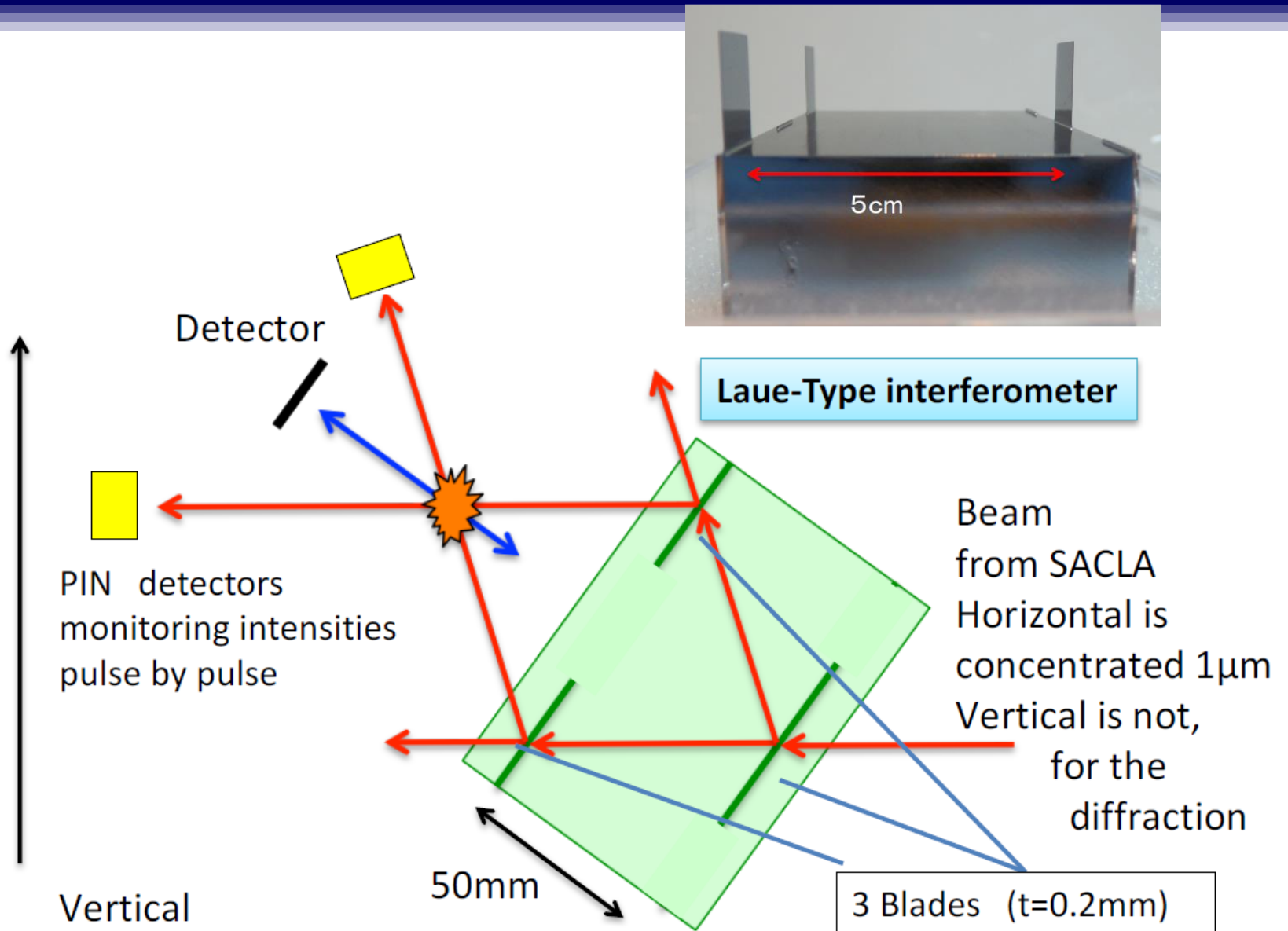


Exploring unknown field by measurement of photon-photon scattering

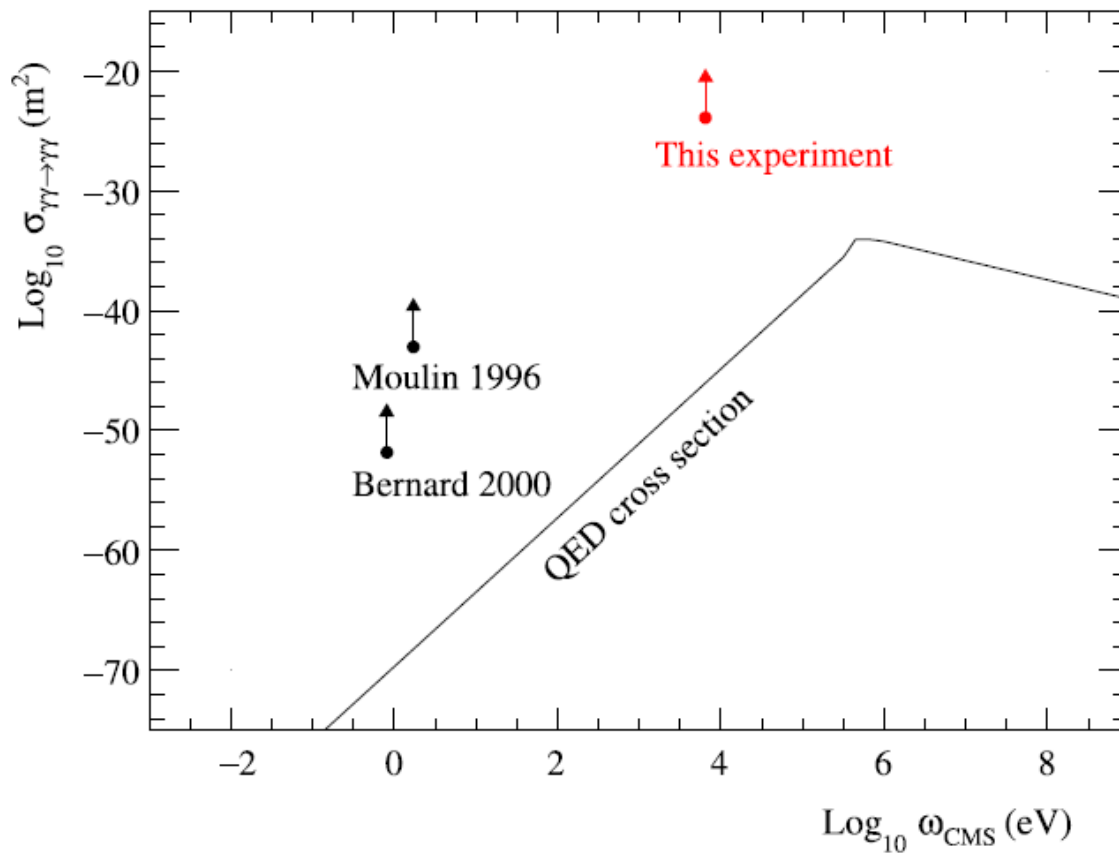


Verification of Quantum electrodynamics (QED)

Experimental setup



Result



Although the signal could not be detected, the new point could be plotted.

But, the point is still 20 order far from the QED theory.

Contents

Brief introduction of SPring-8

Current status of SACLA

Generation of intense XFEL pulses

Application of intense XFEL pulses

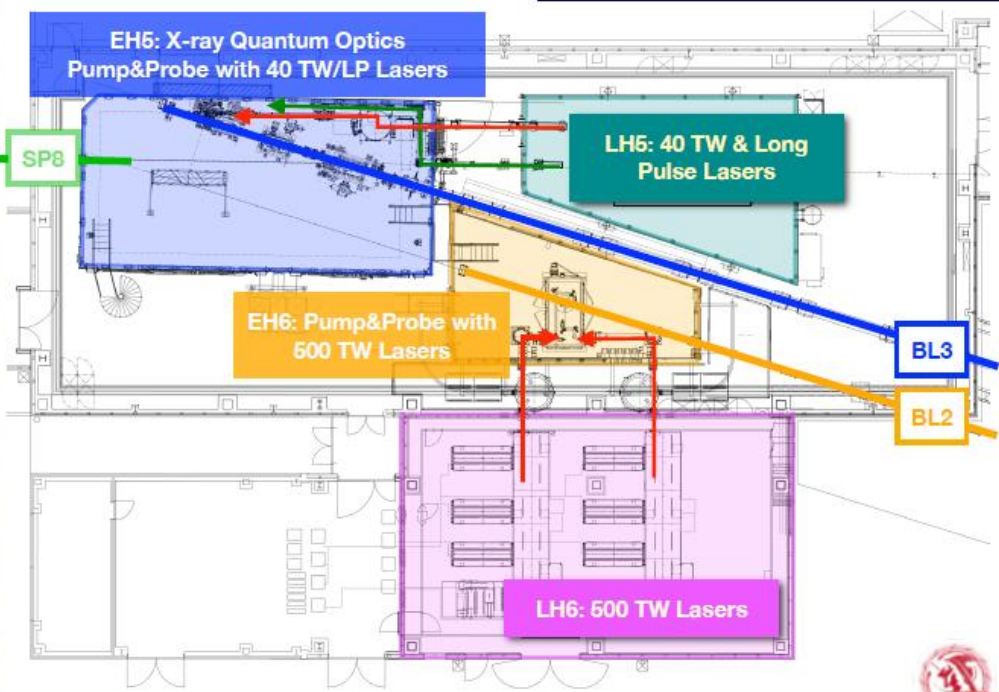
Combination of XFEL and high-power laser

Summary

HEDS (High Energy Density Science) experimental station at SACLA



SACLA - SPring-8 Experimental Facility



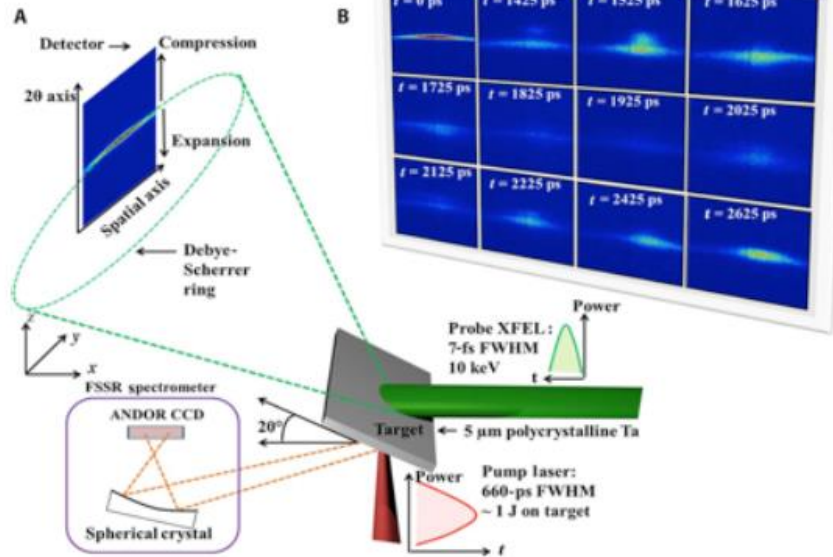
	40 TW Laser	500 TW Laser x2	Long Pulse Laser
Status	Operational	Under Commissioning	Operational
Pulse Energy	~1 J	~10 J	~ 10 J (to be upgraded)
Pulse Duration	~25 fs	~25 fs	~4 ns
Max. Rep. Rate	10 Hz	1 Hz	0.1 Hz
SACLA EH	EH5	EH6	EH5



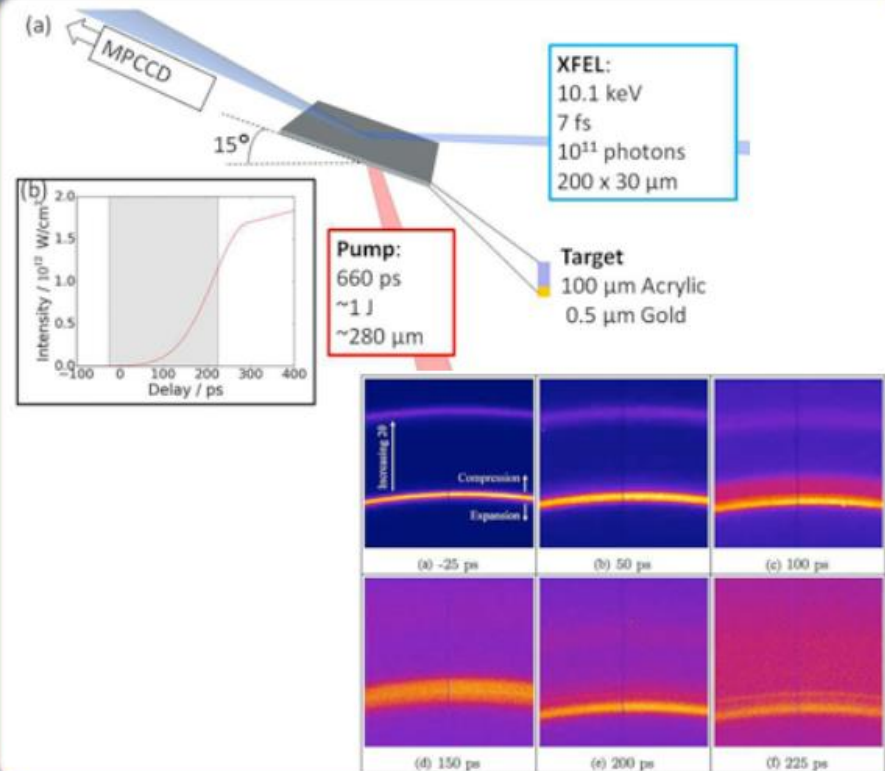
In collaboration with Harima Center for Photon Sciences, Osaka Univ. (Prof. R. Kodama)

Dynamic behavior of matter under high pressure is one of hot topics in HEDS

*B. Albertazzi, N. Ozaki et. al
Science Advances (2017)*



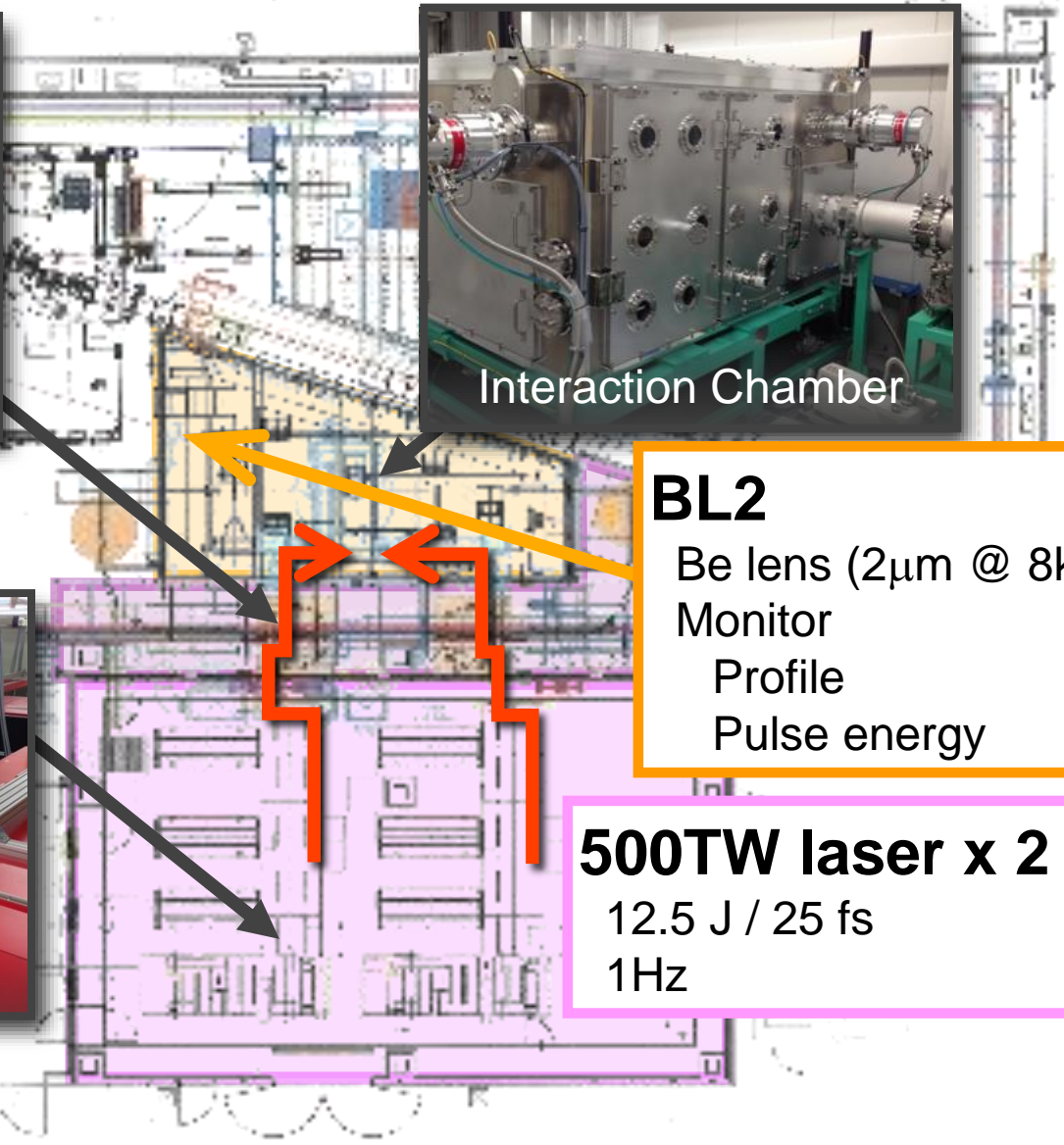
*N. J. Hartley, N. Ozaki et. al
Applied Physics Letters (2017)*



Above experiments were carried out with ~1 J, sub-ns laser.
(up to a few tens of GPa)

→ Long pulse laser (~10 J, ns) has been installed.

Development of 500-TW laser experimental system (EH6)



BL2
Be lens ($2\mu\text{m}$ @ 8keV)
Monitor
Profile
Pulse energy

500TW laser x 2
12.5 J / 25 fs
1Hz

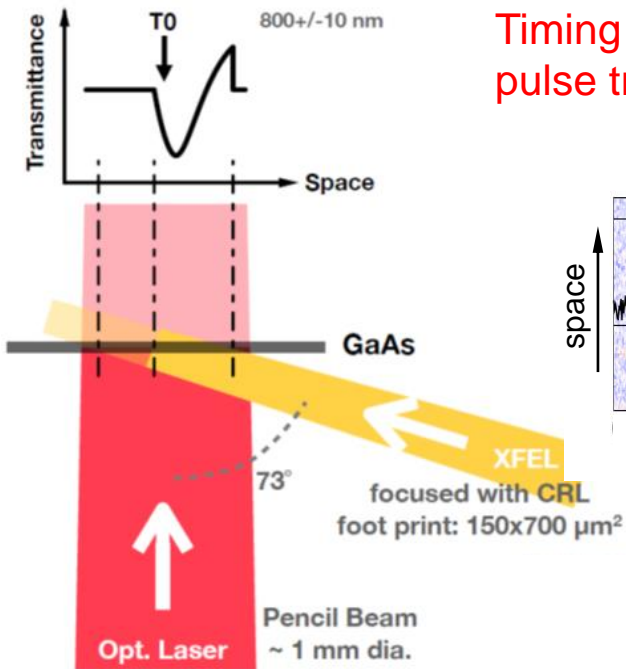
Current status of 500 TW laser

Laser parameters

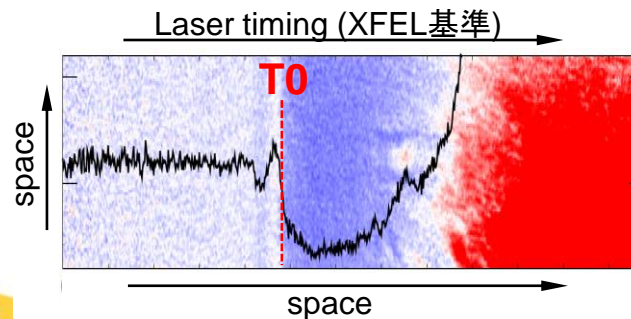
- ✓ Pulse energy: 12.5 J
- ✓ Peak power: 500 TW
- ✓ Wavelength: 800 nm
- ✓ Duration: 25 fs
- ✓ Beam size: $\phi 120$ mm with Top Hat
- ✓ Contrast: 10^{-10} @ -100 ps, 10^{-8} @ -30 ps

Now, only 1 beam is available.

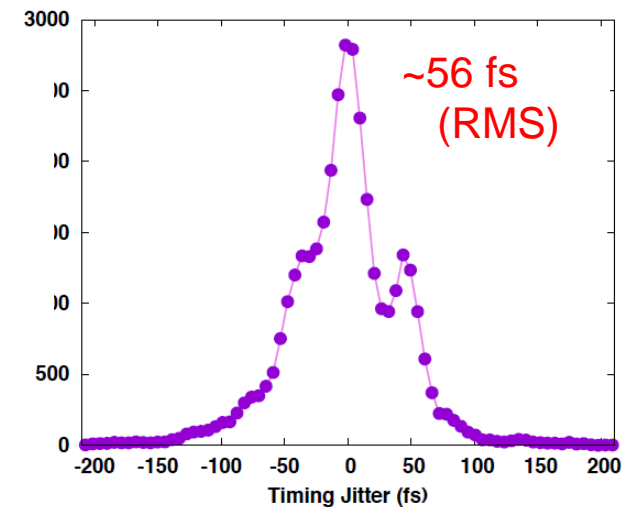
Timing jitter between XFEL and 500 TW laser



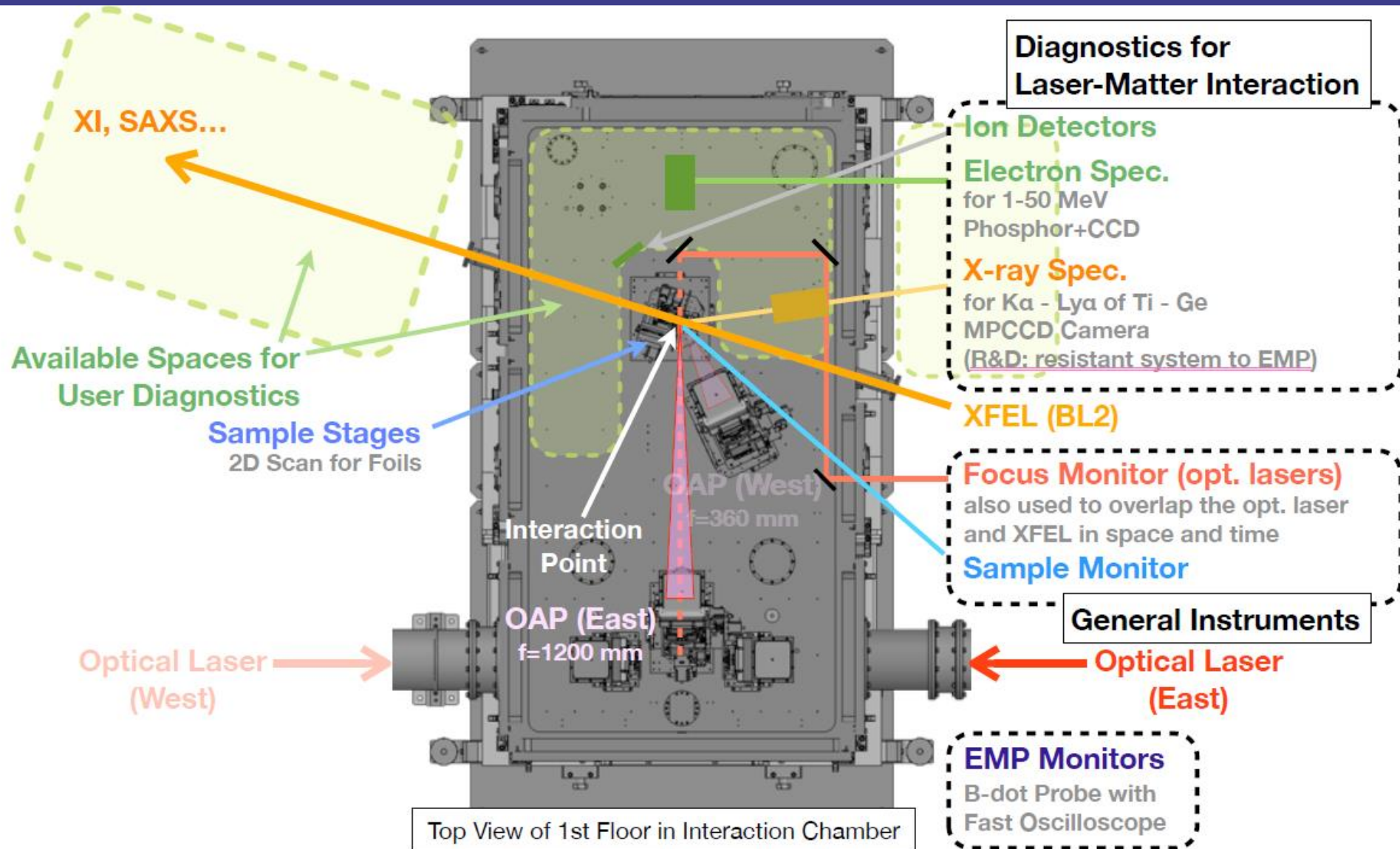
Timing jitter was derived from pulse-by-pulse transmission change of laser



Timing jitter
(36000shots = 60 min.)



Experimental chamber and diagnostics



User operation will start from June 2018

Summary

- Stable user operation of SACLA produced exciting results in wide scientific fields.
- Intense XFEL pulses, which is one of features of SACLA, has opened new scientific field.
- User operation of combination of high power laser (500 TW laser) and XFEL will start in June. This experimental scheme is expected to produce many interesting results.

Acknowledgements

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Especially,

Makina Yabashi, Kensuke Tono, Tadashi Togashi,
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Takahisa Koyama, Kenji Tamasaku, Takahiro Inagaki,
Kazuaki Togawa, Takashi Tanaka, Toru Hara, Mitsuhiro
Yamaga, Hitoshi Tanaka, Tetsuya Ishikawa



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The University of Tokyo Hidekazu Mimura

The University of Electro-Communications Hitoki Yoneda

Thank you for your kind attention!