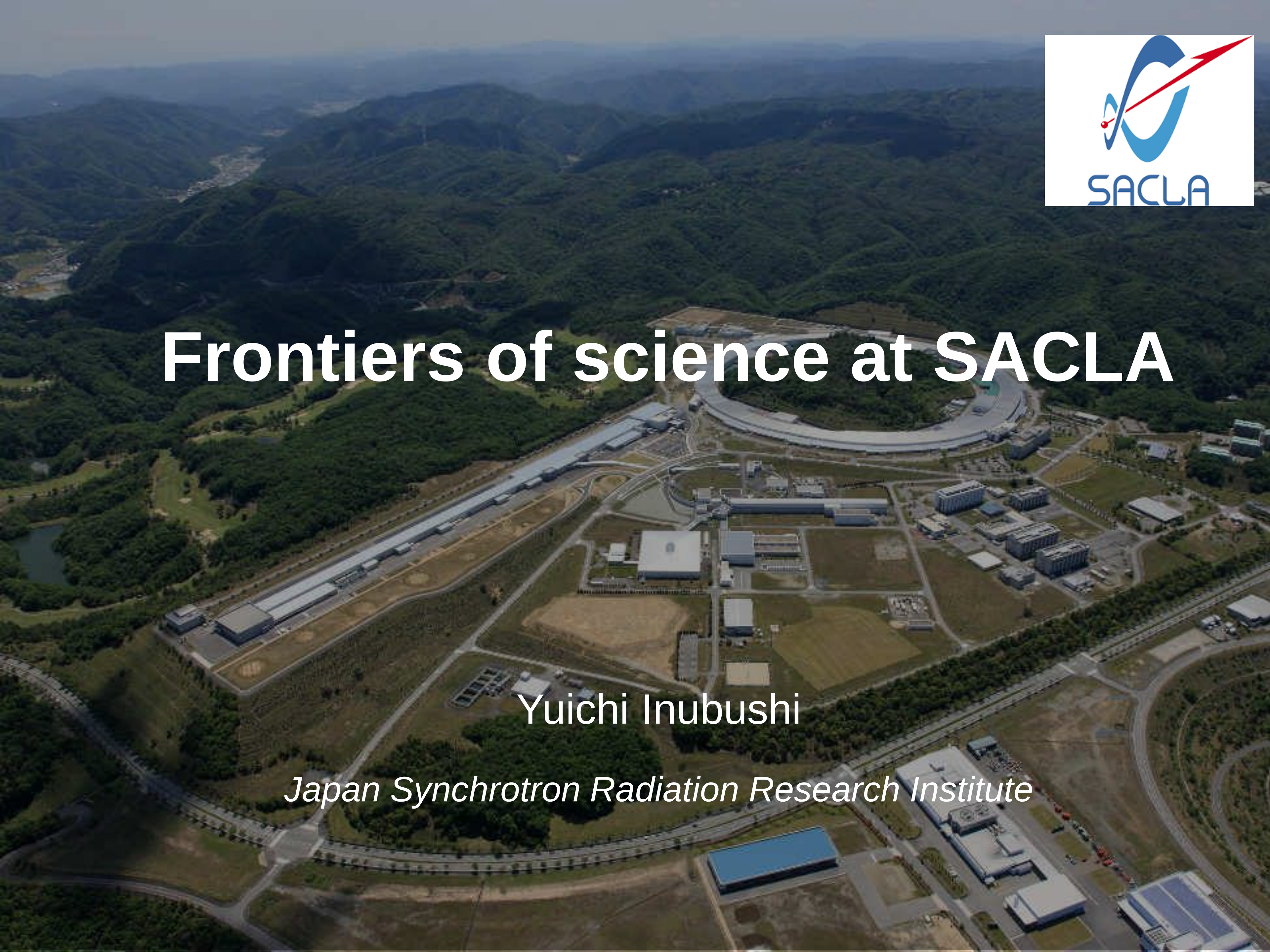


Frontiers of science at SACLA

Yuichi Inubushi

Japan Synchrotron Radiation Research Institute


SPring-8
SACLA

Contents

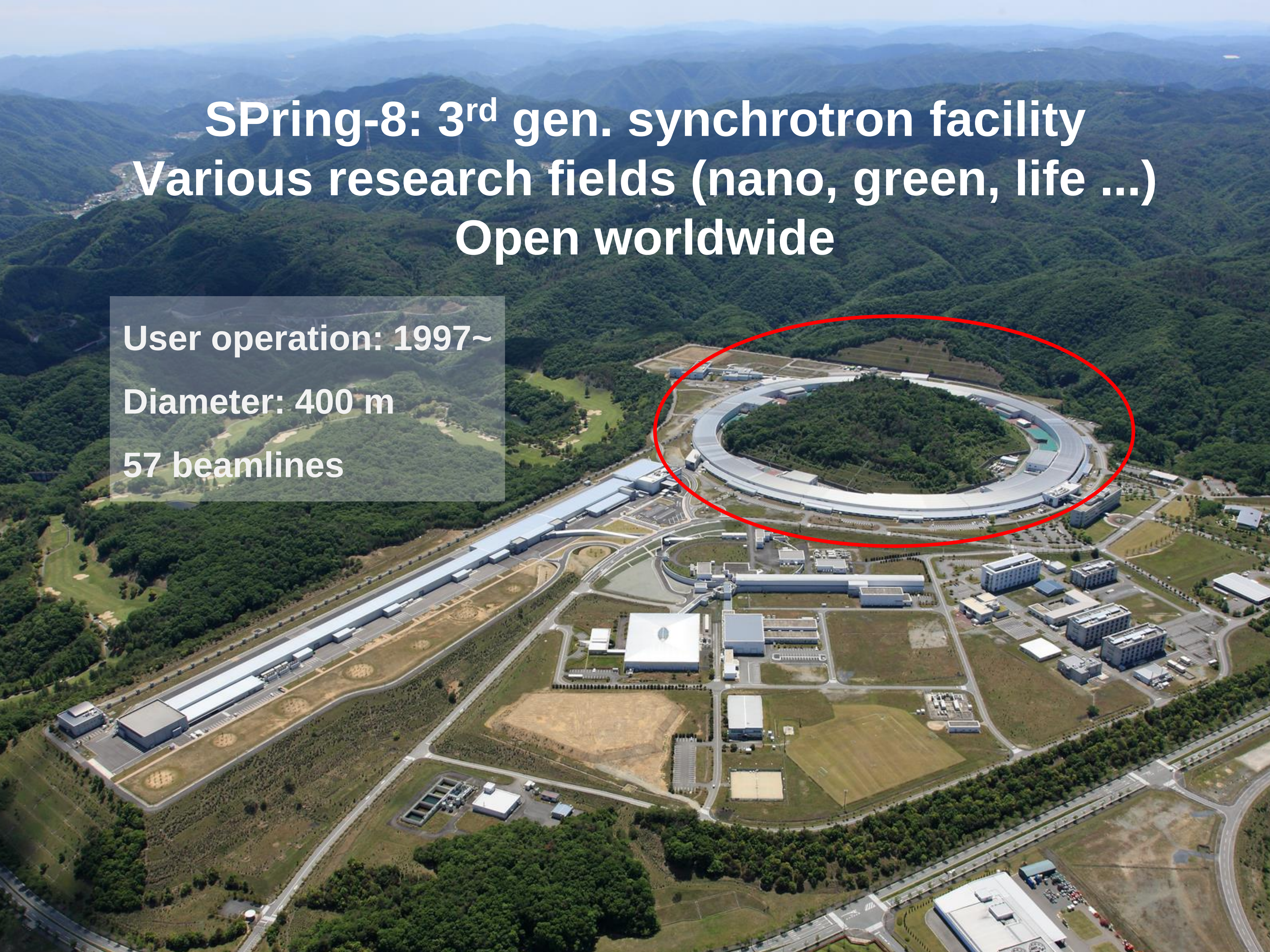
Contents

SPring-8: 3rd gen. synchrotron facility
Various research fields (nano, green, life ...)
Open worldwide

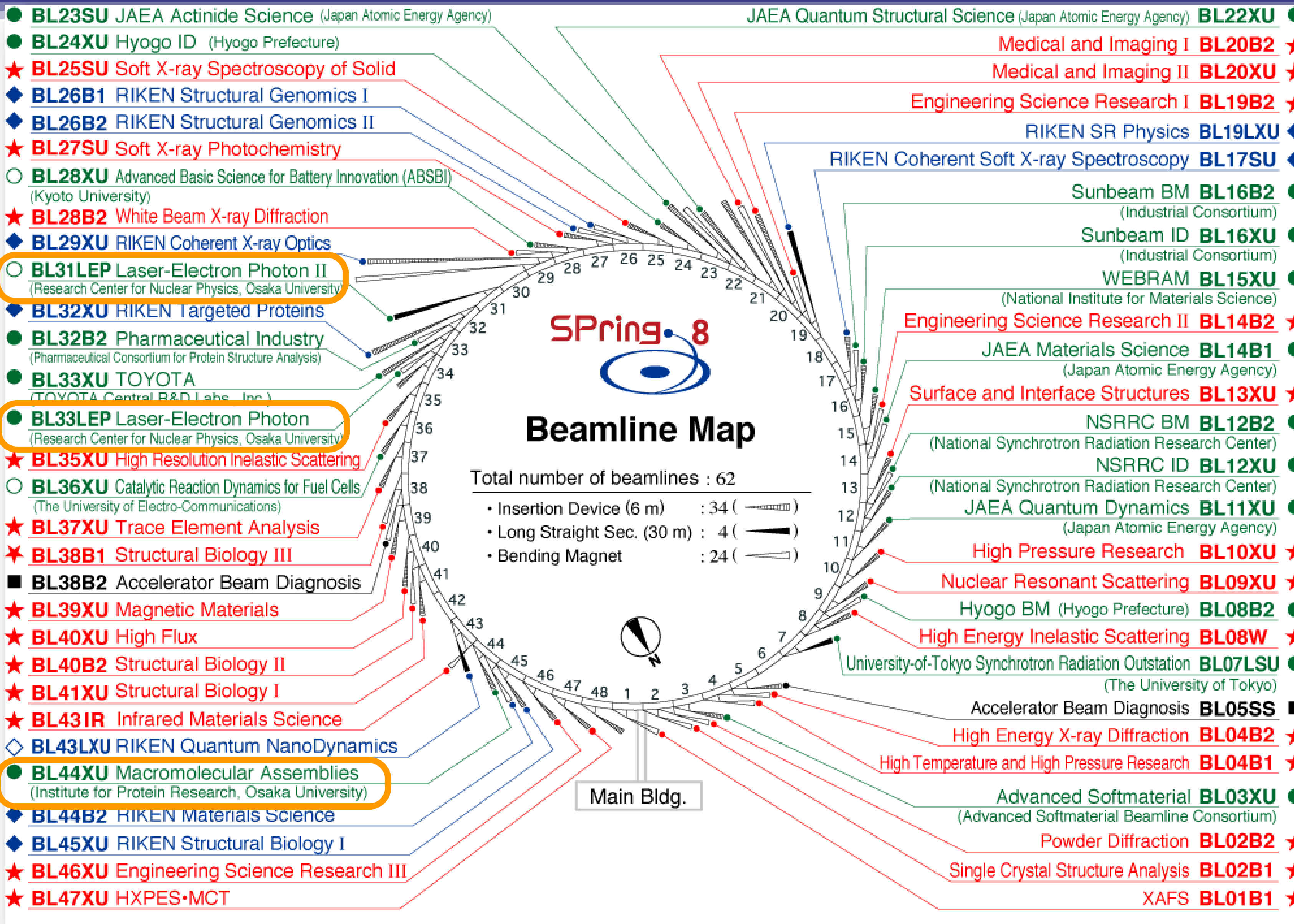
User operation: 1997~

Diameter: 400 m

57 beamlines



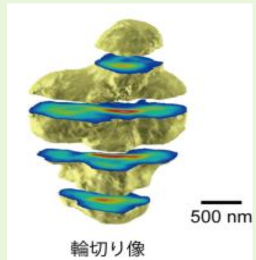
Beamline map

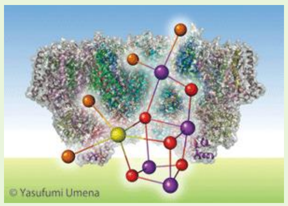


Application fields and achievements of SPring-8

Life science

Development of X-ray microscope enabling intracellular 3D imaging





Structural elucidation of core protein complex in photosynthesis

Material science Industrial applications

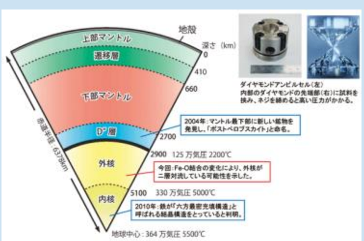
Development of fuel-efficient tires using 3D measurement technique

Structural Analysis of Human Hair for development of functional shampoo

Elucidation of anti-caries mechanism of chewing gum

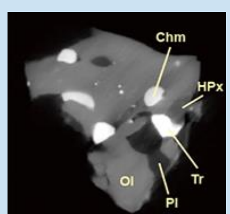
SPring-8

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)

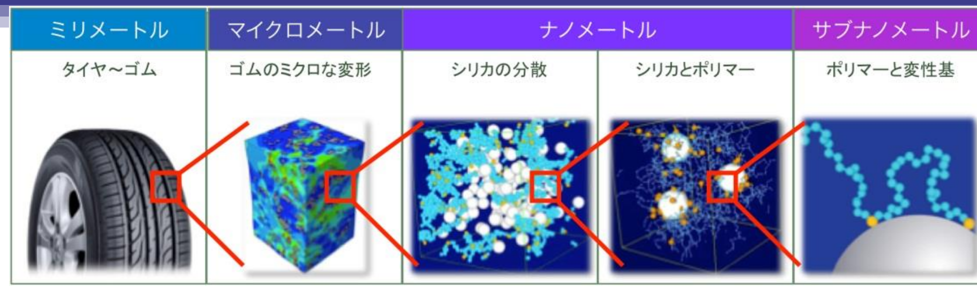
Archeology

Material investigation of Sankaku-buchi Shinjukyo (ancient mirror) by fluorescent X-ray analysis

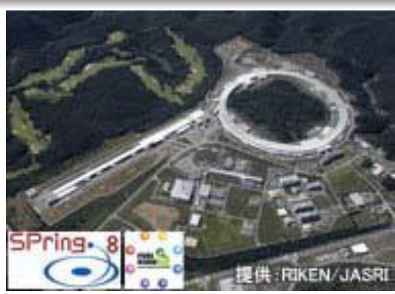
Materials identified using pieces from old wooden surface

Industrial applications: Molecular Design for Energy Saving Tire

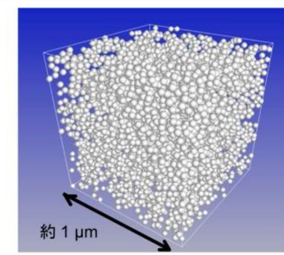
Sumitomo Rubber Industries Ltd.



Sophisticated Analysis at FSBL, SPring-8



Multi-Scale Simulation of Rubber Molecule Dynamics by Super Computer



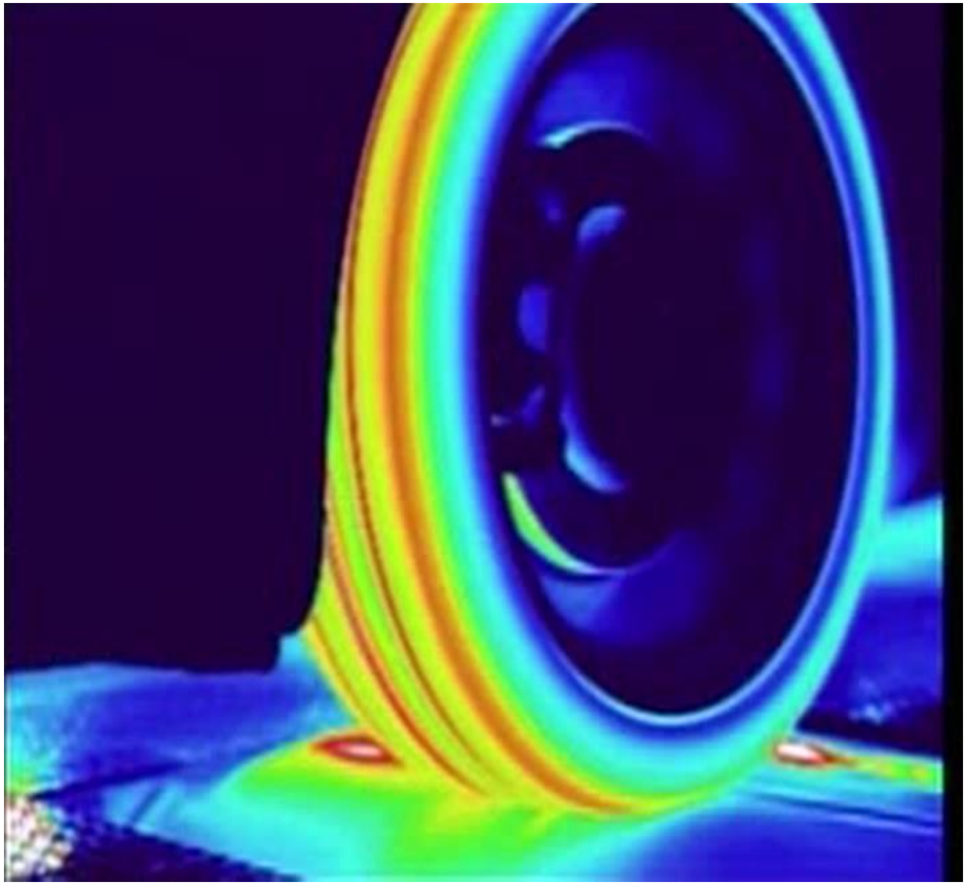
President Ikeda presents new energy saving tire. 1st Dec. 2011

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

"EnerSave" Premium Performance

Existing Tire

エナセーブ PREMIUM



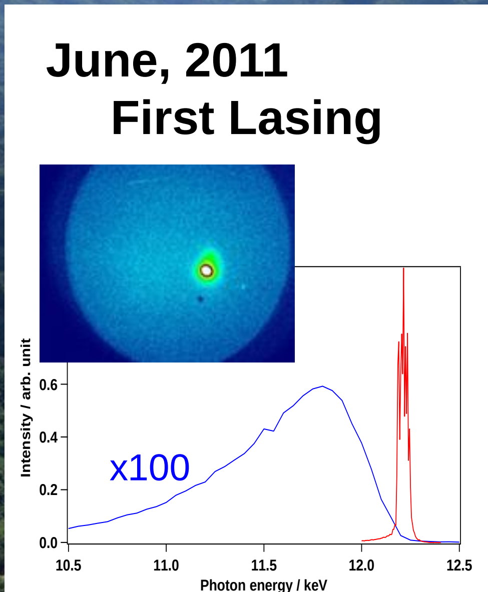
Lower Energy Loss

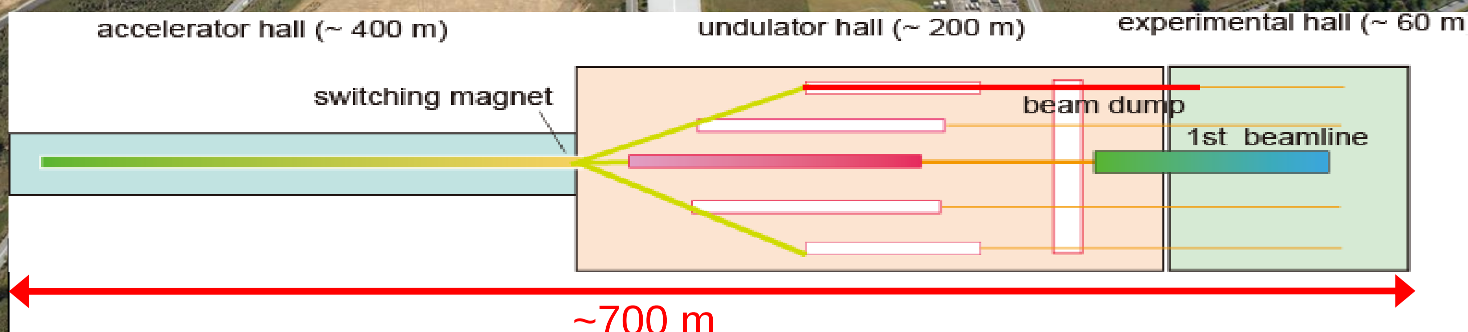
Contents

SACLA

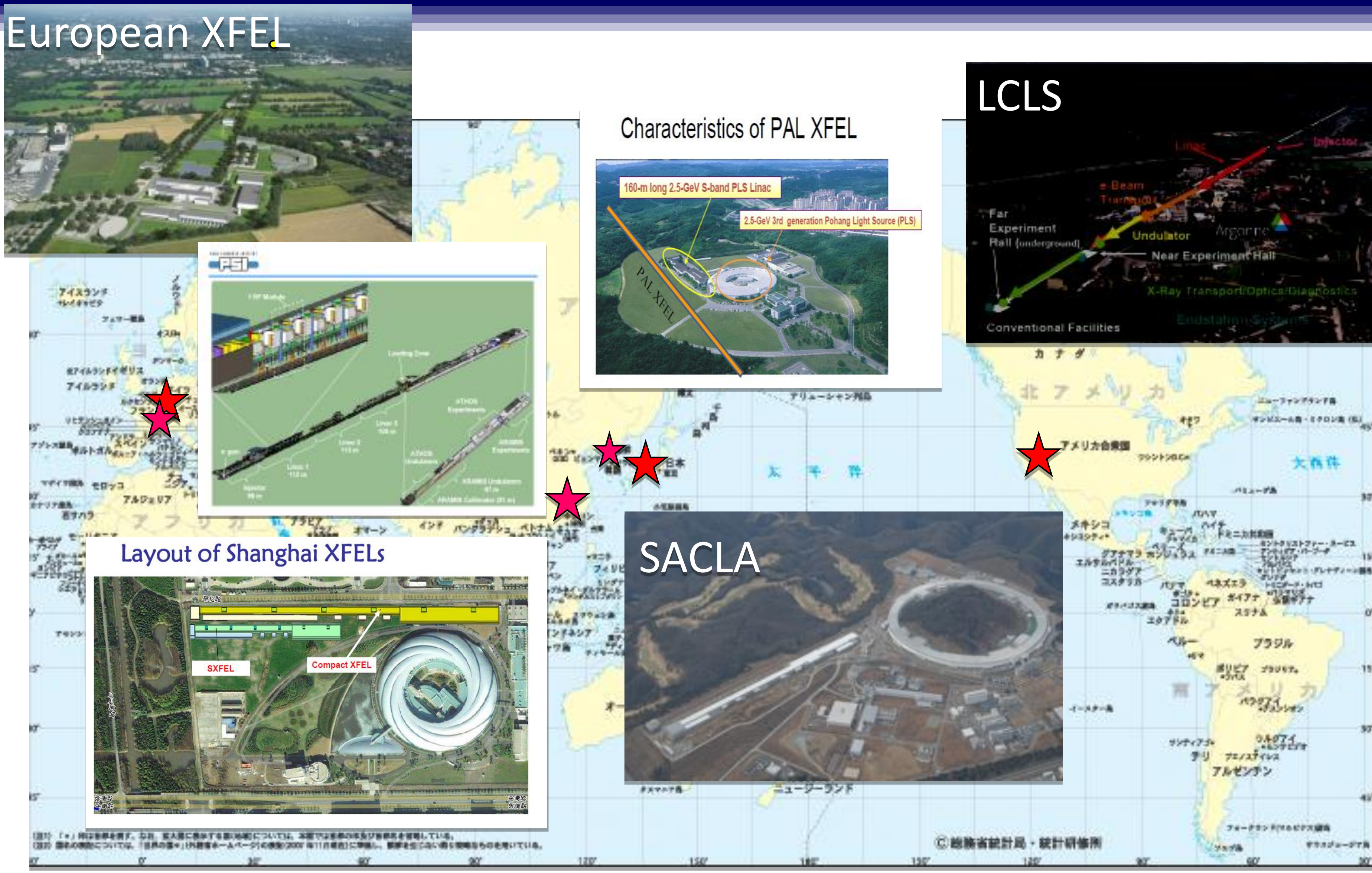
SPring-8 **A**ngstrom **C**ompact free electron **L**aser

First compact XFEL
Construction: 2006~2010
User operation: March 2012~



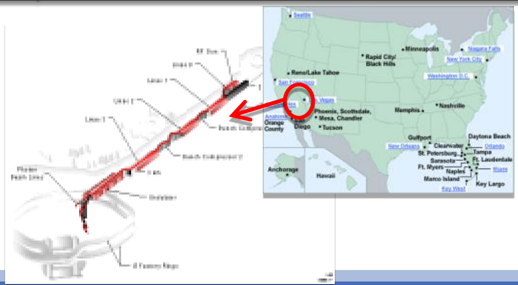


XFELs in the world

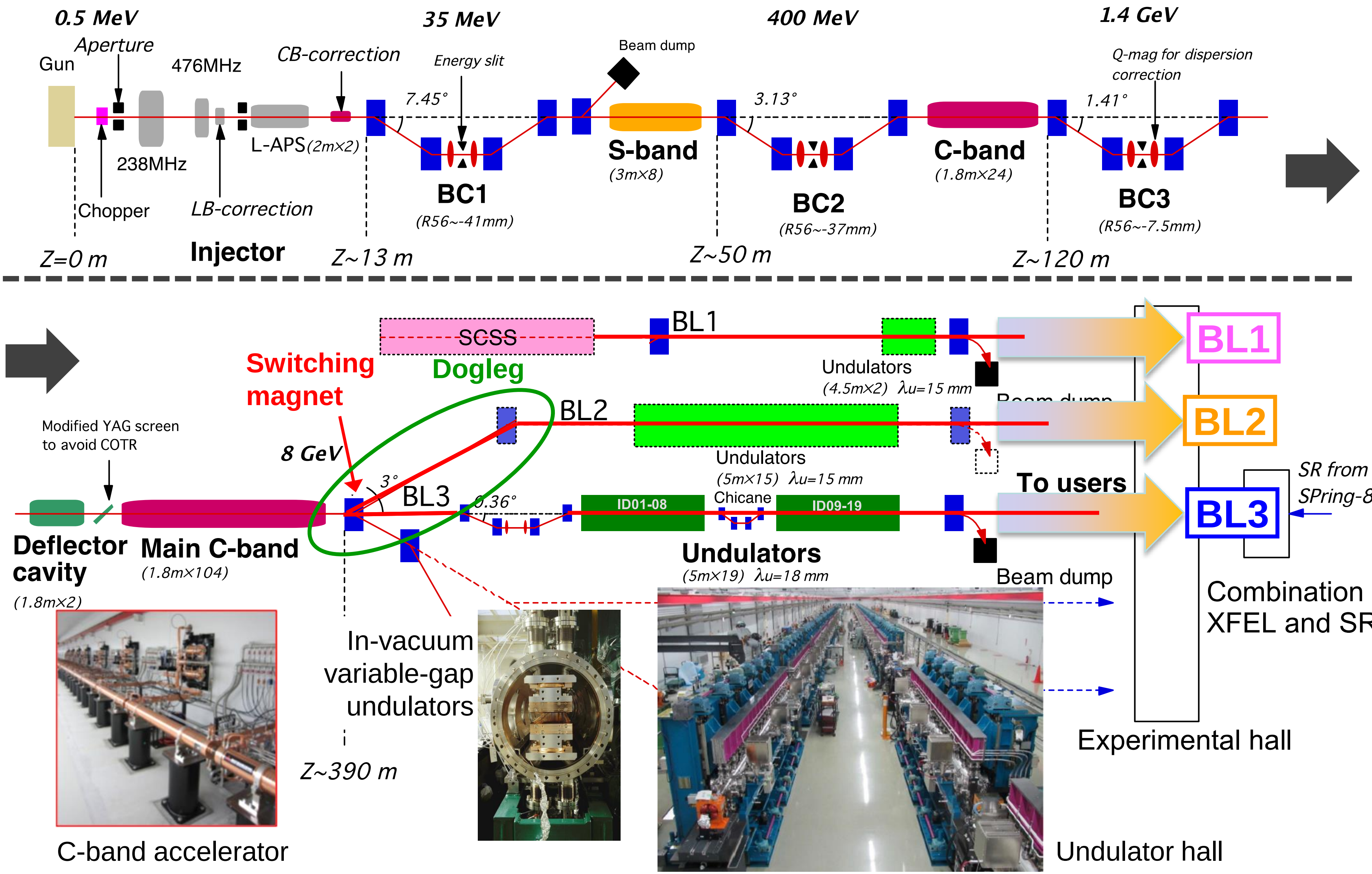


Comparison

	European XFEL	SACLA	LCLS
Length	3.3 km	**700 m**	~ 2 km
Beam energy	17 GeV	**8 GeV**	14 GeV
Wavelength	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

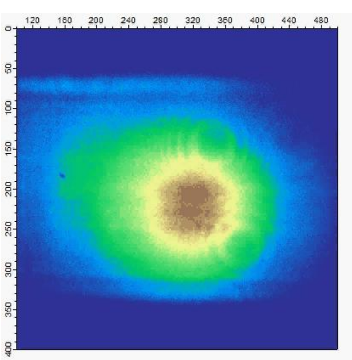


SACLA accelerator and beamlines (2017~)



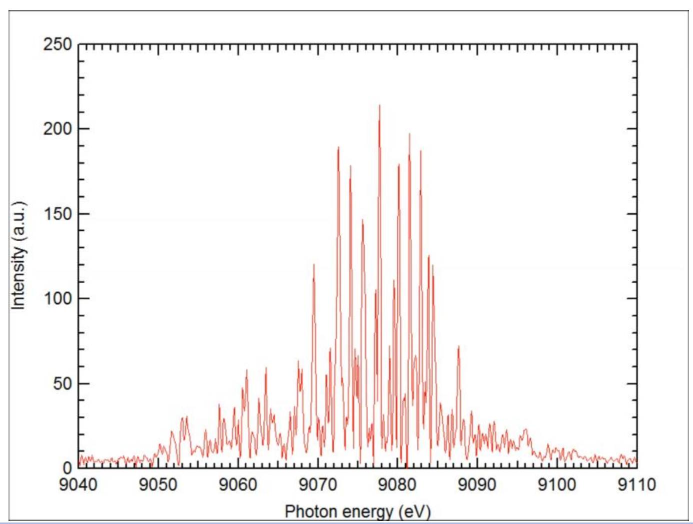
Performance

	BL3	BL2	BL1
Photon energy	4~15 keV	4~15 keV	40 ~ 150 eV
Bandwidth($\Delta E/E$)	< $5\text{x}10^{-3}$	< $5\text{x}10^{-3}$	~ 0.01
Pulse energy	~ 500 μJ @10keV	~ 400 μJ @10keV	~ 90 μJ@ 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	> 50GW	> 40GW	> 100 MW
Repetition rate	30Hz (60Hz: Single beamline operation)	30Hz	60Hz



Profile

FWHM: ~300 μm
10 keV (BL3)

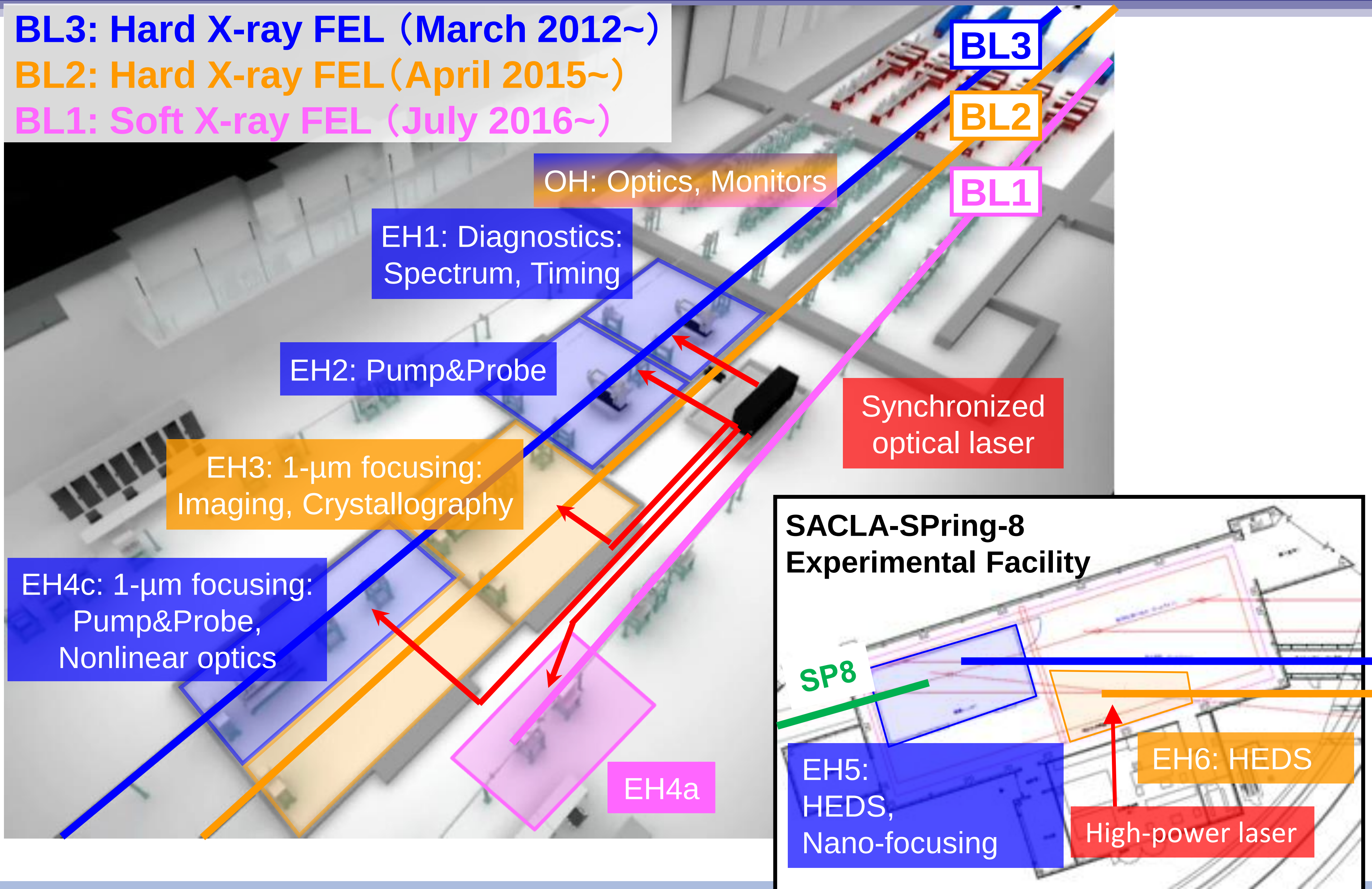


Spectrum

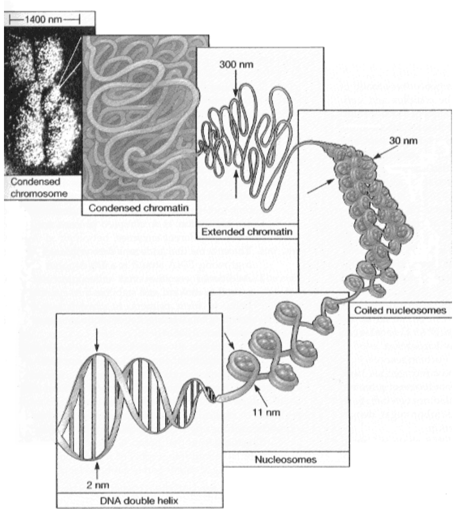
9 keV (BL3)

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

Experimental hall

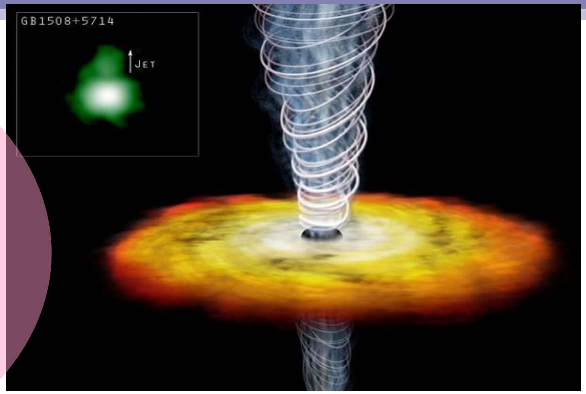


XFEL sciences



Imaging Biology

Brilliance (X10^9)



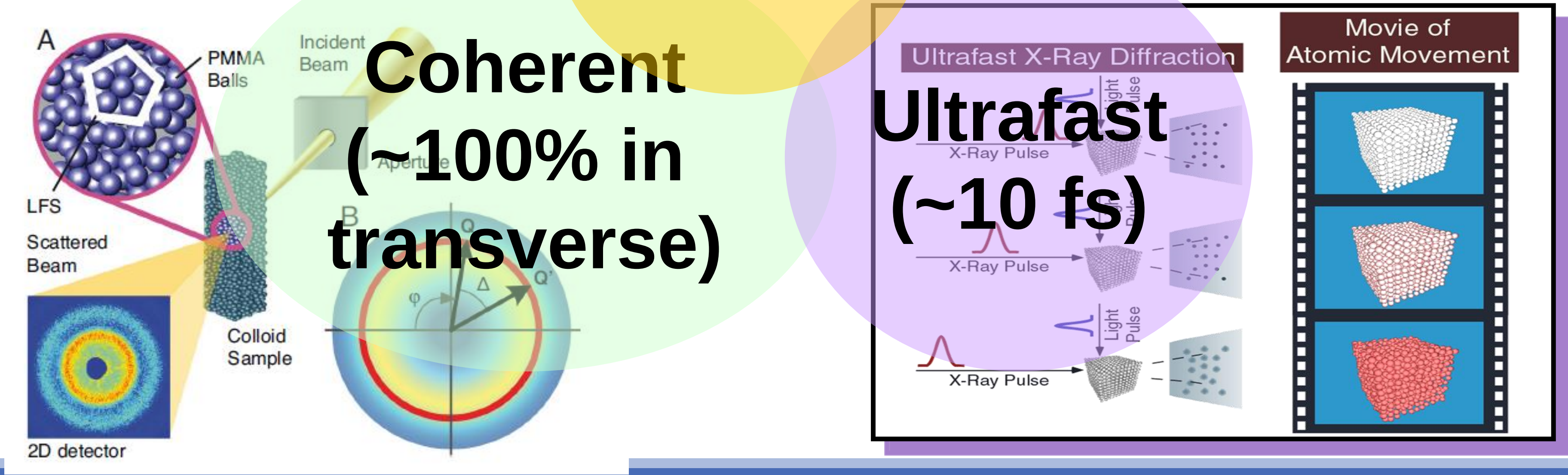
NL & Quantum X-ray Science
High Energy Density Science
AMO science

XFEL

Protein Crystallography
Ultrafast Materials Science

Coherent (~100% in transverse)

Ultrafast (~10 fs)



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Brief introduction of SPring-8

Current status of SACLA

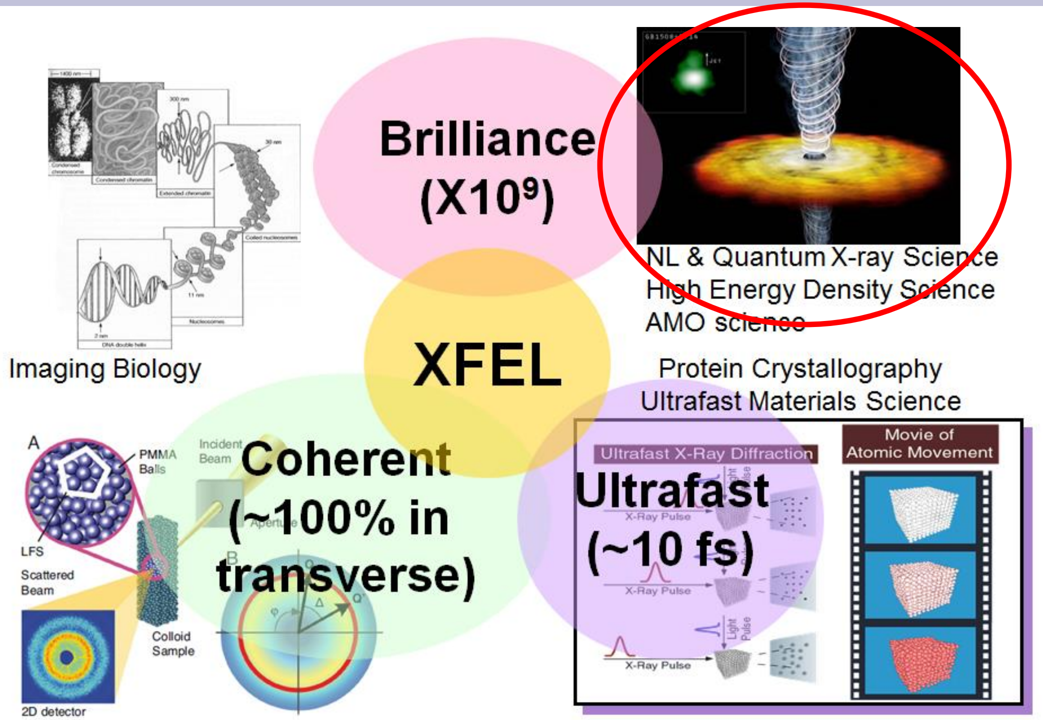
Generation of intense XFEL pulses

Application of intense XFEL pulses

Combination of XFEL and high-power laser

Summary

Intense XFEL pulses has opened new sciences



Application of intense X-ray source as a pumping source

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

Intensity

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

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 ⟷ **FT** ⟷ **Temporal domain**

Pulse duration ← Spike width

Spectral resolution: < 100 meV

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

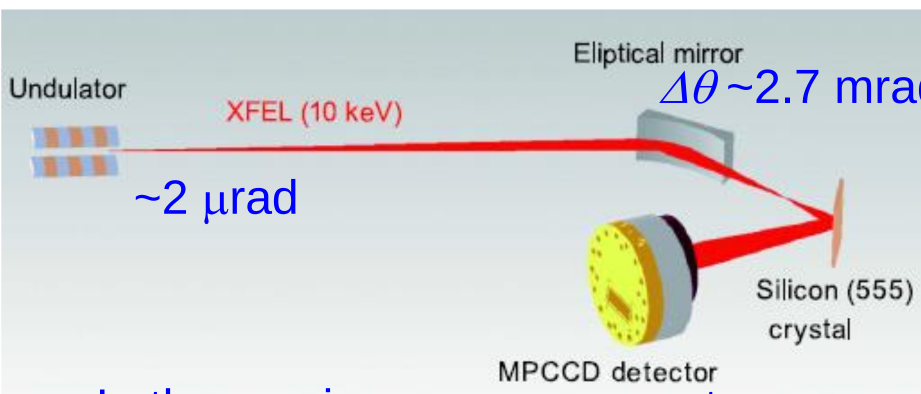
p: Pixel size
L: Distance from source to detector
ω: Darwin width
θ_B: Bragg angle

Longitudinal mode number ← Number of spikes

Observation range: > 50 eV

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

$\Delta\theta$: angular divergence on analyzer crystal

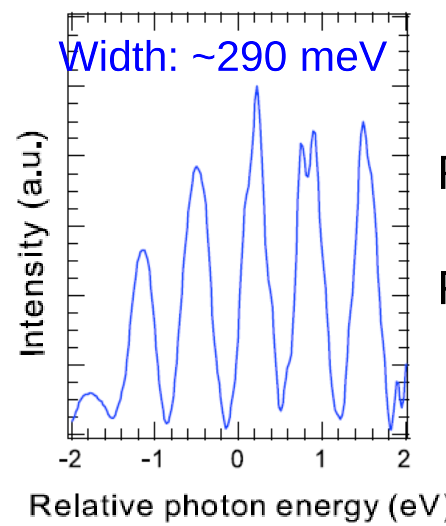


$\Delta\theta$ ~2.7 mrad

~2 μrad

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

Width: ~290 meV

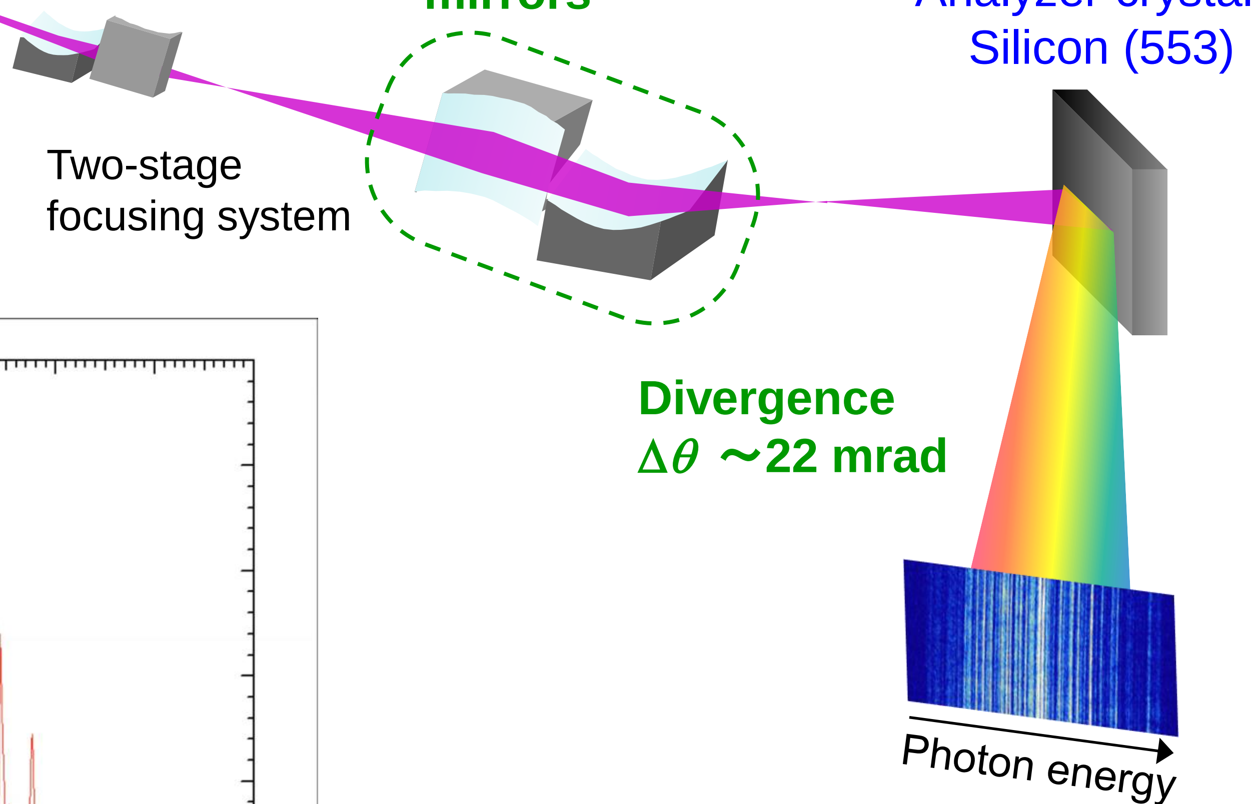


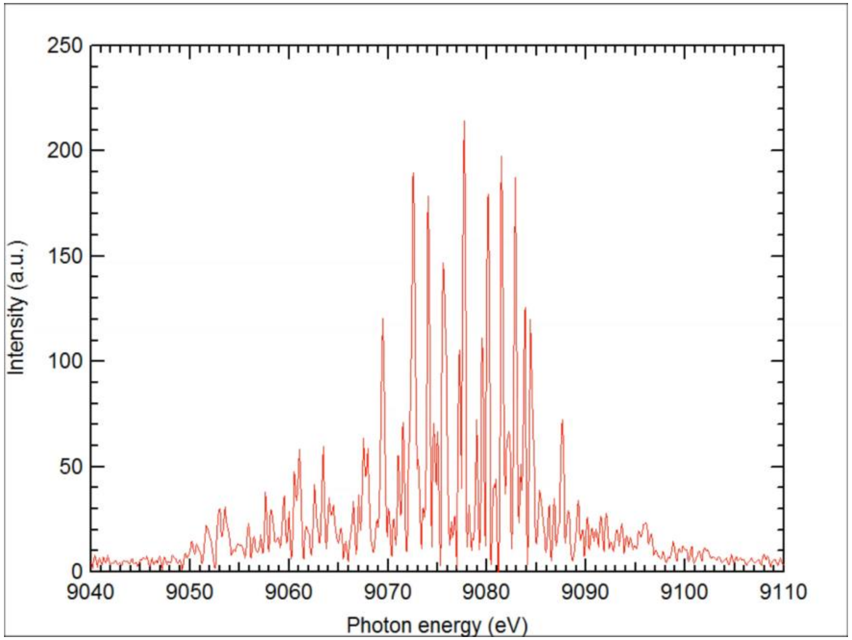
Resolution: ~ 15 meV

Range: ~ 4eV

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

Single-shot spectrometer with multilayer mirror

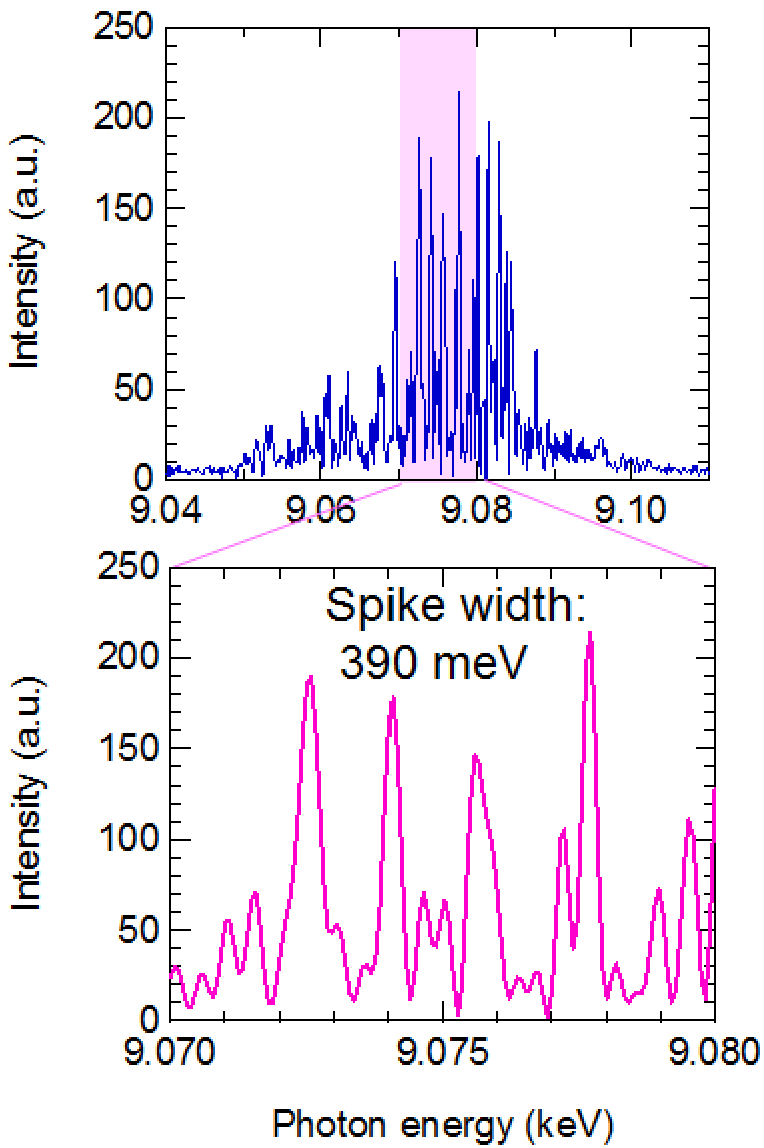




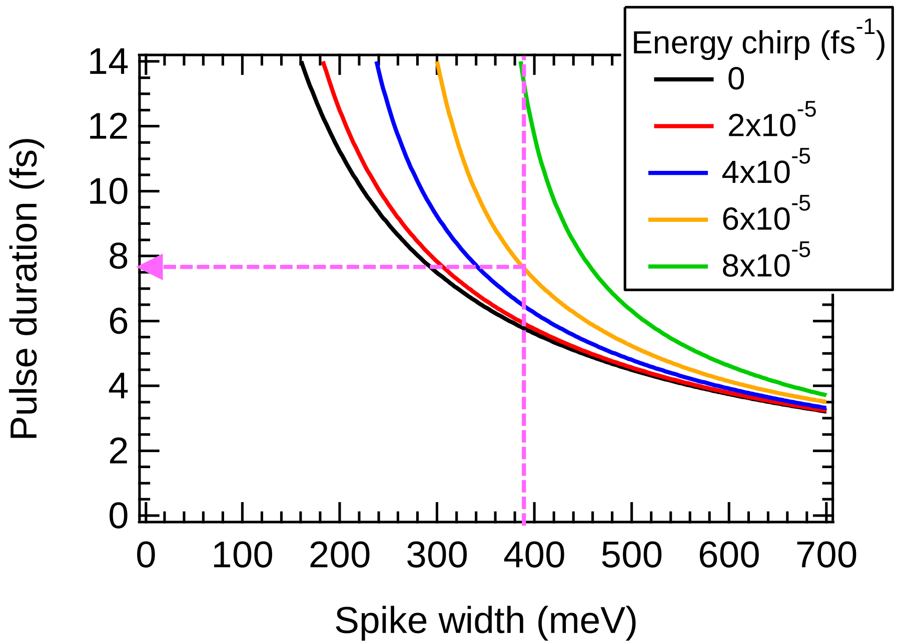
Spectral resolution: ~ 80 meV

Observation range: ~ 60 eV

Pulse duration and longitudinal mode number



Determination of pulse duration



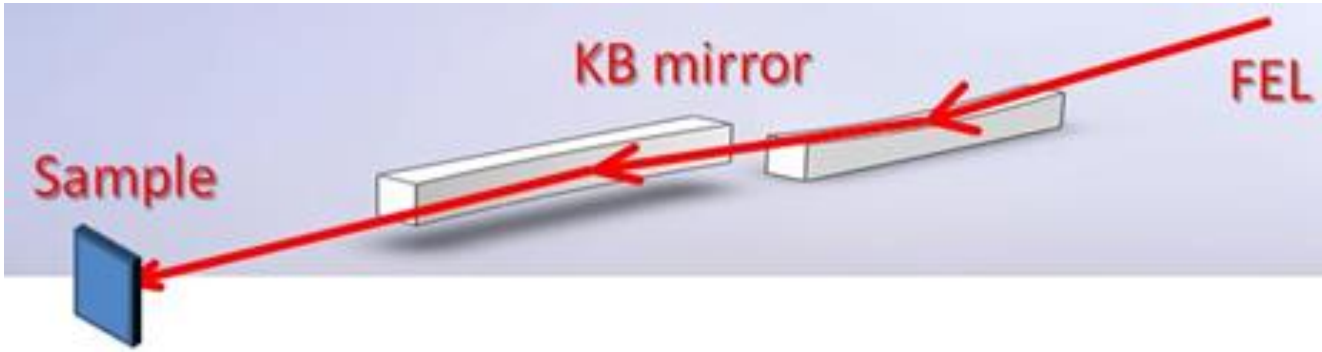
Pulse duration: ~ 8 fs

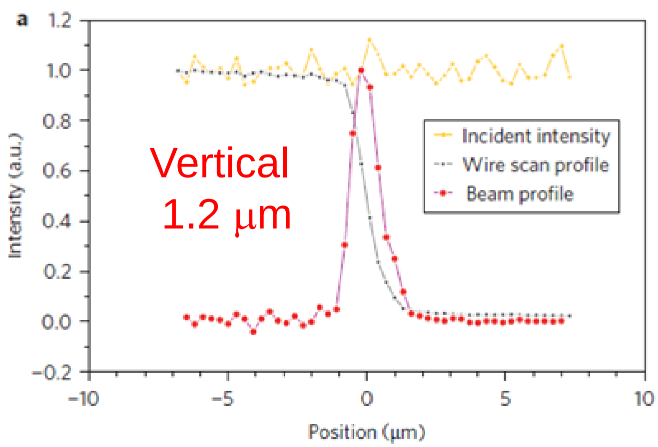
(assuming energy chirp of 6×10^{-5} fs^{-1})

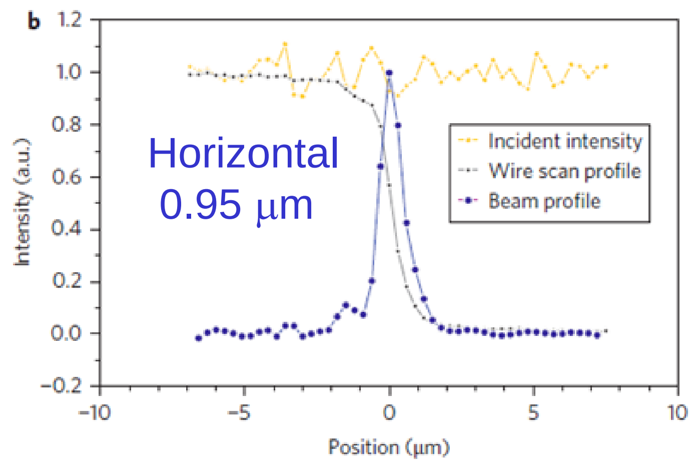
Longitudinal mode number: ~ 60

Y. Inubushi, et al., *Appl. Sci.* **7**, 584 (2017).

1-μm focusing system



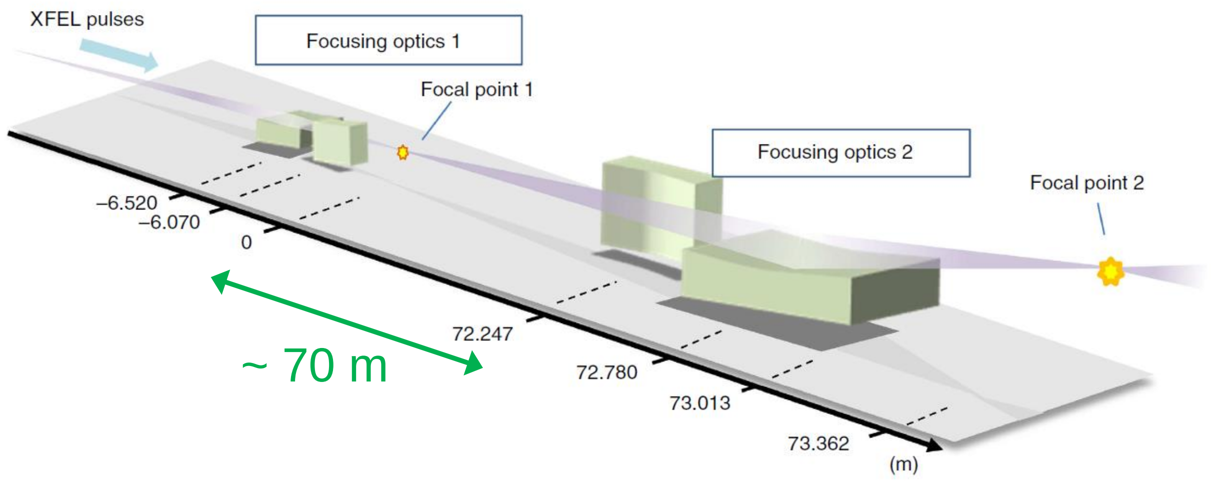


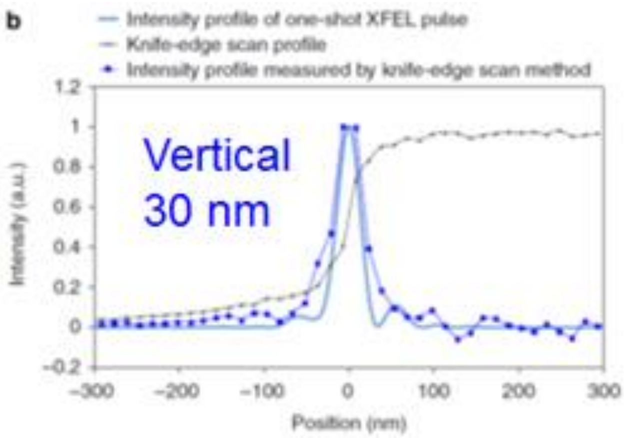


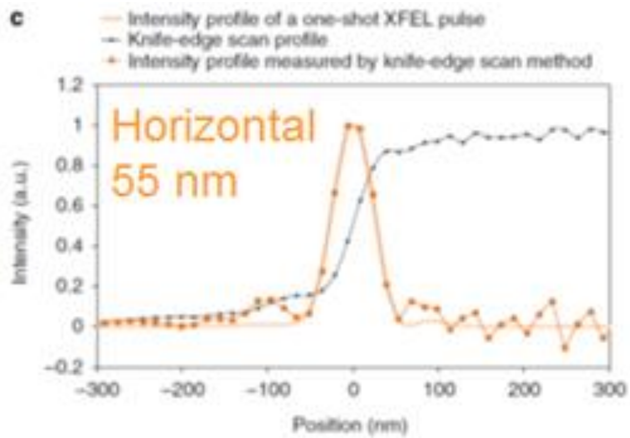
~10^{18} W/cm^2

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

2-stage focusing system







~10^{20} W/cm^2

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

Parameters of XFEL pulse

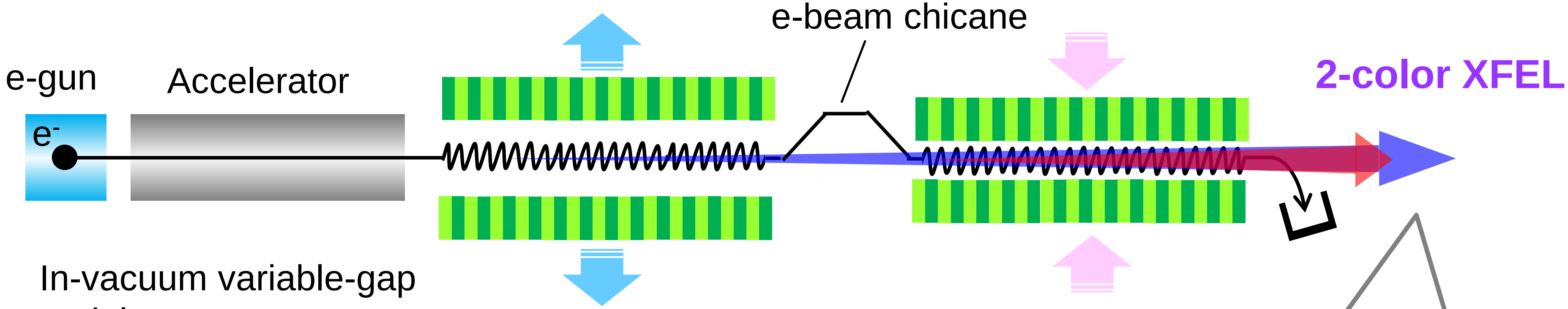
Pulse energy:	500 μJ @10keV
	(Throughput depends on optics)
Pulse duration:	~ 8 fs
Bandwidth:	~ 40 eV
Peak power:	~ 50 GW
Intensity:	~ 10^{14} W/cm^2 (300 $\mu m\phi$, raw beam)
	~ 10^{18} W/cm^2 (1 $\mu m\phi$)
	~ 10^{20} W/cm^2 (50 nmϕ)

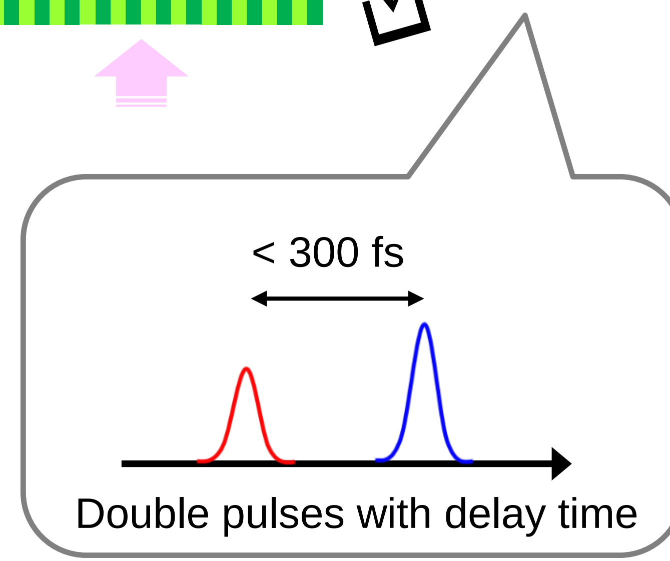
2-color double-pulse XFEL

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

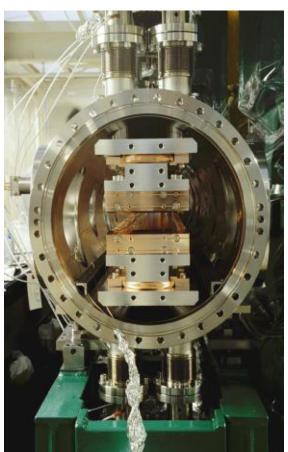
Applicable to XFEL pump - probe

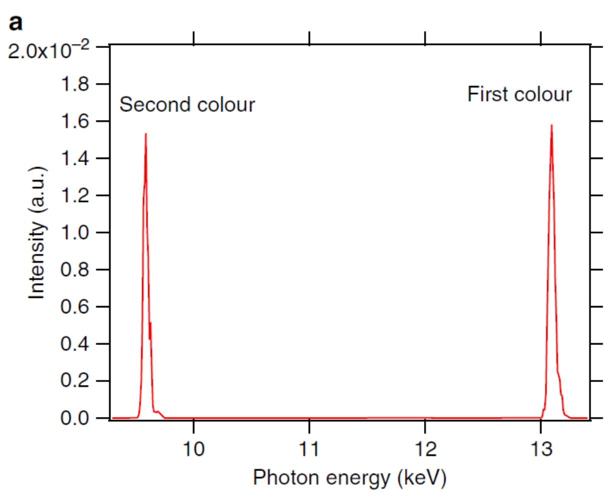
- 2-color XFEL with the energy separation up to 30 %
- Setting of delay time between two pulses





In-vacuum variable-gap undulator





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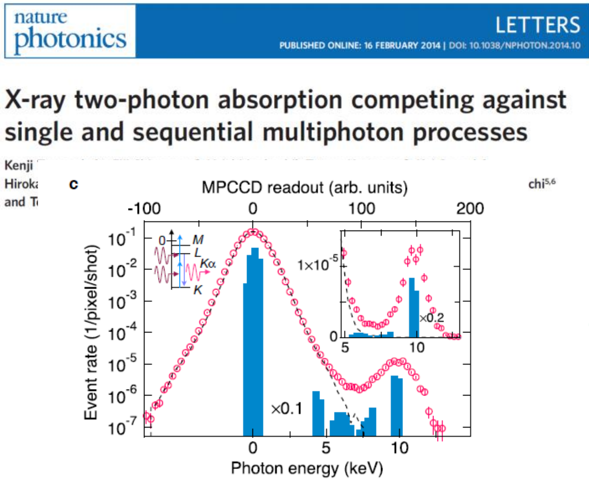
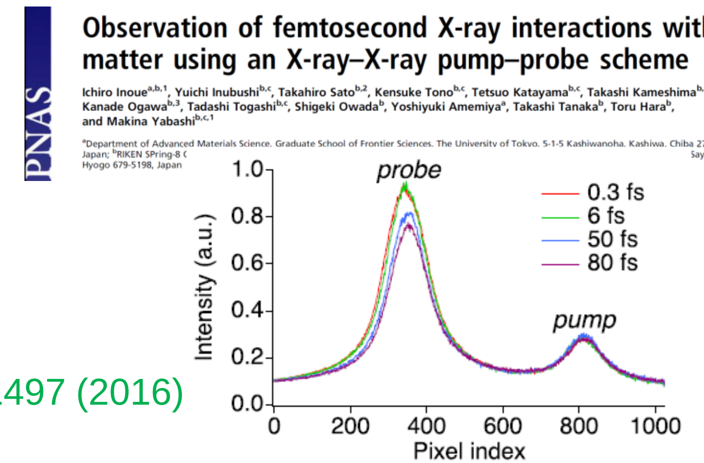
Applications of intense XFEL pulses

X-ray two-photon absorption

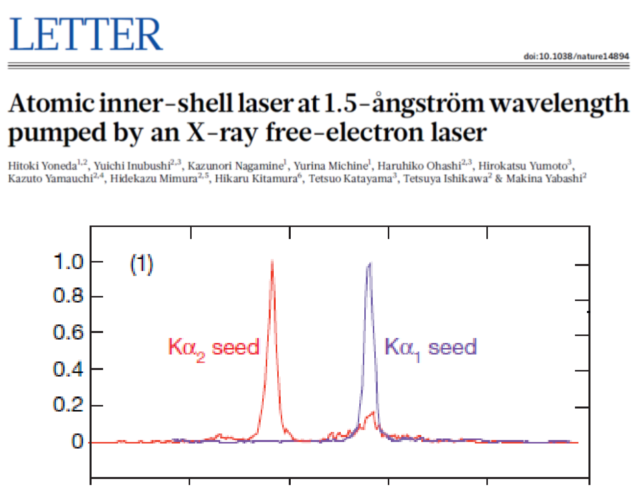


Tamasaku *et al*, *Nature Photon* **8** 313 (2014)

Femtosecond damages

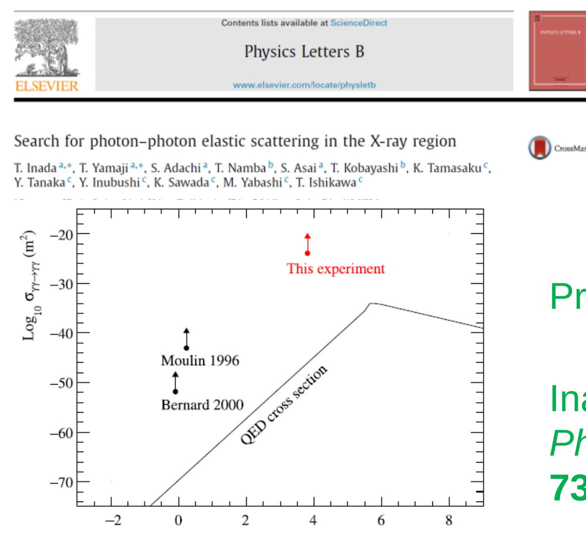


Inoue *et al*., *PNAS* **113** 1497 (2016)



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

XFEL-pumped Kα laser



Prof. Asai (U Tokyo)

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

Photon-photon scattering

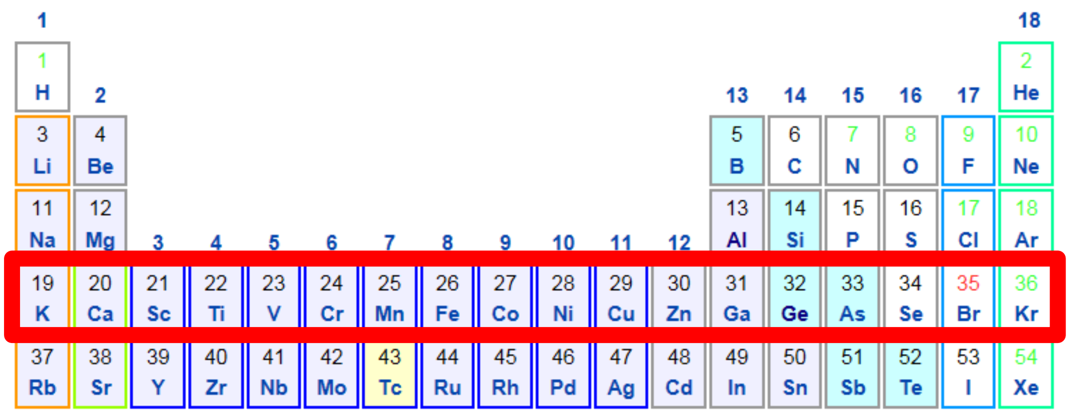
Interaction of intense XFEL pulses with matter

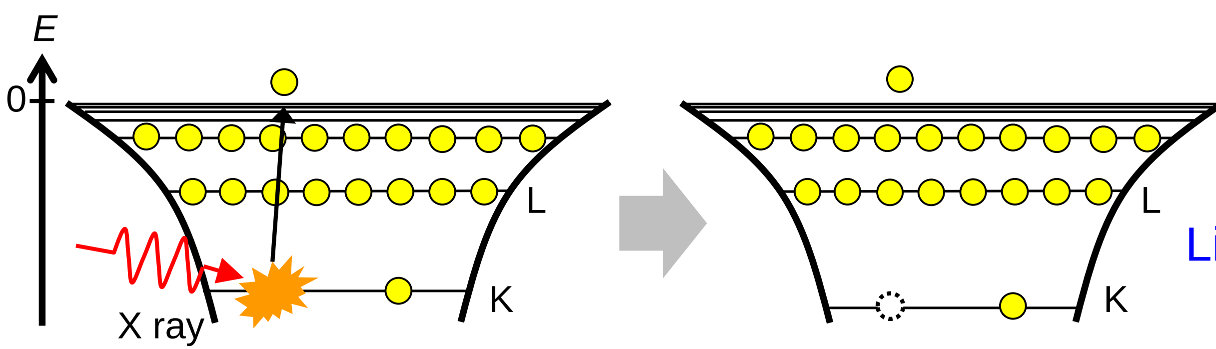
- Low ponderomotive force ($\propto \sqrt{I\lambda^2}$) due to short wavelength
- **Penetration to matters （Cut-off density: ~10^{29} cm^{-3}）**
- **Ionization and excitation of inner-shell electrons due to high photon energy**

XFEL photon energy

4～15keV

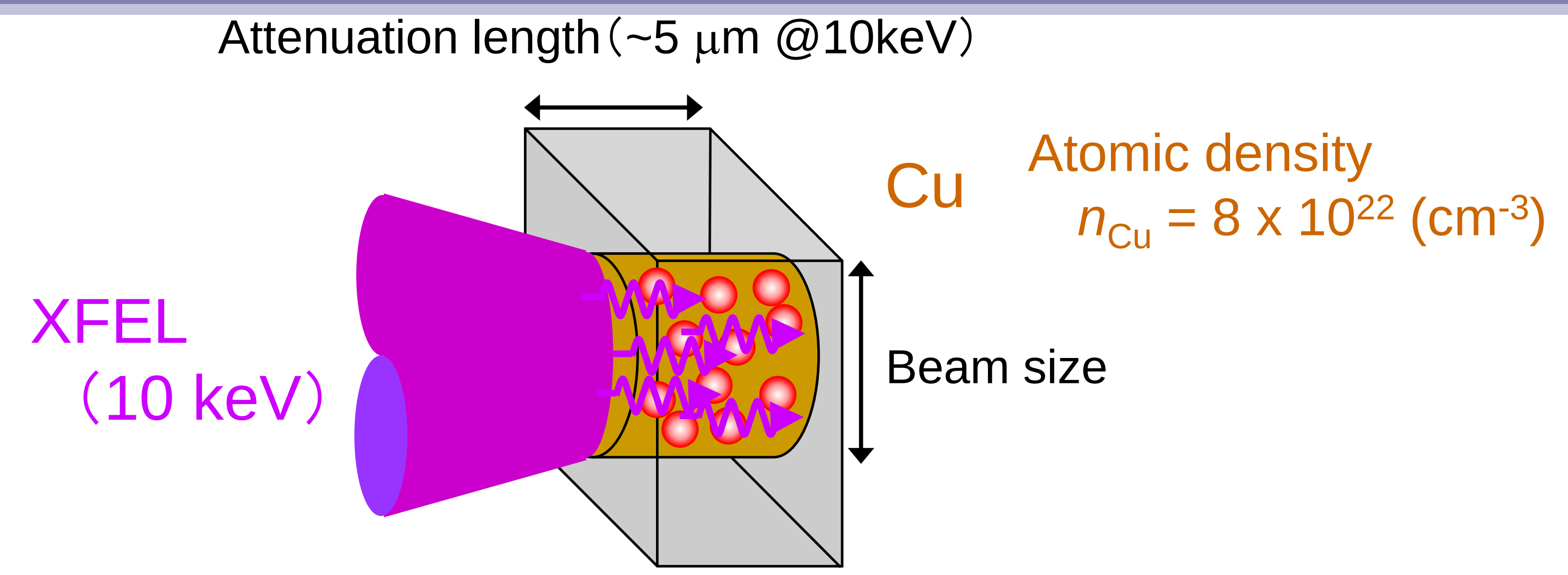
corresponding to transition energy of inner-shell electrons





Lifetime: asec~ fsec

XFEL photon density（10keV、Cu sample）



XFEL beam size	Intensity（W/cm^2）	Absorbed photon density （cm^{-3}）
Un-focus（300μmϕ）	~10^{14}	~10^{17} （<< n_{Cu})
1-μm focus	~10^{18}	~10^{22} （< n_{Cu})
100-nm focus	~10^{20}	~10^{23} （> n_{Cu})

Cross section of K-shell >> Lshell
Almost all atoms become “core-hole atoms”.

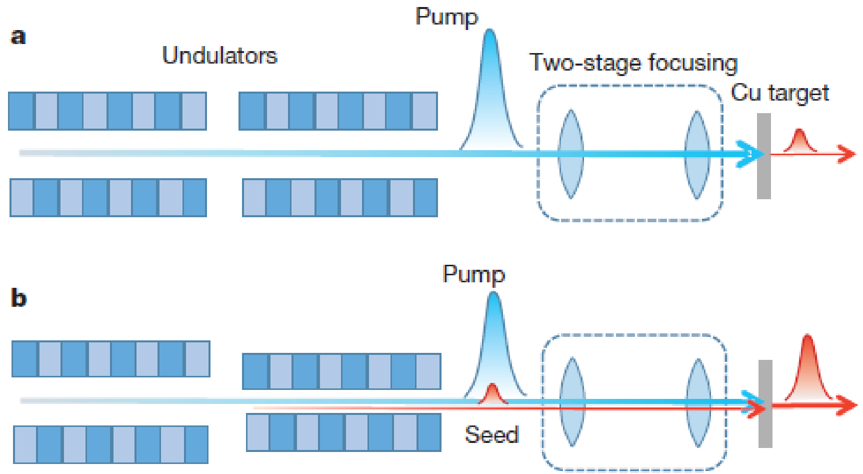
Kα laser pumped by intense XFEL pulse

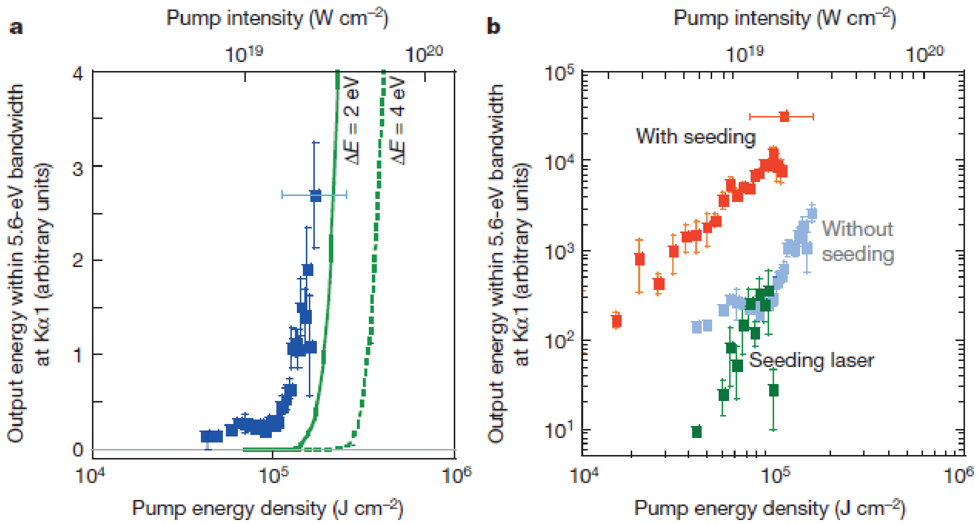
LETTER

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 Nagamine[1], Yurina Michine[1], Haruhiko Ohashi[2,3], Hirokatsu Yumoto[3], Kazuto Yamauchi[2,4], Hidekazu Mimura[2,5], Hikaru Kitamura[6], Tetsuo Katayama[3], Tetsuya Ishikawa[2] & Makina Yabashi[2]

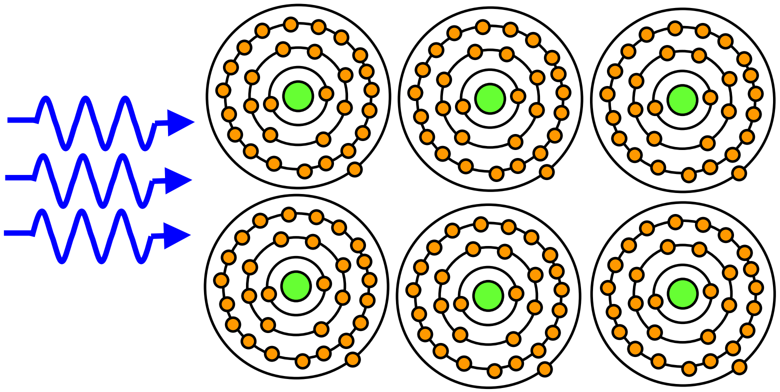




Kα laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, Kα emission becomes laser via stimulated emission process.

Weak X rays



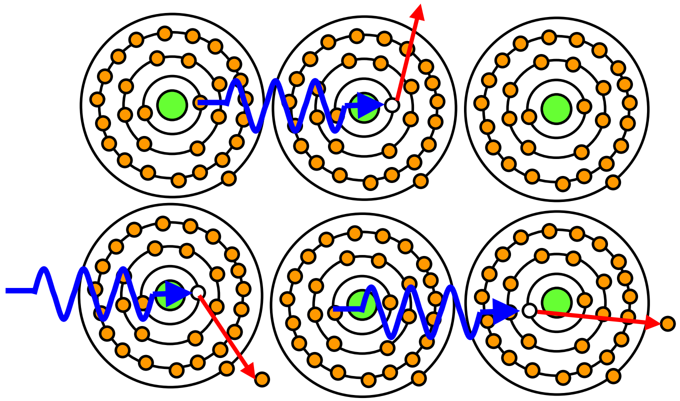
Incidence of X rays

Intense XFEL

Kα laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, Kα emission becomes laser via stimulated emission process.

Weak X rays



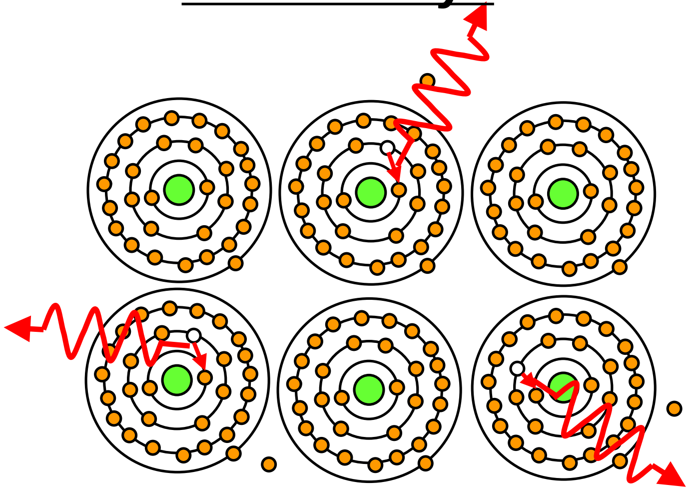
Creation of core-hole atoms

Intense XFEL

Kα laser pumped by intense XFEL

Intense XFEL create a lot of core-hole atoms.
Then, Kα emission becomes laser via stimulated emission process.

Weak X rays



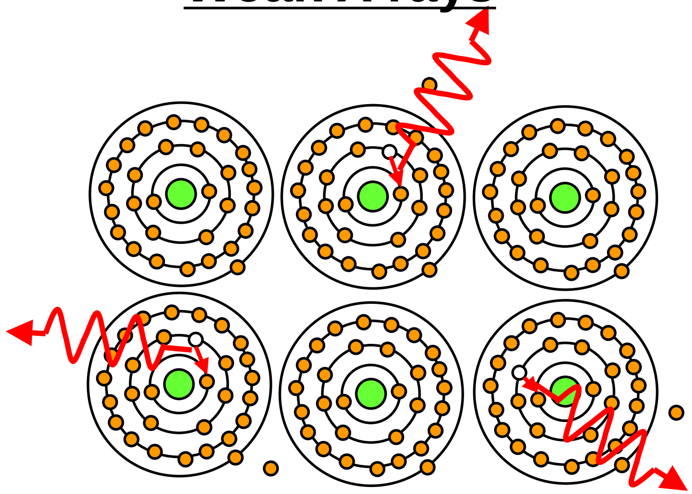
Kα emission
(isotropic)

Intense XFEL

Kα laser pumped by intenser

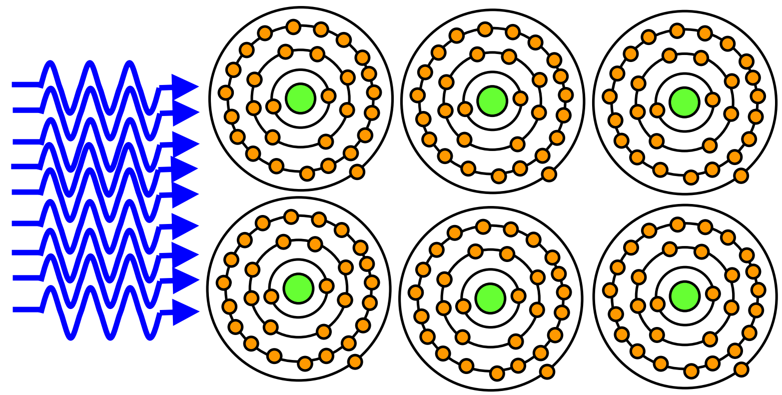
Intense XFEL create a lot of core-hole atoms. Then, Kα emission becomes laser via stimulated emission process.

Weak X rays



Kα emission
(isotropic)

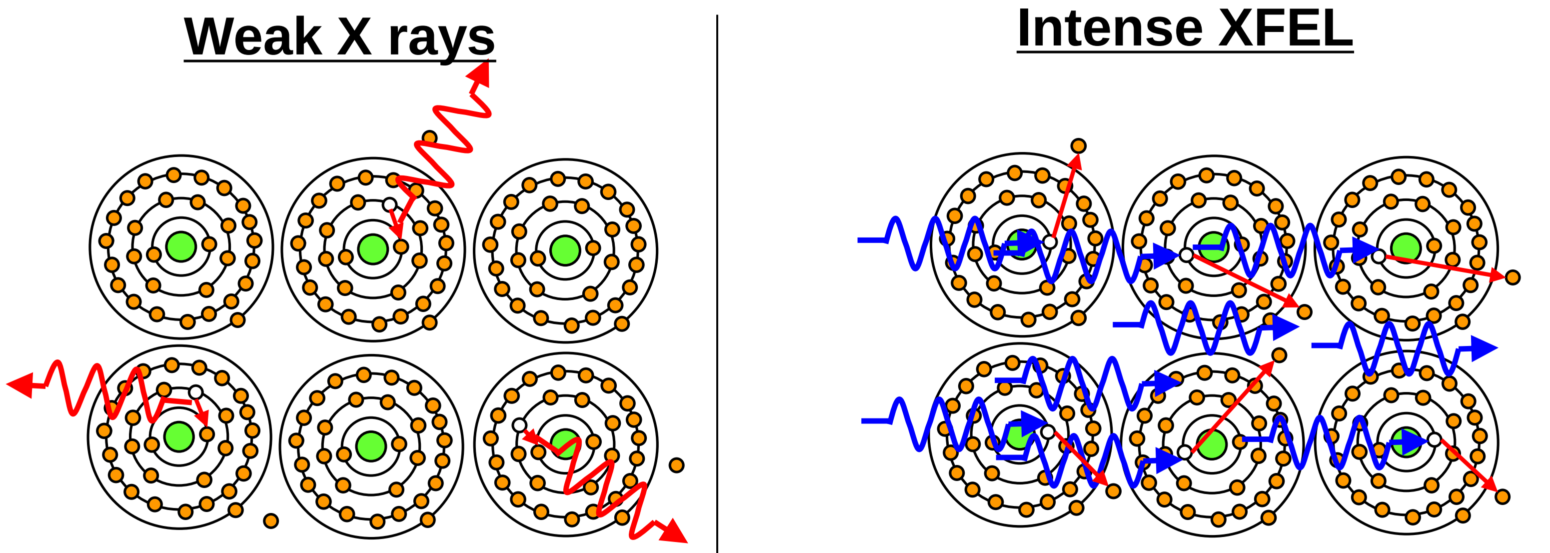
Intense XFEL



Incidence of X rays

Kα laser pumped by intenser

Intense XFEL create a lot of core-hole atoms.
Then, Kα emission becomes laser via stimulated emission process.



Kα emission
(isotropic)

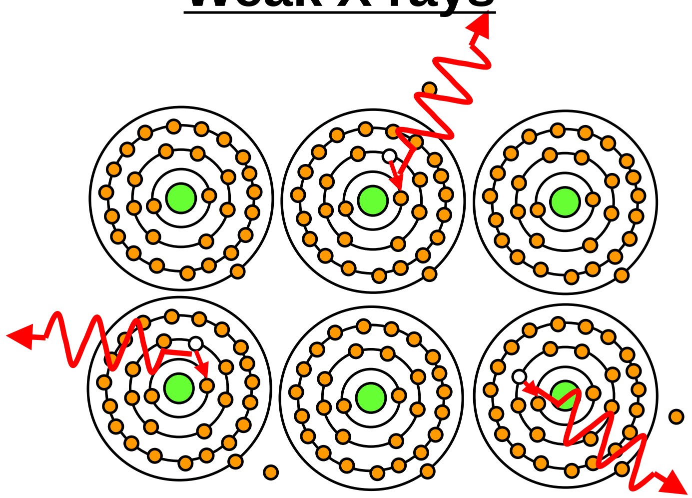
Creation of core-hole atoms

⇒ **Population inversion**

Kα laser pumped by intense XFEL

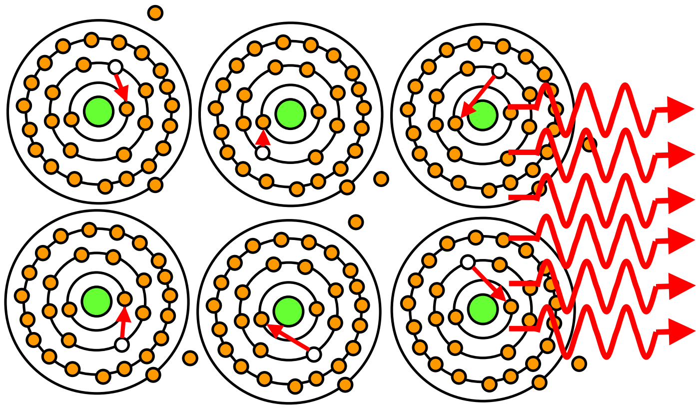
Intense XFEL create a lot of core-hole atoms.
Then, Kα emission becomes laser via stimulated emission process.

Weak X rays



Kα emission
(isotropic)

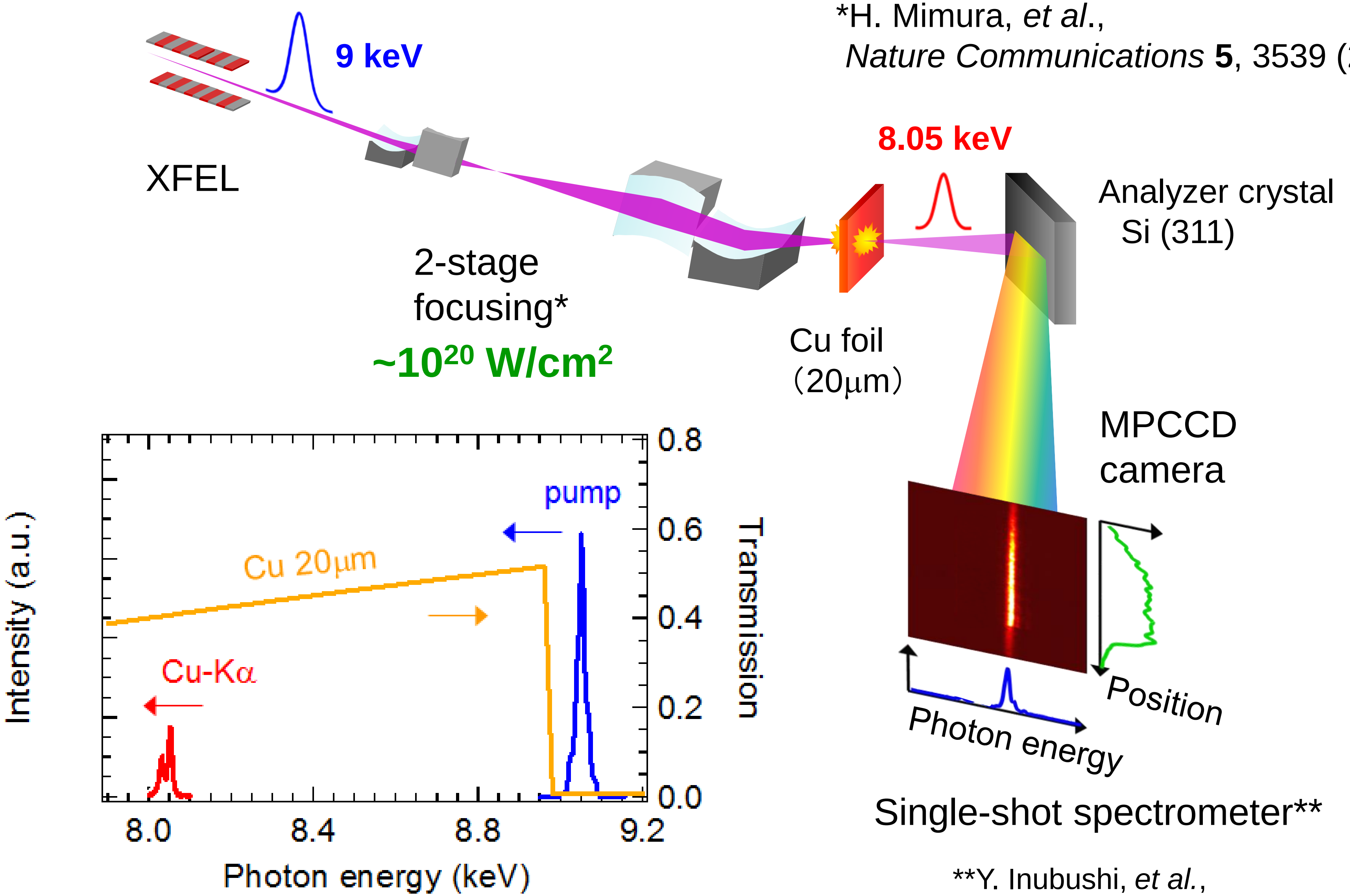
Intense XFEL



Kα laser
via stimulated emission process

Kα laser pumped by intense XFEL

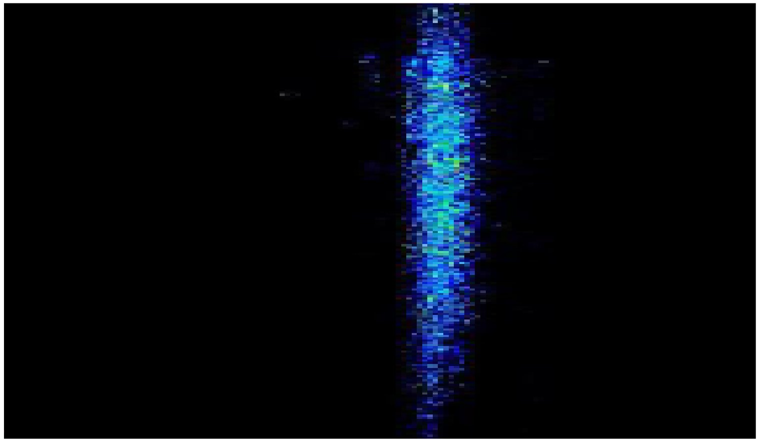
*H. Mimura, *et al.*,
Nature Communications **5**, 3539 (2014).

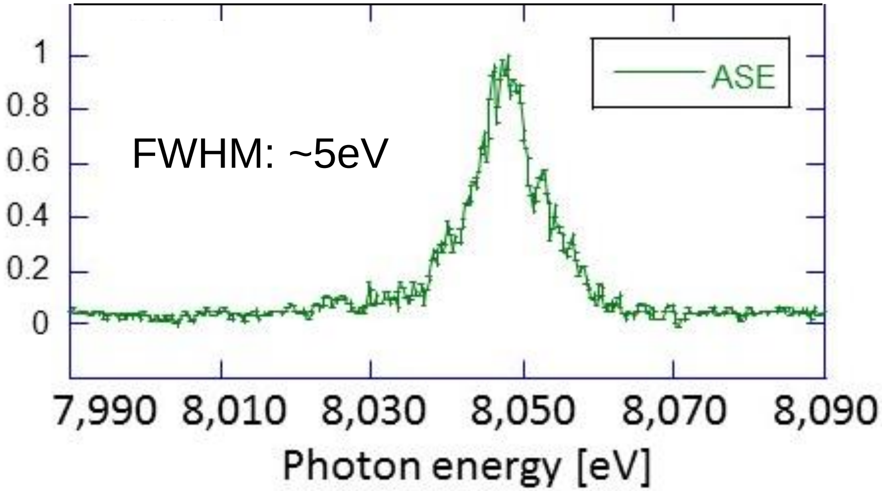


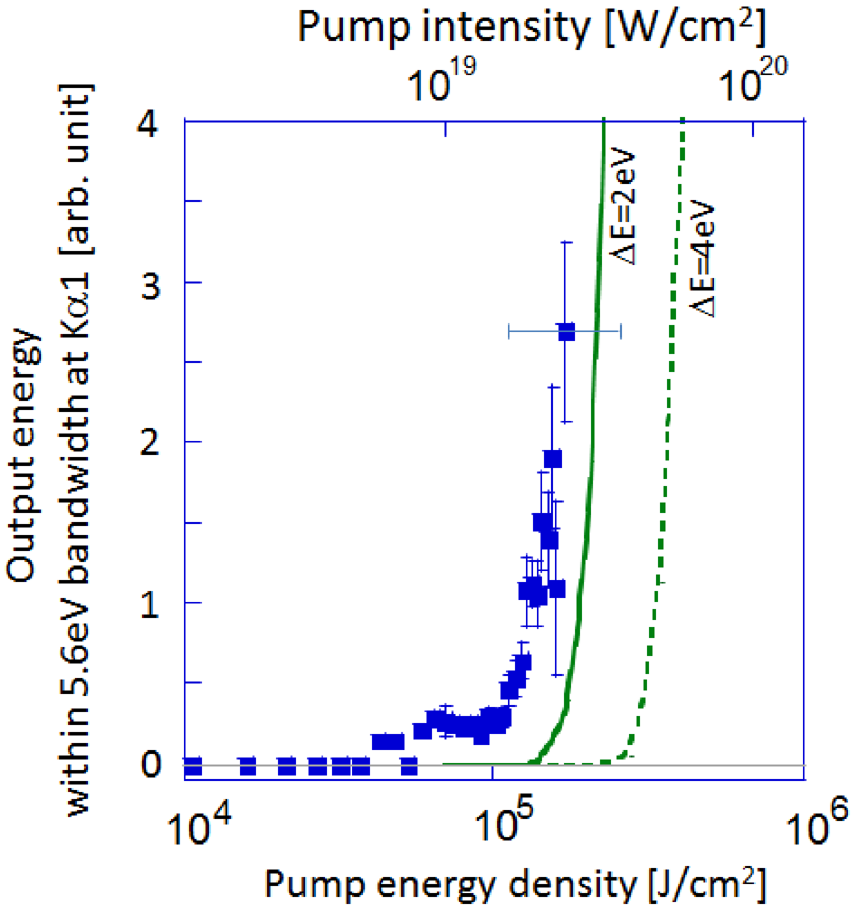
Single-shot spectrometer**

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

Kα laser pumped by intense XFEL





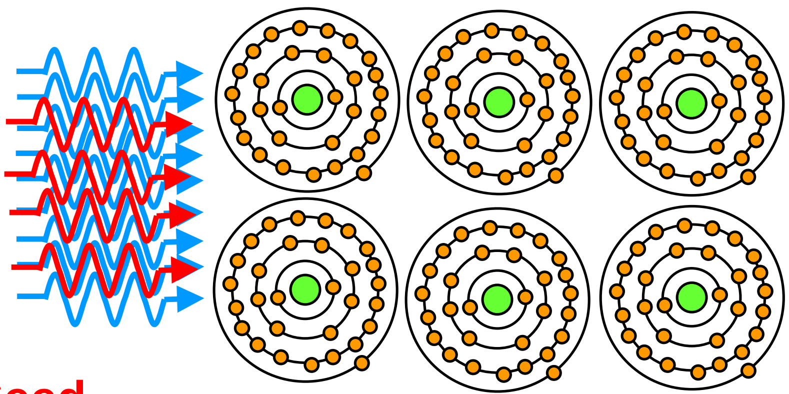


First hard x-ray laser using atomic level

Seeding in hard x-ray region

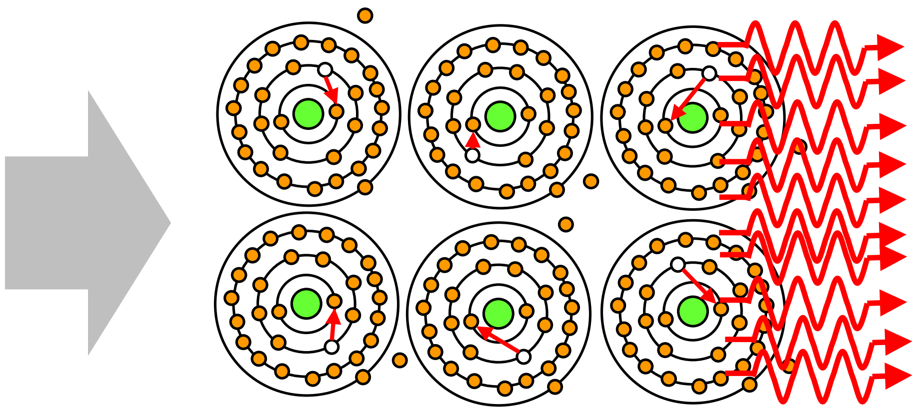
Pump

creation of core-hole atoms (9keV)



Seed

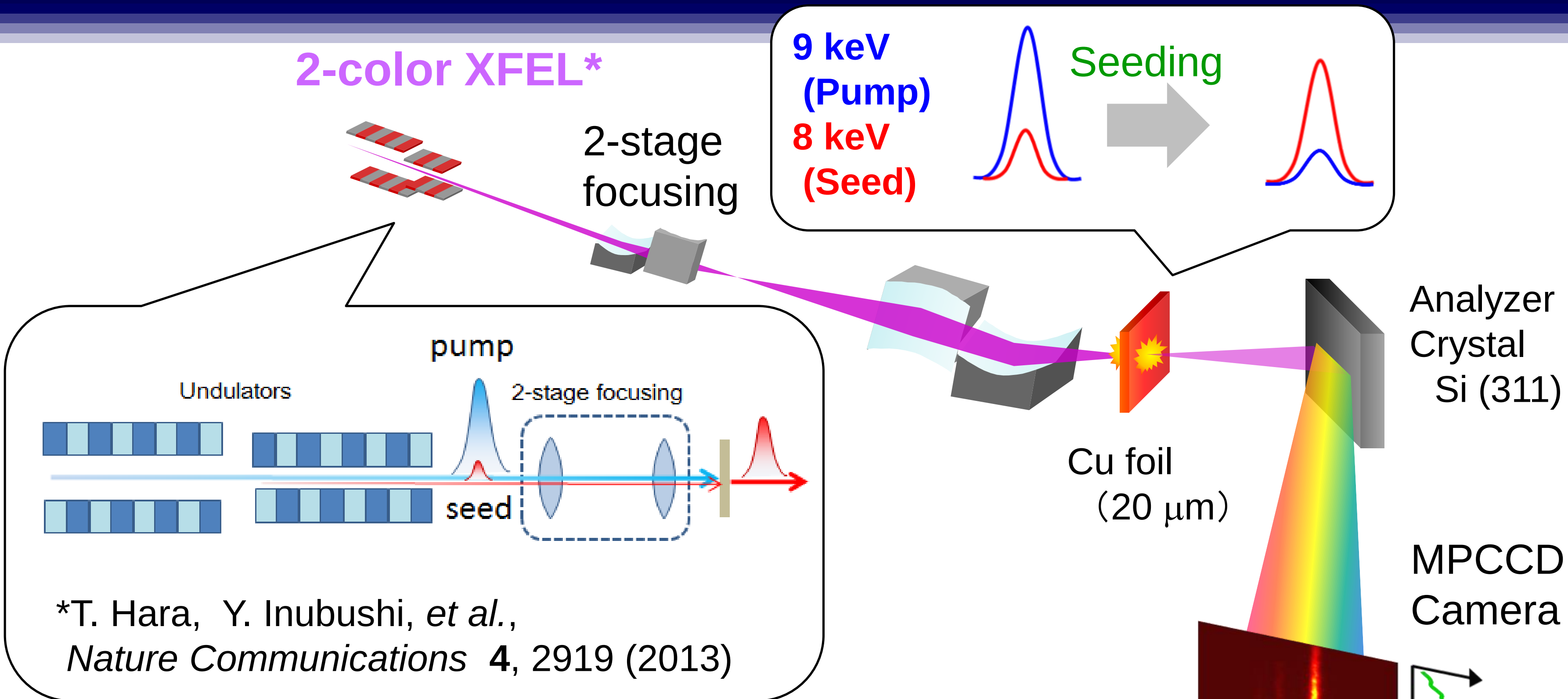
Same photon energy of Kα（8keV）

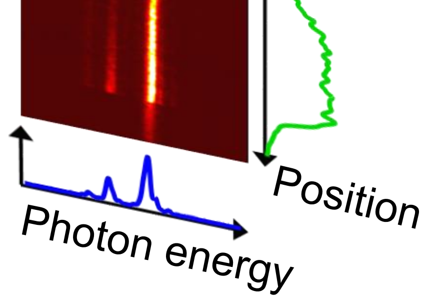


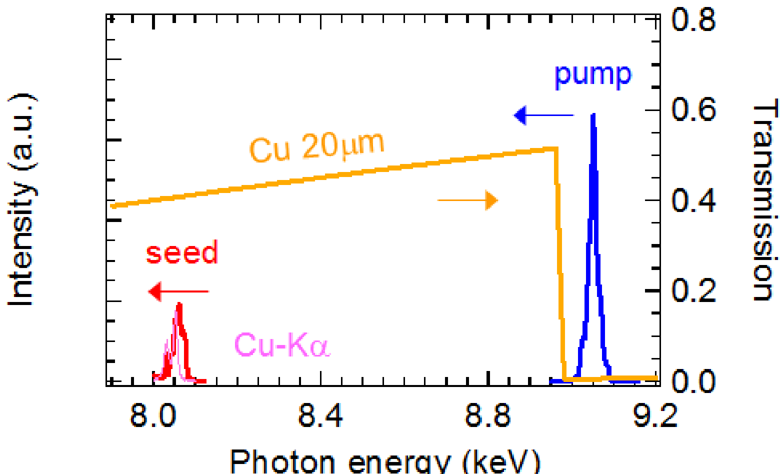
<u>Incidence of two-color XFEL</u>

<u>Amplification of seed pulse</u>

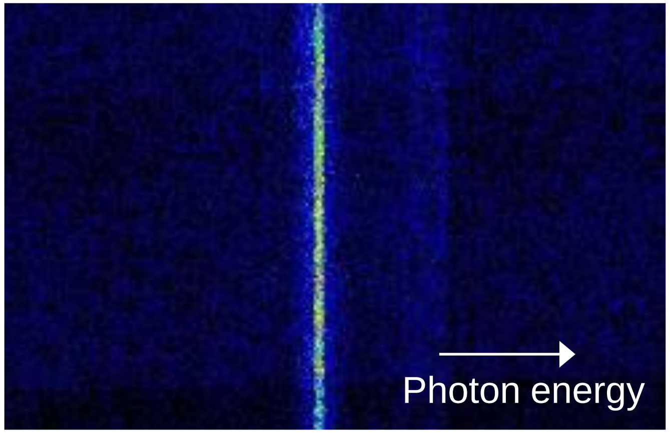
Hard x-ray seeding using 2-color XFEL

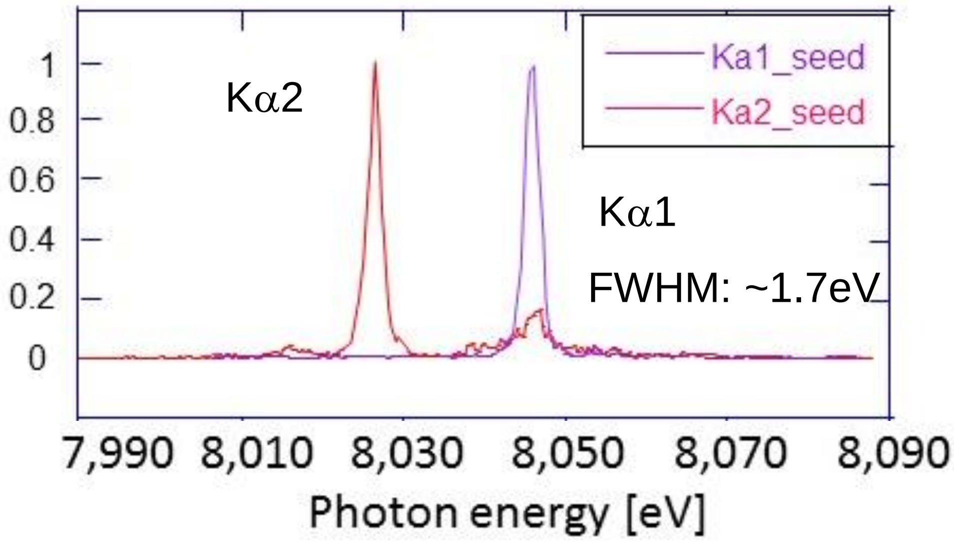


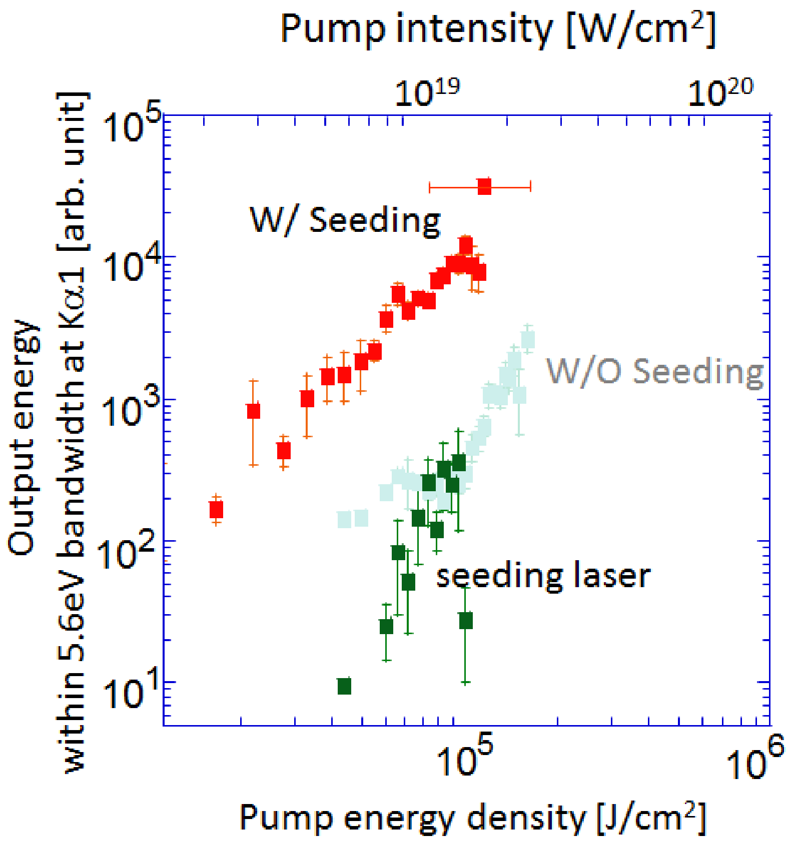




Hard x-ray seeding using 2-color XFEL

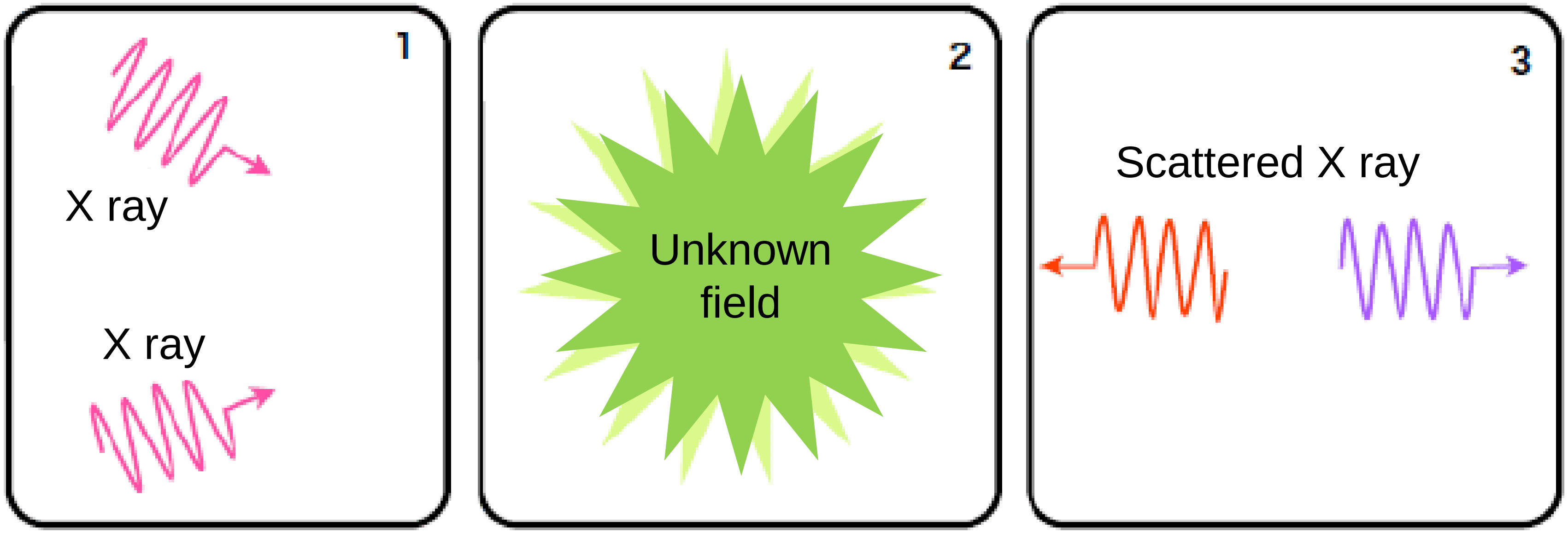






First hard x-ray seeding

Photon-Photon scattering

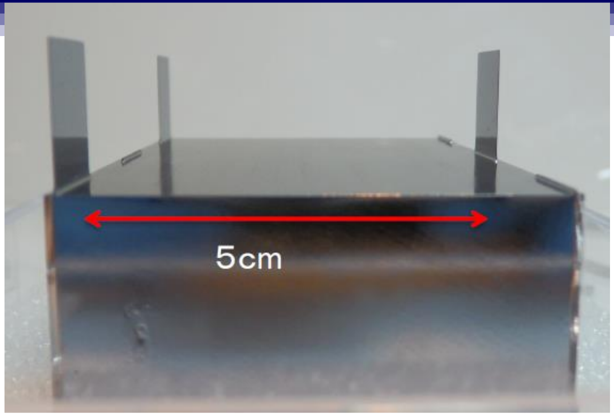


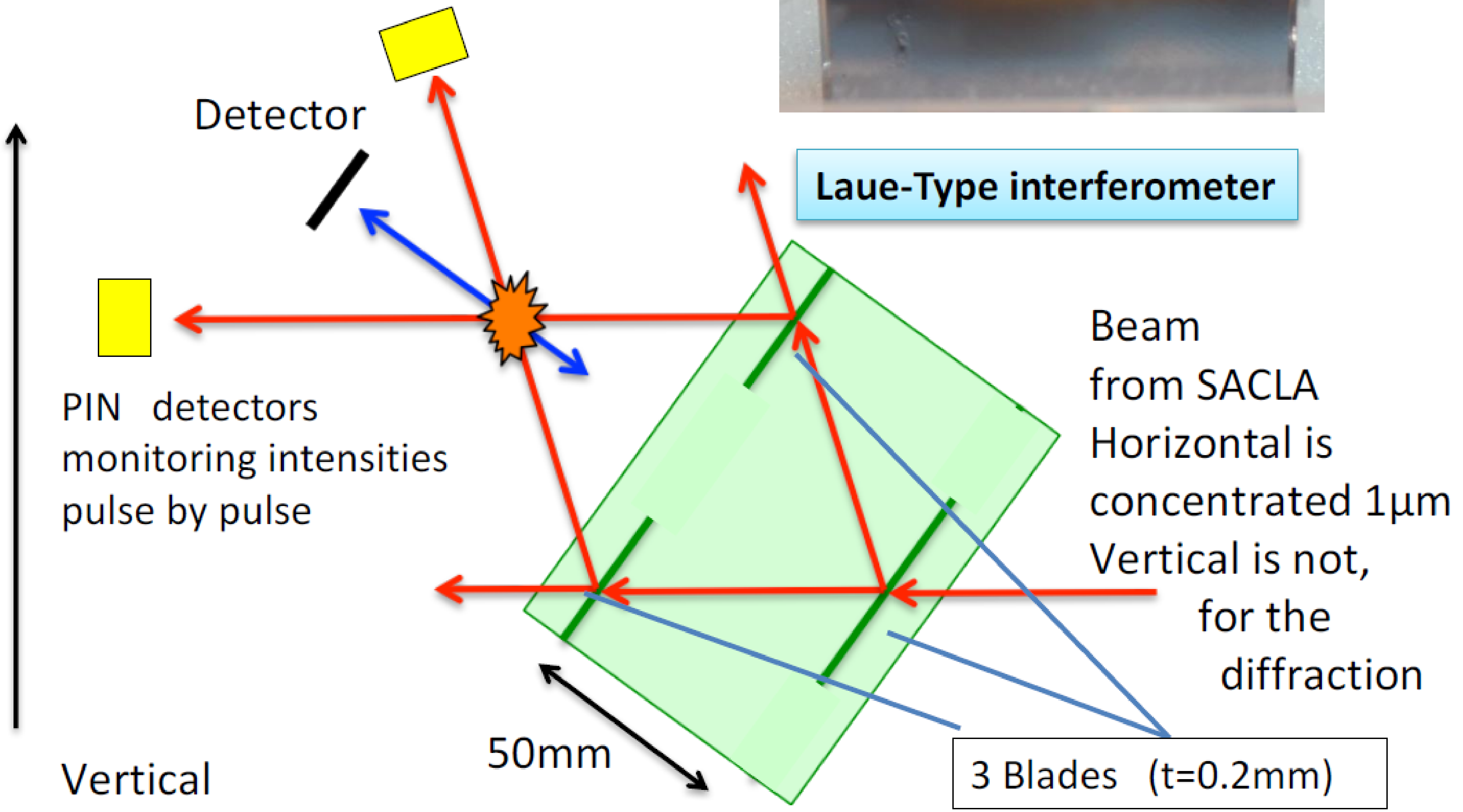
Exploring unknown field by measurement of photon-photon scattering

Verification of Quantum electrodynamics (QED)

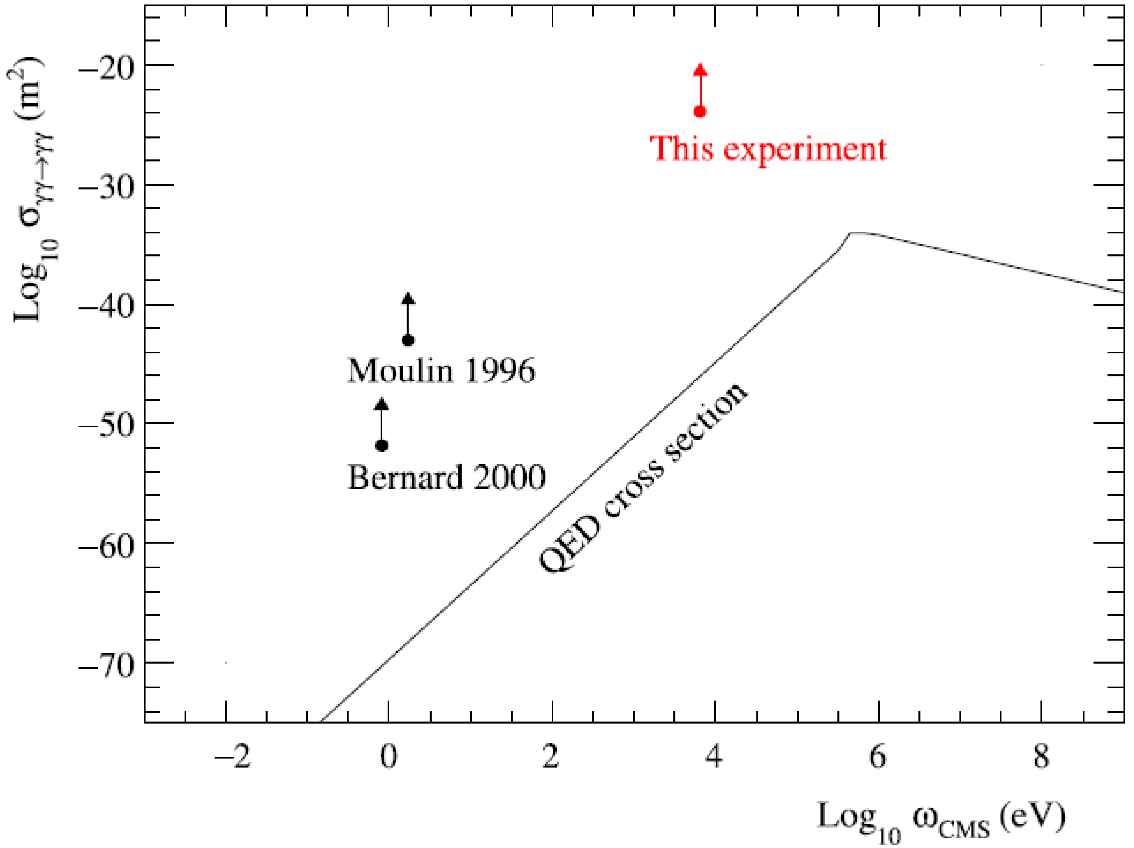
T. Inada, *et al*., *Phys. Lett. B*, **732**, 356-359 (2014).

Experimental setup





Result

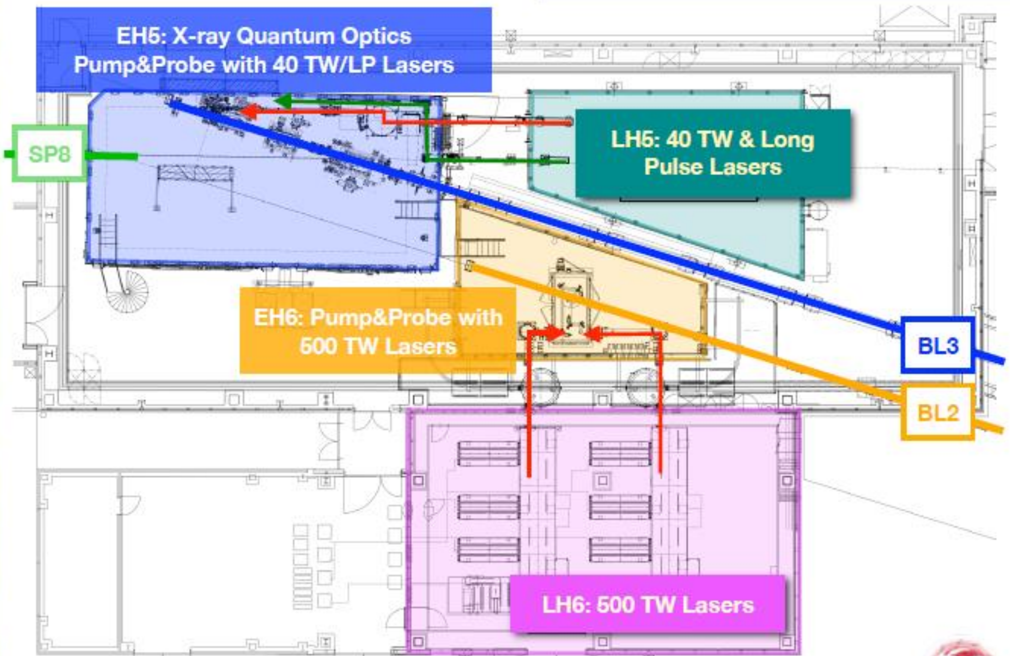


Although the signal could not be detected, the new point could be plotted.

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

Contents

HEDS (High Energy Density Science) experimental station at SACLA

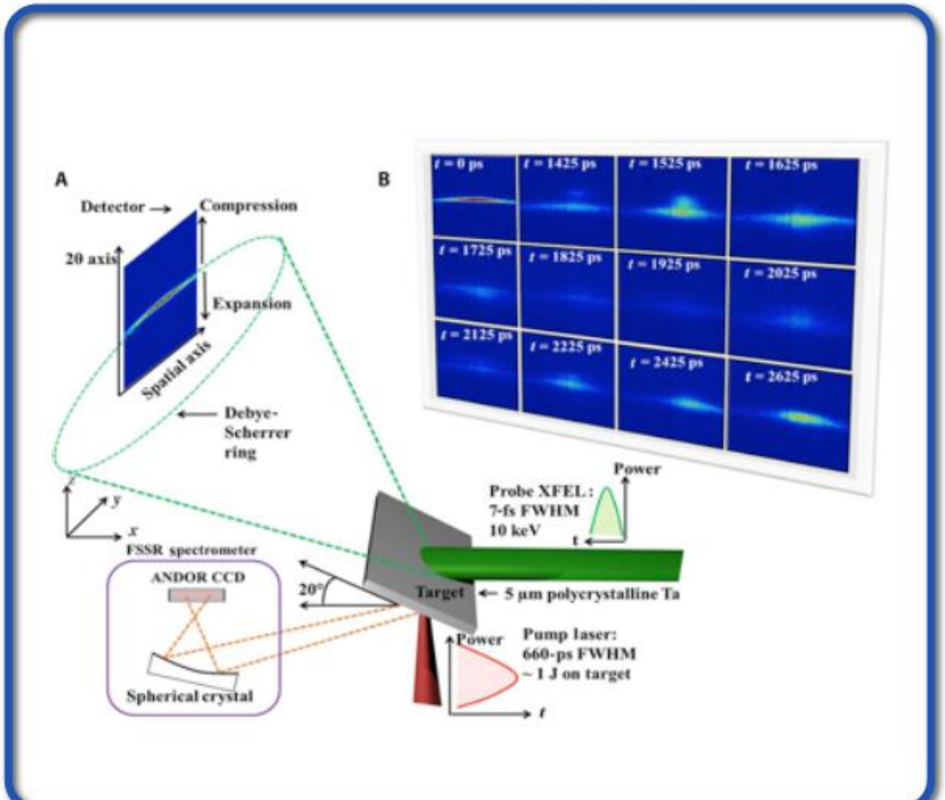


	40 TW Laser	500 TW Laser x2	Long Pulse Laser
Status	Operational	Under Commissioning	Operational
Pulse Energy	~1 J	~10 J	~ 10 J (to be upgraded)
Pulse Duration	~25 fs	~25 fs	~4 ns
Max. Rep. Rate	10 Hz	1 Hz	0.1 Hz
SACLA EH	EH5	EH6	EH5

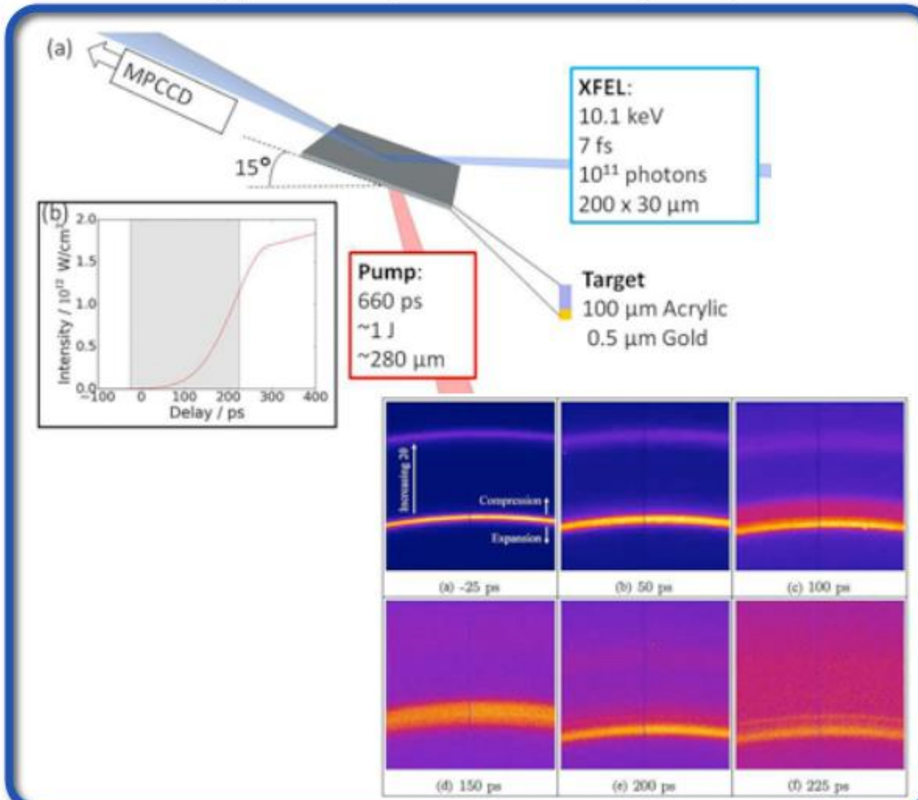
In collaboration with Harima Center for Photon Sciences, Osaka Univ. (Prof. R. Kodama)

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

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

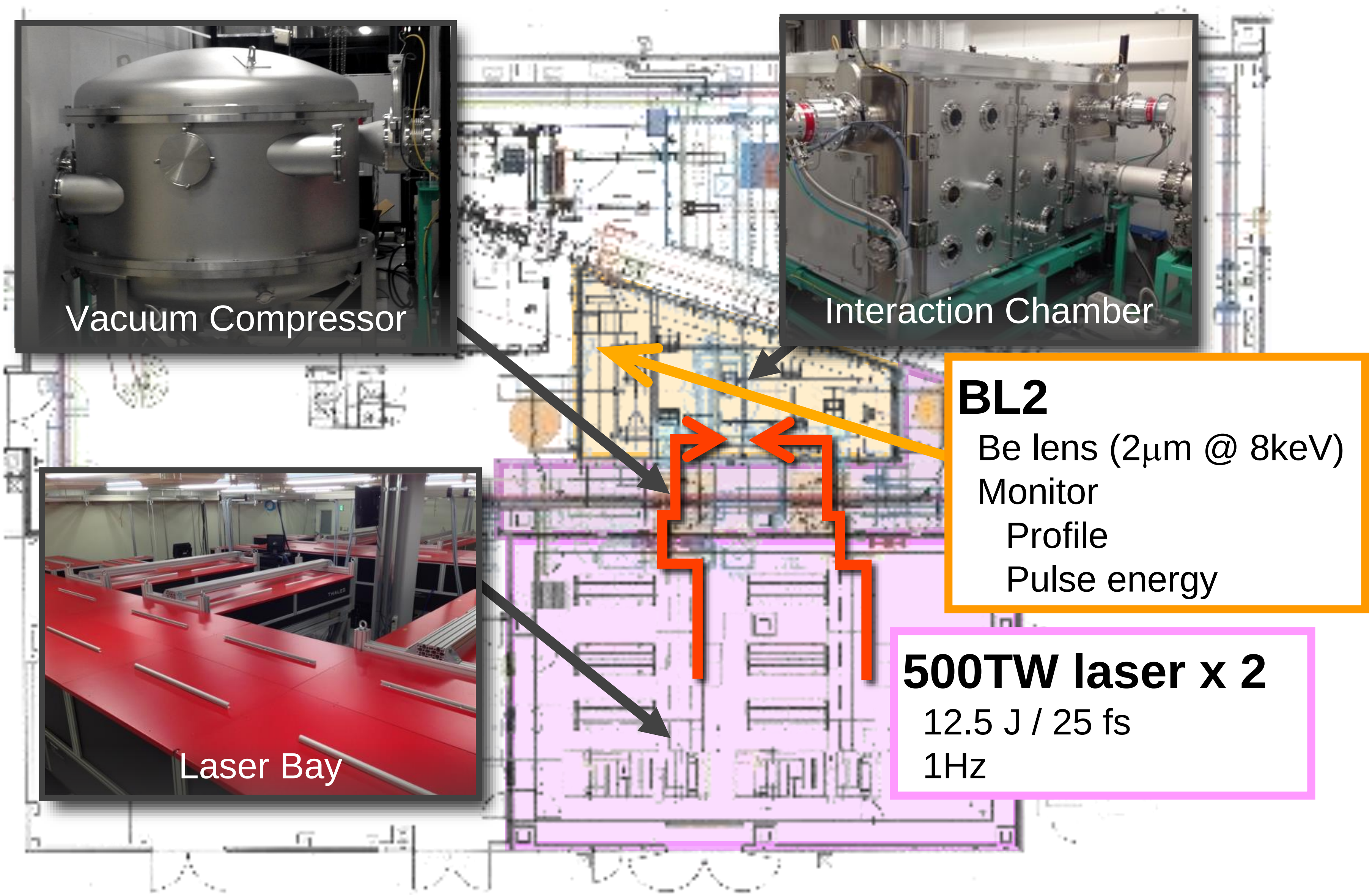


N. J. Hartley, N. Ozaki et. al
Applied Physics Letters (2017)



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）



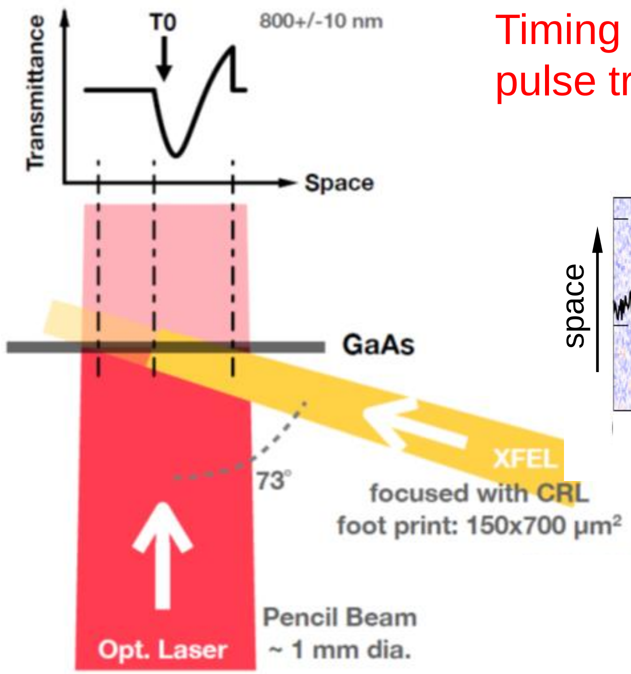
Current status of 500 TW laser

Laser parameters

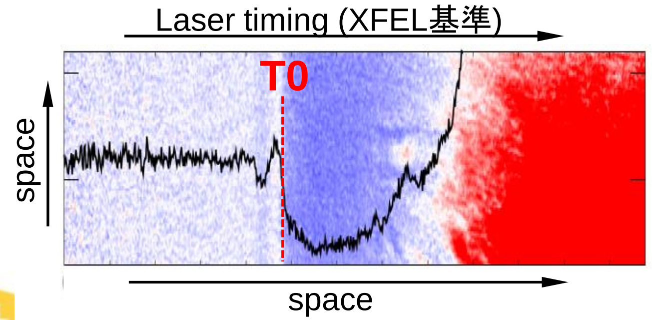
☑Pulse energy: 12.5 J
☑Peak power: 500 TW
☑Wavelength: 800 nm
☑Duration: 25 fs
☑Beam size:ϕ120 mm with Top Hat
☑Contrast: 10^{-10}@−100 ps, 10^{-8}@−30 ps

Now, only 1 beam is available.

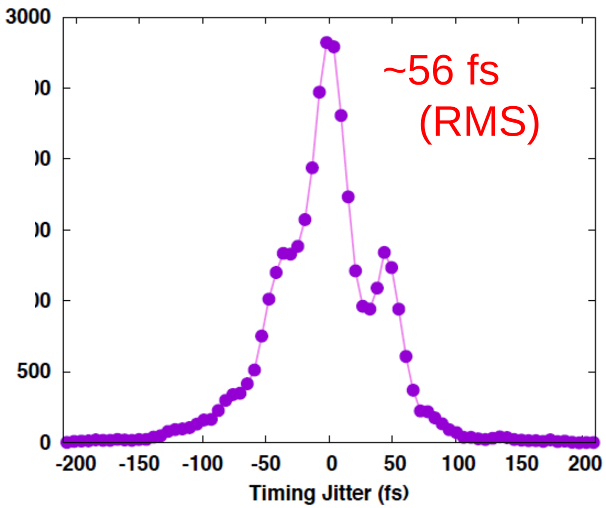
Timing jitter between XFEL and 500 TW laser



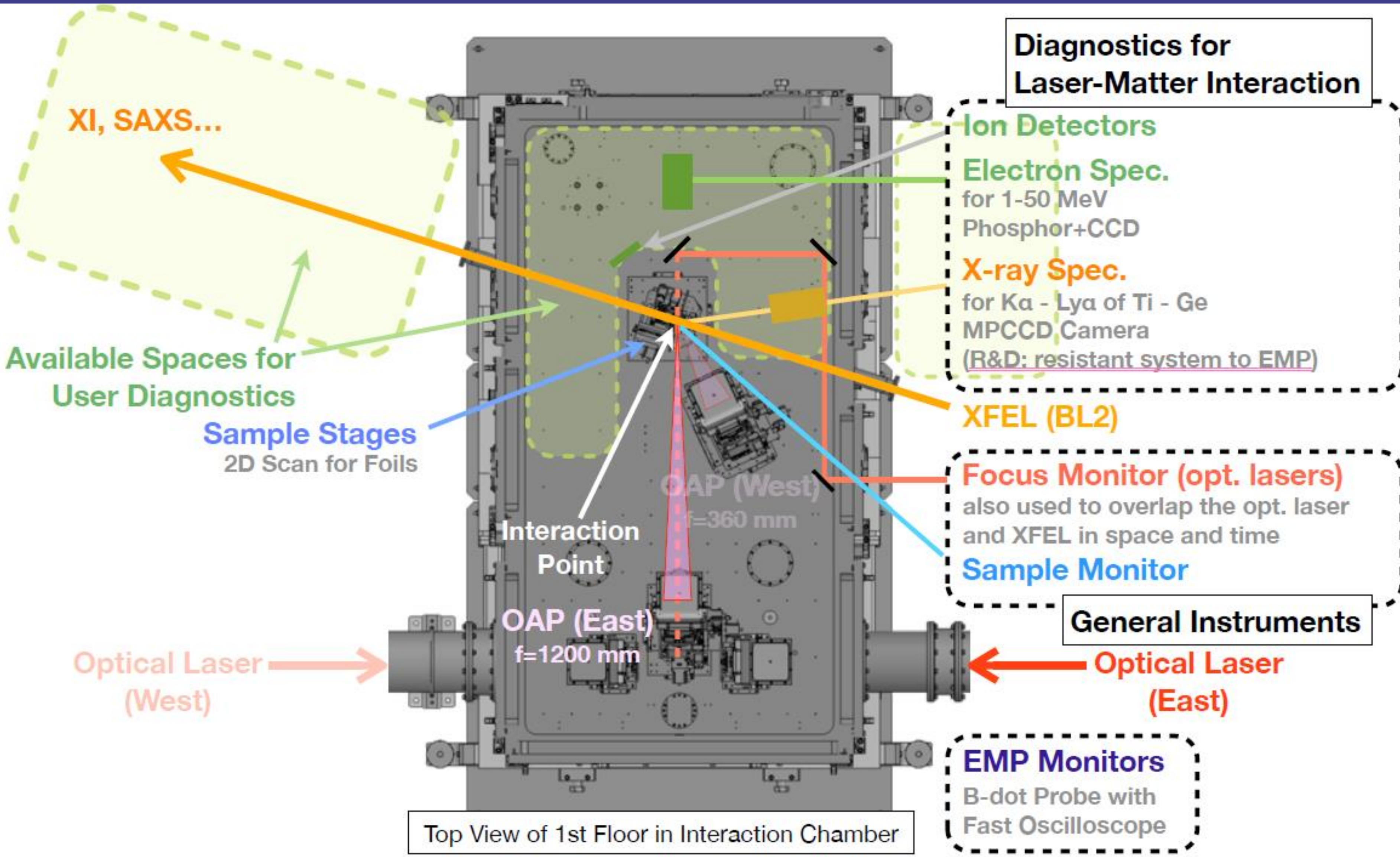
Timing jitter was derived from pulse-by-pulse transmission change of laser



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

XFEL R&D Division, RIKEN SPring-8 Center/JASRI

Especially,
Makina Yabashi, Kensuke Tono,Tadashi Togashi, Tetsuo Katayama, Shigeki Owada, Toshiki Yabuuchi, Akira Kon, Ichiro Inoue, Taito Osaka, Yuya Kubota, Takaki Hatsui, Yasumasa Joti, Togo Kudo, Takashi Kameshima, Kyo Nakajima, Hiroaki Kimura, Hiromitsu Tomizawa, Haruhiko Ohashi, Hirokatsu Yumoto, 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!