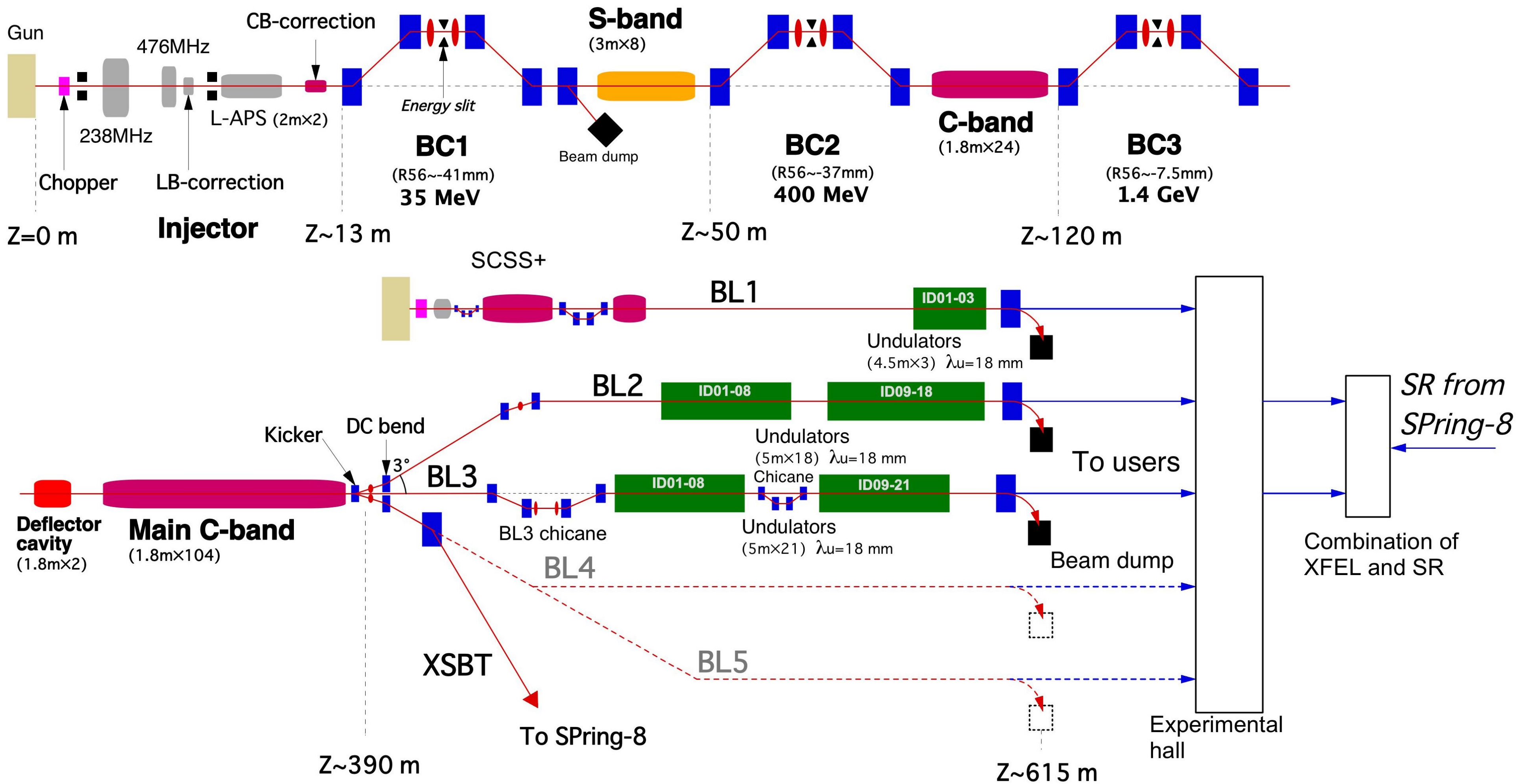
Reflection Self-Seeding at SACLA

Ichiro Inoue, Taito Osaka, Toru Hara, Takashi Tanaka, Takahiro Inagaki, Toru Fukui, Shunji Goto, Yuichi Inubushi, Hiroaki Kimura, Ryota Kinjo, Haruhiko Ohashi, Kazuaki Togawa, Kensuke Tono, Mitsuhiro Yamaga, Hitoshi Tanaka, Tetsuya Ishikawa, Makina Yabashi

RIKEN SPring-8 Center and JASRI

SACLA
(SPring-8 Angstrom Compact free-electron LAser)



BL1: EUV and soft x-ray (20-150 eV)

BL2 and BL3: hard x-ray (4-15 keV)

Multi-beamline operation

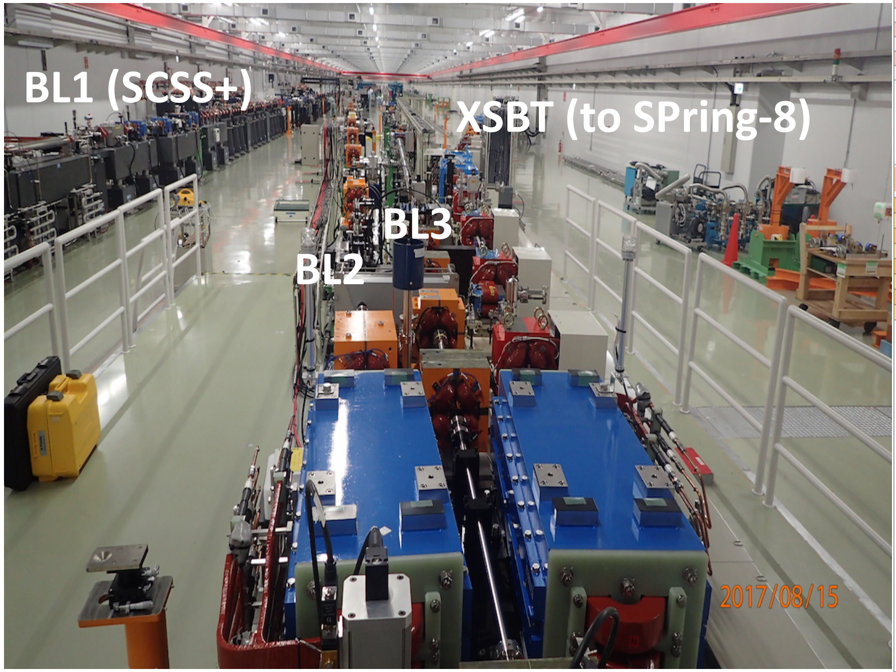
Parallel operation of three beamlines to expand the opportunity of user experiments.

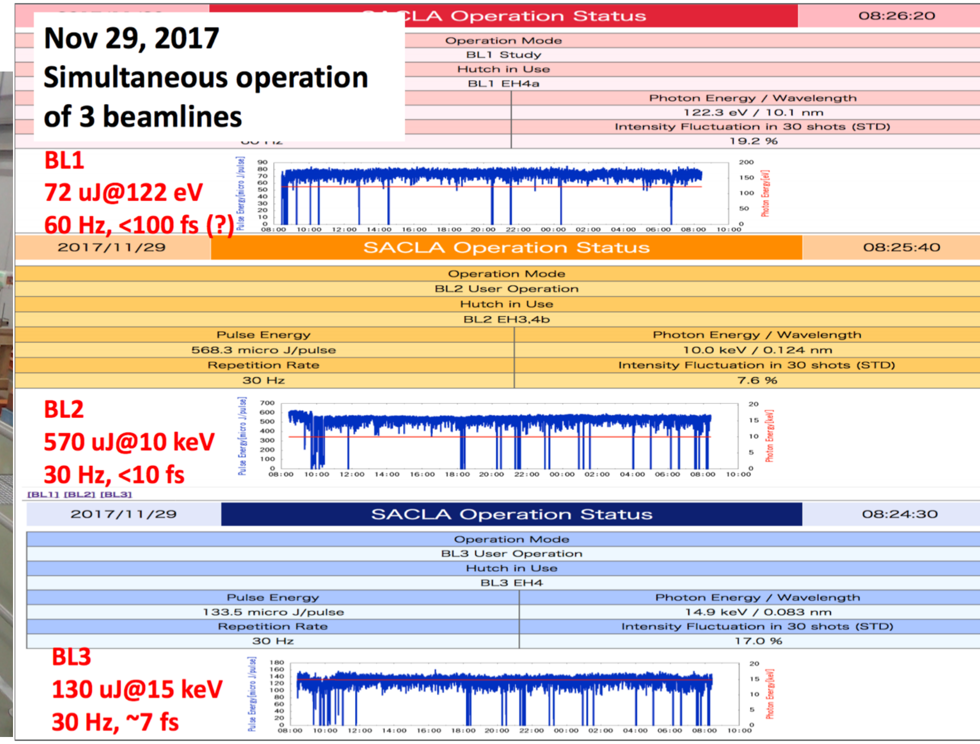
BL1 soft x-ray FEL	
Beam energy	800 MeV max.
Bunch charge	0.2-0.3 nC
Peak current	0.3 kA
Bunch length	< 1 ps (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.1
Number of undulators	4.5 m x 3
Photon energy	20-150 eV
FEL pulse energy	0.1 mJ at 100 eV

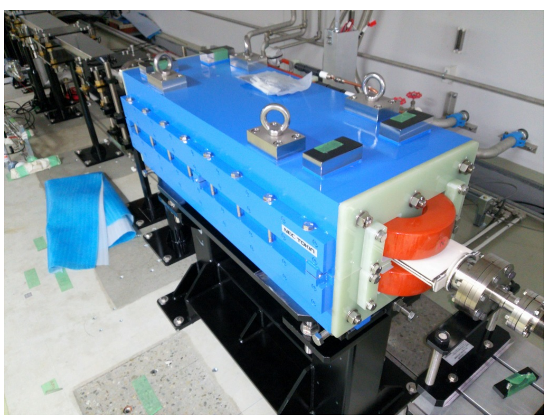
BL1 is driven by SCSS+ accelerator.

BL2 and BL3 XFEL	
Beam energy	8.5 GeV max.
Bunch charge	0.2-0.3 nC
Peak current	> 10 kA
Bunch length	< 20 fs (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.6
Number of undulators	5 m x 18 (BL2) 5 m x 21 (BL3)
Photon energy	4-15 keV
FEL pulse energy	0.7 mJ at 10 keV

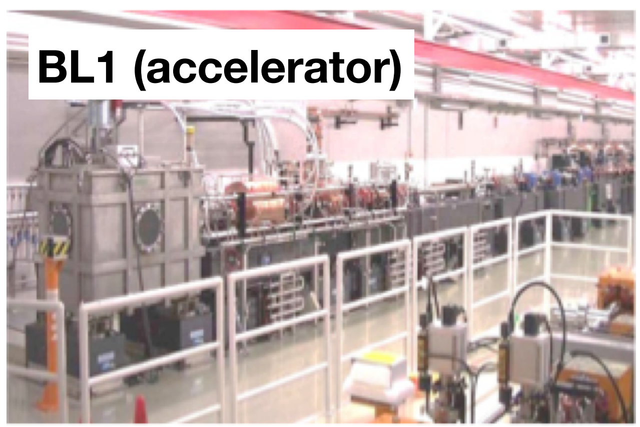
BL2 and BL3 share the electron beam of SACLA main accelerator.

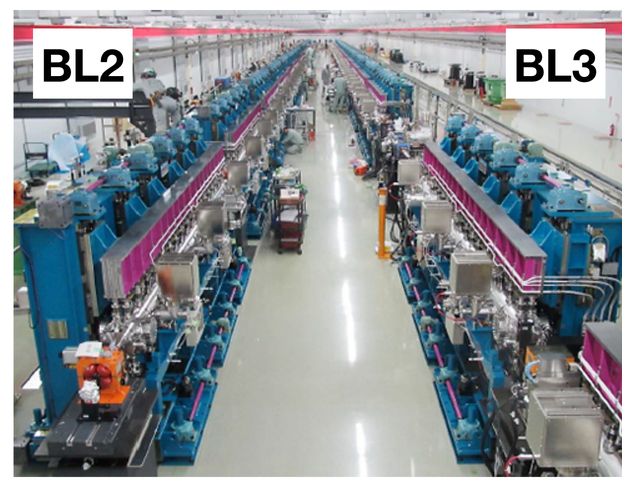






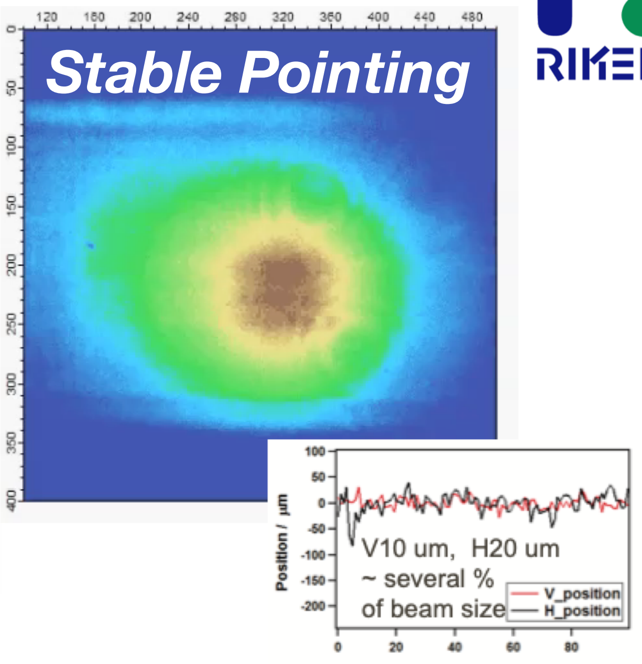
Kicker magnet
(Yoke length 0.95 m, B_{max}=0.9 T)



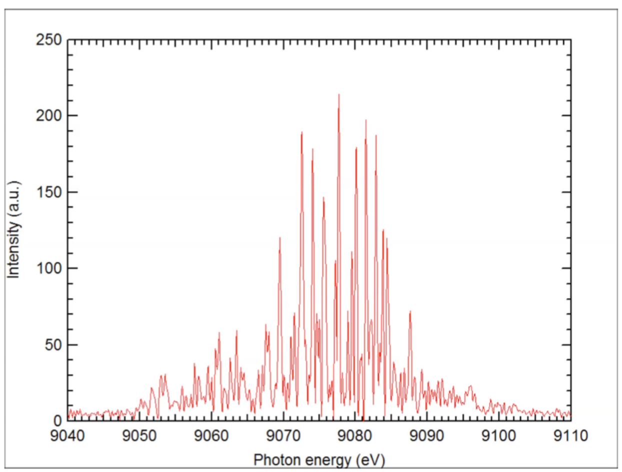


XFEL properties of SACLA (BL2&BL3)

Photon energy & Photon number (Pulse energy)	4－15 keV >10^{11} photons/pulse (max. 600 μJ)
Pulse duration	<10 fs
Peak power	>60 GW @ 10 keV
Rep. rate	Max. 60Hz
Band width: Pink	~5×10^{-3} plane mirrors
Monochromatic	~1×10^{-4} Si(111)
Coherence length	Almost the same as beam size

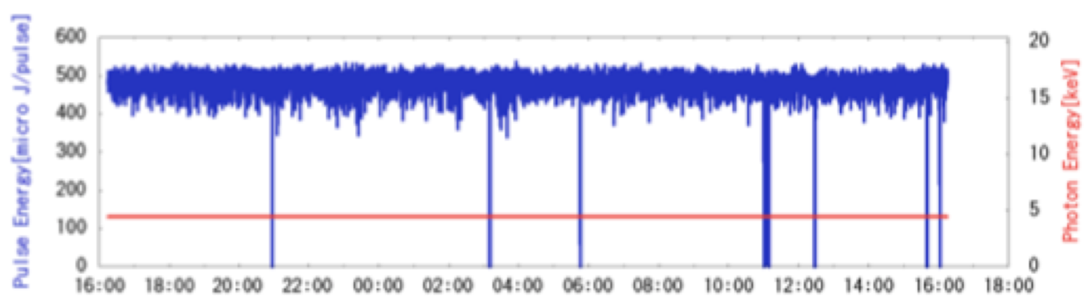


Stable Spectrum



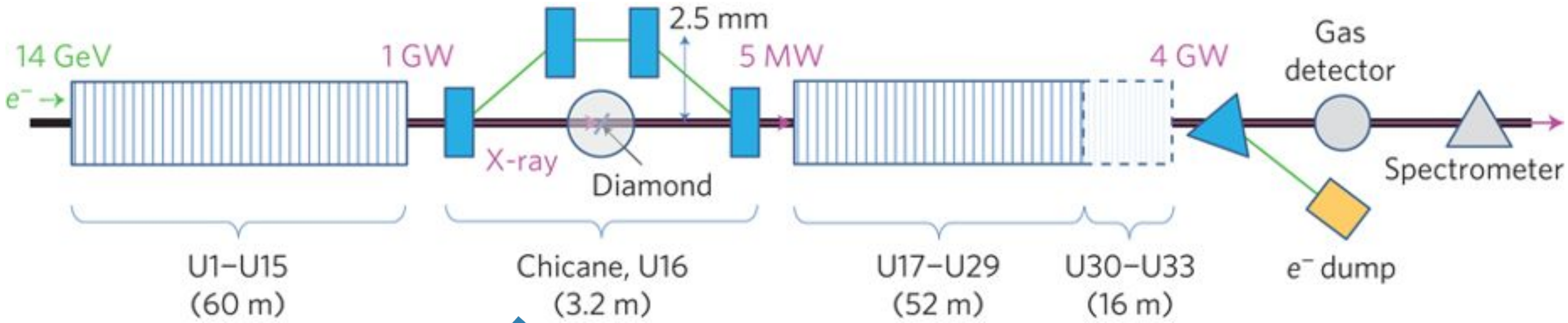
Stable Operation

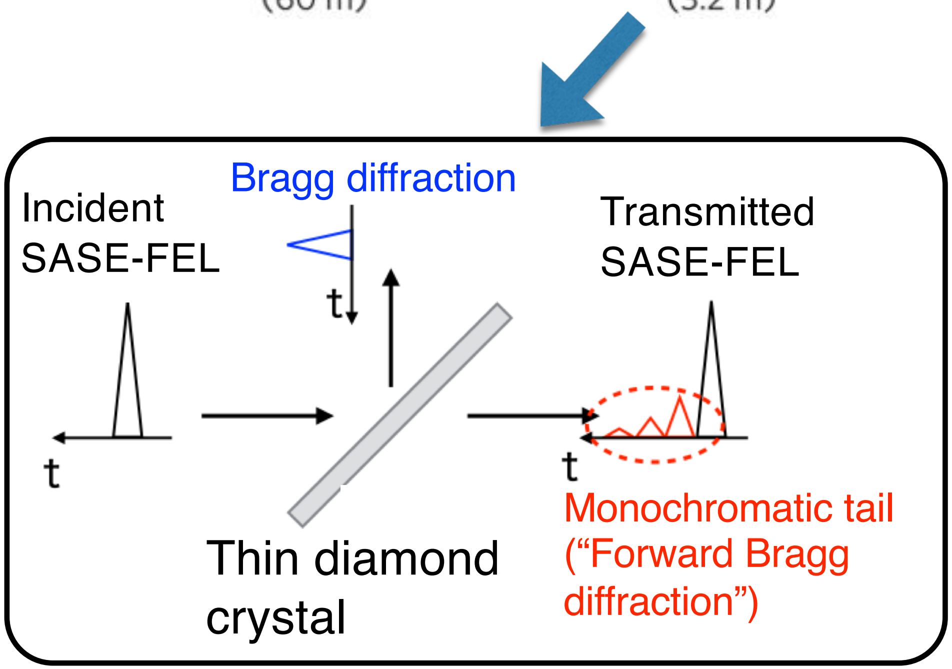
Pulse Energy	Photon Energy / Wavelength
509.2 micro J/pulse	4.4 keV / 0.279 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
60 Hz	11.1 %

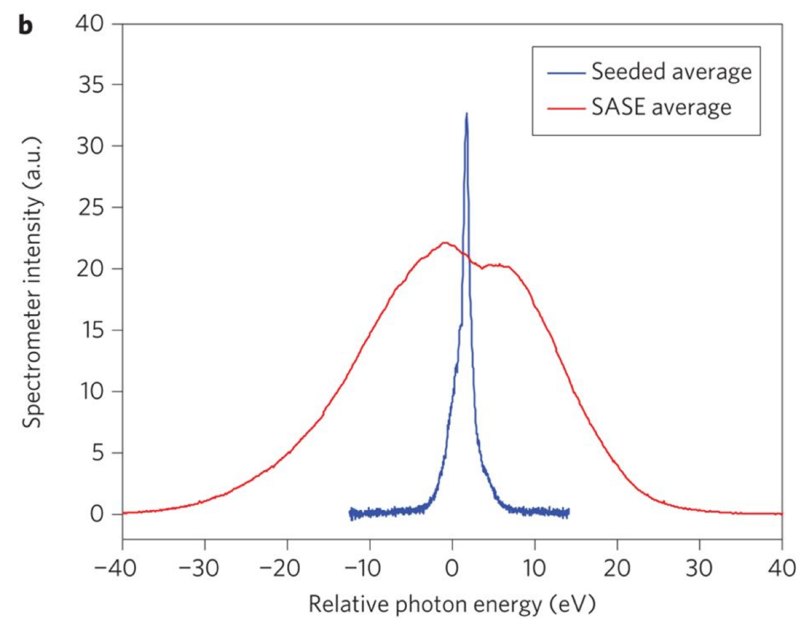


Central photon energy stability: 10 eV (STD)
Spectral band width: ~ 15 eV (STD) @ 10keV

Transmission type self-seeded XFEL

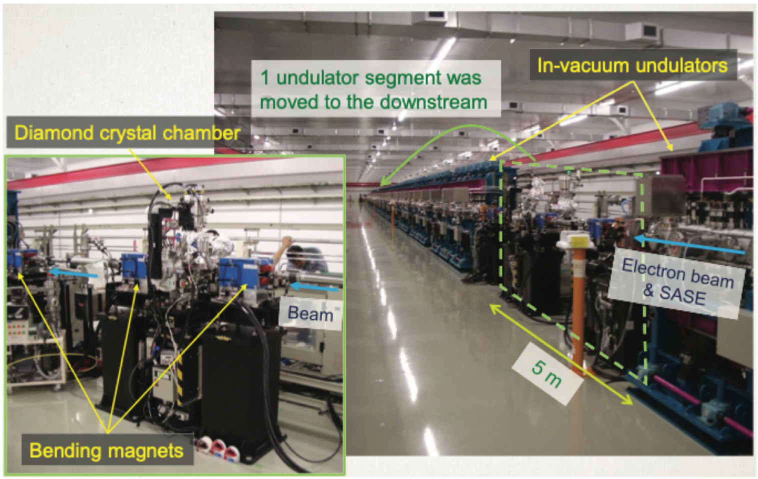


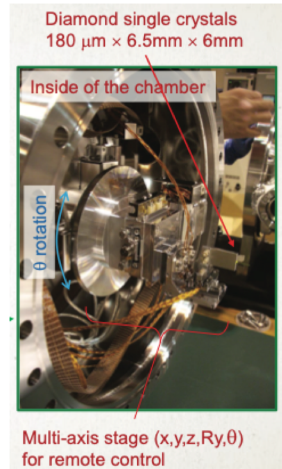


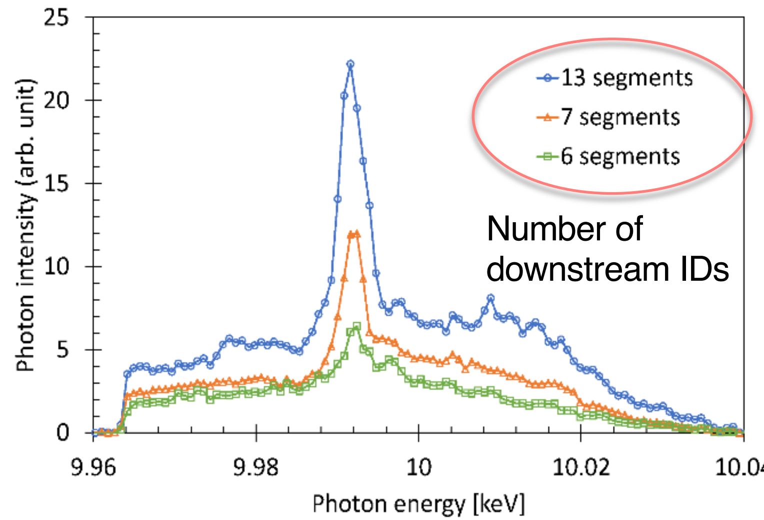


J. Amann *et al.*, *Nat. Photon.* (2012).
R. Lindberg & Yu. Shvyd’ko, *PRST* (2012).
G. Geloni, V. Kocharyan and E. Saldin, *J. Mod. Opt.* (2011).

Transmission type self-seeding at SACLA BL3







T. Inagaki et al., *Proc. FEL* 2014.

Two problems:

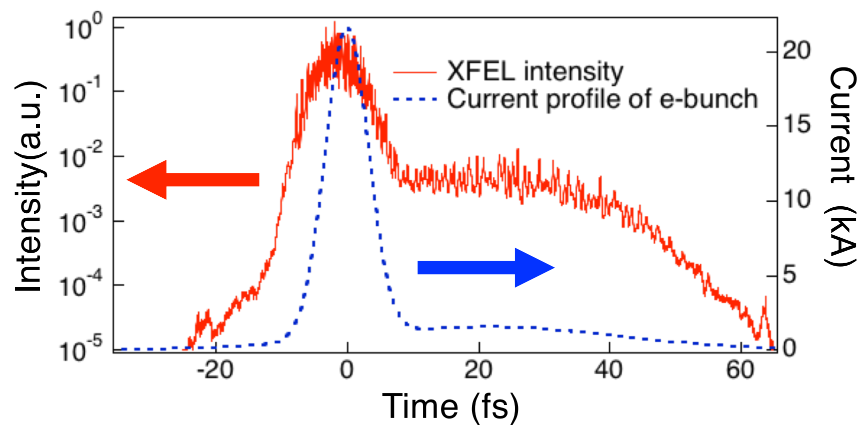
- **Broad SASE background**

  Comparable transmitted SASE tail and monochromatic seed?

- **Transmitted SASE makes the tuning difficult**

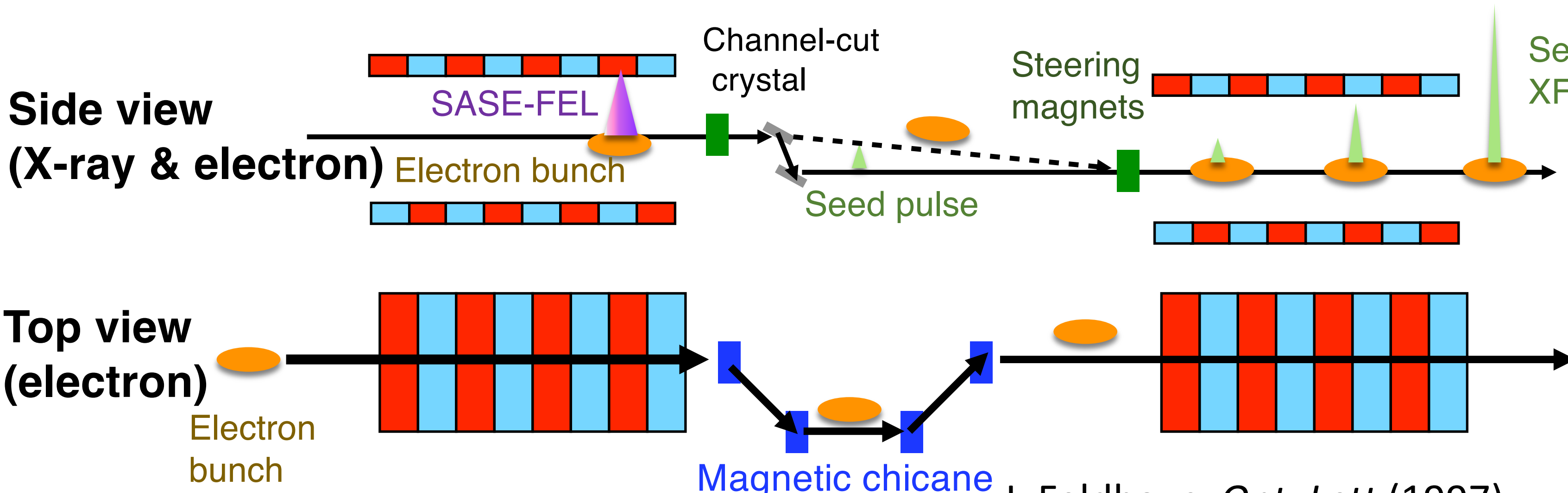
  We cannot directly see the seed pulse, such as, intensity, profile, pointing etc.

The electron bunch and XFEL pulse of SACLA has a tail.



I. Inoue et al., *Phys. Rev. Accel. Beams* (2018).

Reflection type self-seeding



J. Feldhaus, *Opt. Lett* (1997).
I. Inoue et al., *Nature Photonics* (2019).

- **Only the seed beam is delivered to the downstream IDs**

  ➡ Direct observation of the seed pulse results in easy alignment and tuning.

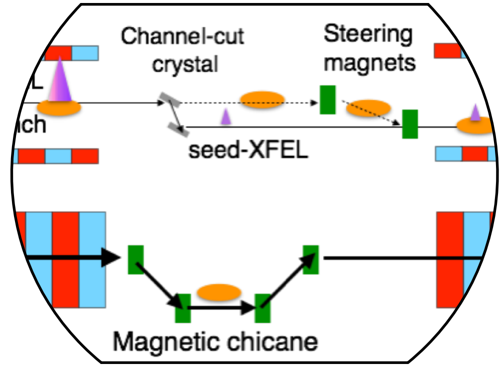
- **High extraction efficiency of mono-beam from SASE-FEL**

$$\frac{\text{(Seed power)}}{\text{(Input SASE power)}} = \begin{array}{l} \sim 3\times10^{-2} \text{ for reflection seeding (Si(111) channel cut)} \\ \sim 5\times10^{-3} \text{ for transmission seeding (C(400), 100 } \mu\text{m)} \end{array}$$

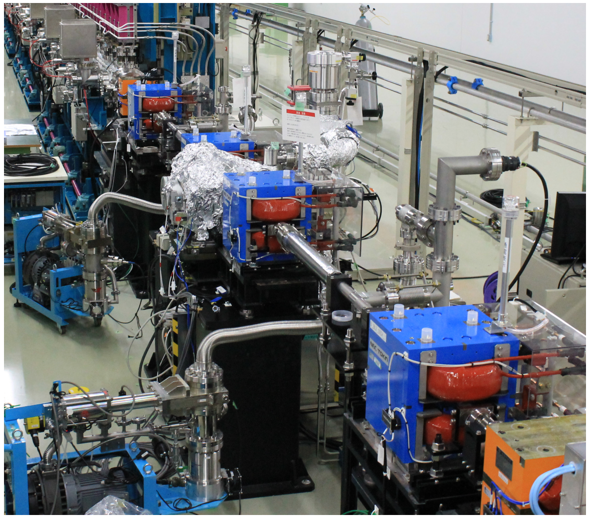
➡ Less damage on the electron beam at upstream IDs.

Challenge for reflection type self-seeding

Large delay is necessary for the electron beam to assure temporal overlap.

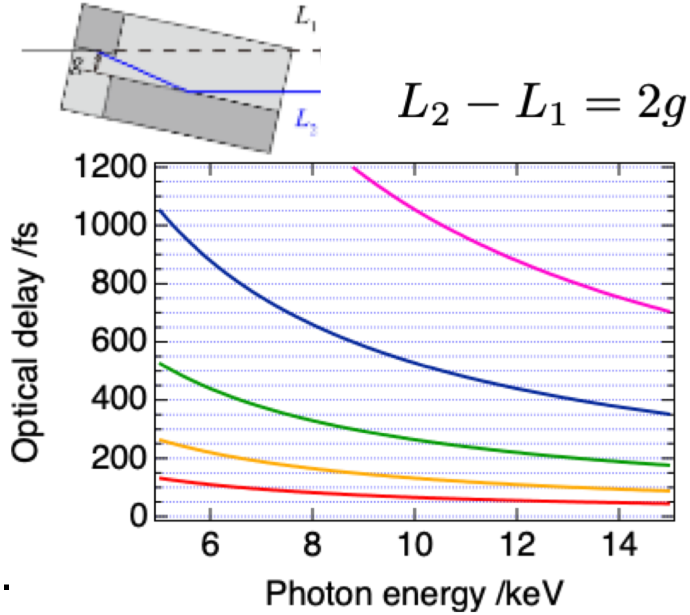


~100 ps for typical channel-cut crystals



5 m compact chicane can provide up to a 300 fs delay.

Optical delay by Si 111 CC-crystal

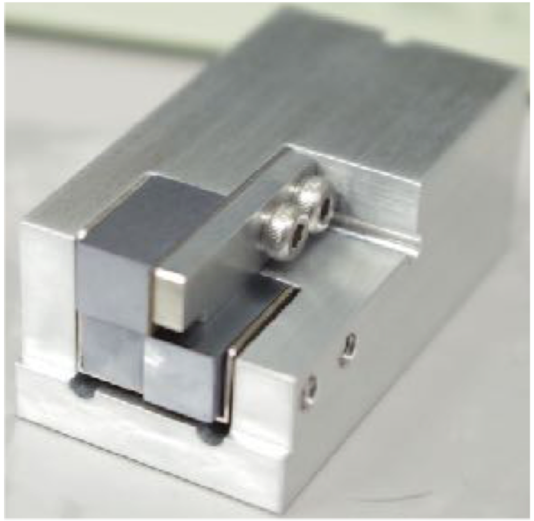


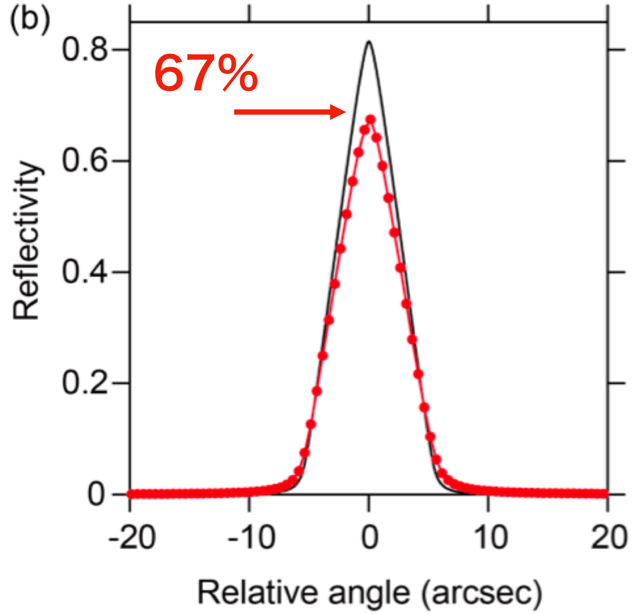
$$L_2 - L_1 = 2g \sin \theta_B$$

gap
800 μm
400 μm
200 μm
100 μm
50 μm

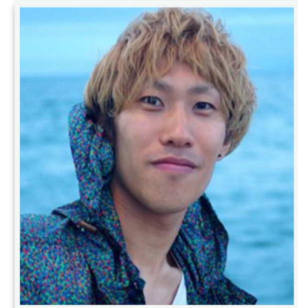
T. Hara, *Nature Commun.* (2013).
I. Inoue, *Proc. Natl. Aca. Sci. USA* (2016).

100 µm gap Si(111) micro-channel-cut crystal



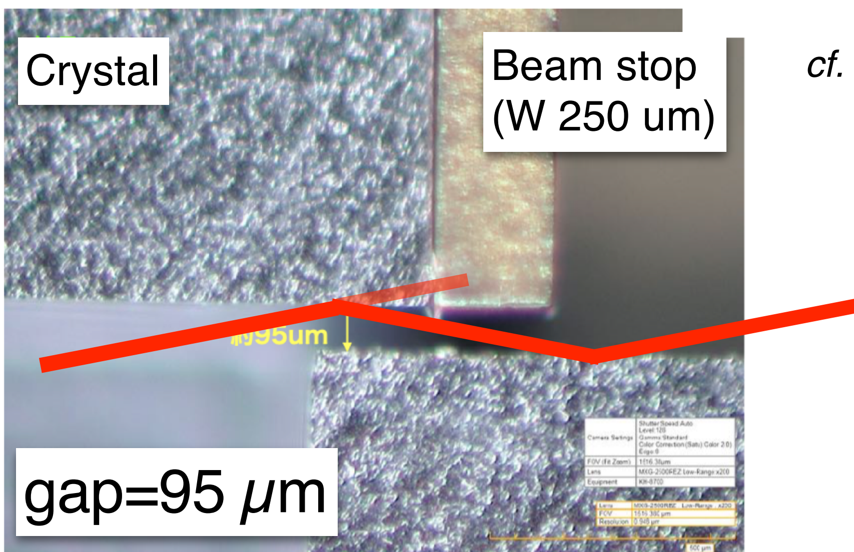


cf. Theoretical value@peak: ~80%



Taito Osaka
(RIKEN/SACLA)

Rocking curve measured with 10 keV synchrotron radiation monochromatized by Si(111) DCM.



Photon energy: 5 keV or higher

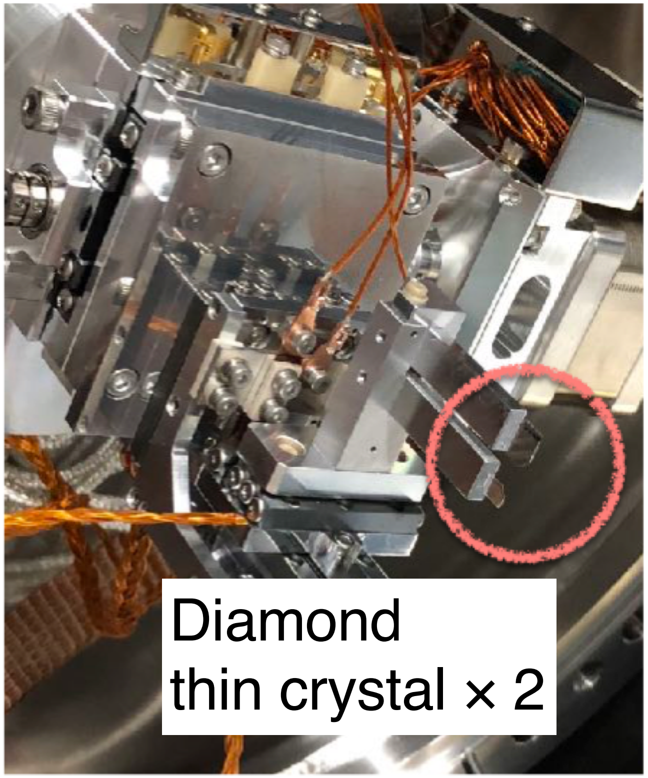
Aperture: 50 µm@10 keV

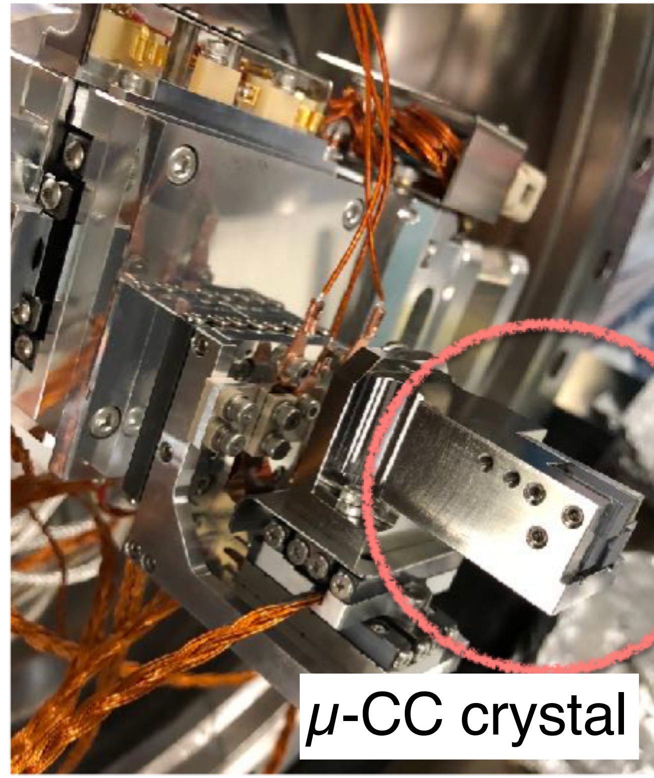
Optical delay: 120 fs@10 keV

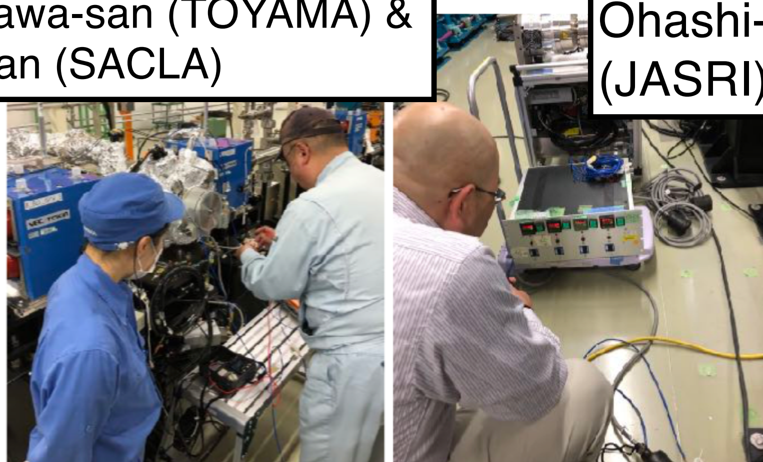
X-ray beam offset: 180 µm@10 keV

T. Osaka et al., arXiv: 1811.0860 (2018).

Installation of micro-channel-cut crystal

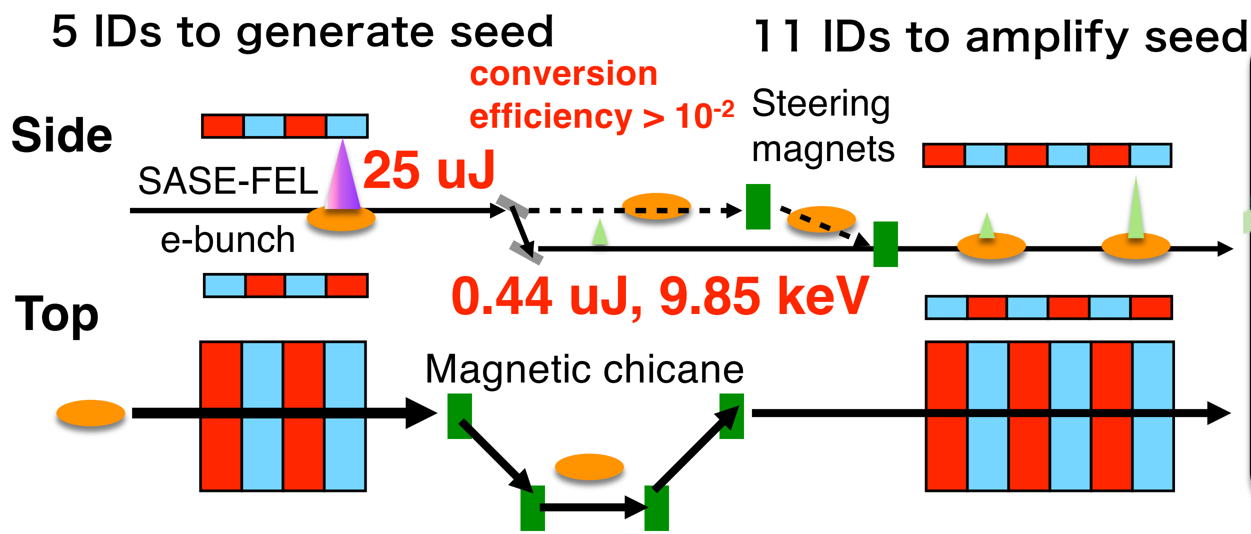




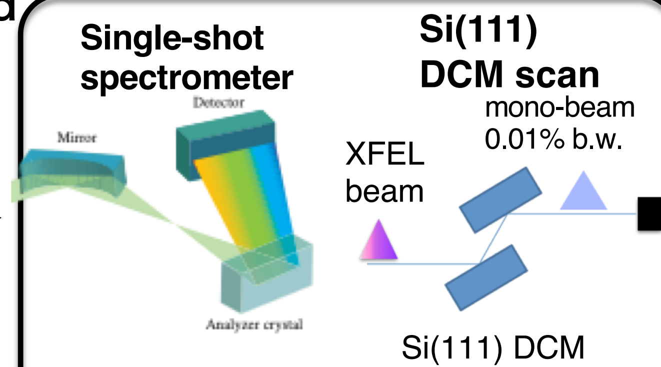


Dec.23-25 2017

Early commissioning results (July 2018)



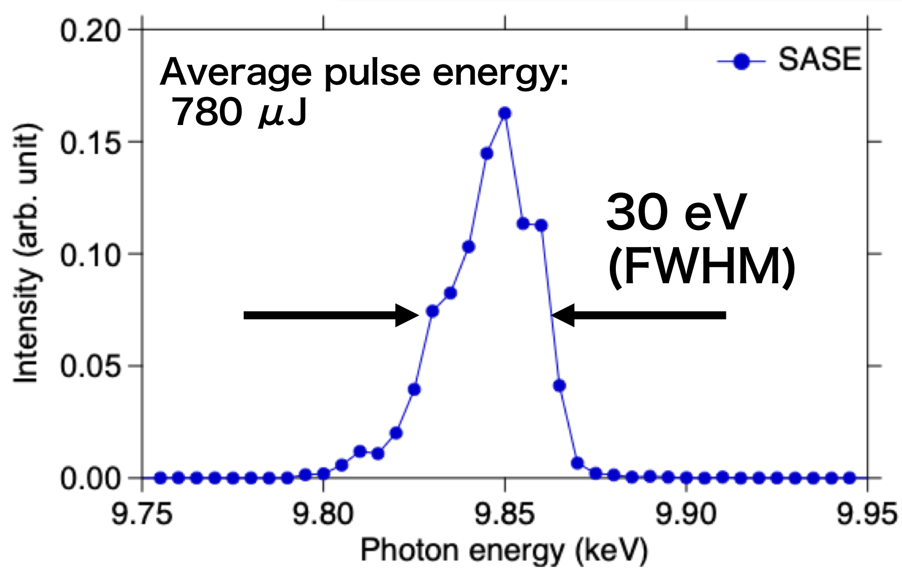
Photon diagnostics



Yabashi, *PRL* (2006),
Inubushi, *PRL* (2012)

Electron beam parameters

Beam energy: 7.8 GeV
Bunch duration: ~10 fs
Beam charge: 270 pC
K-value: 2.1
Photon energy: 9.85 keV



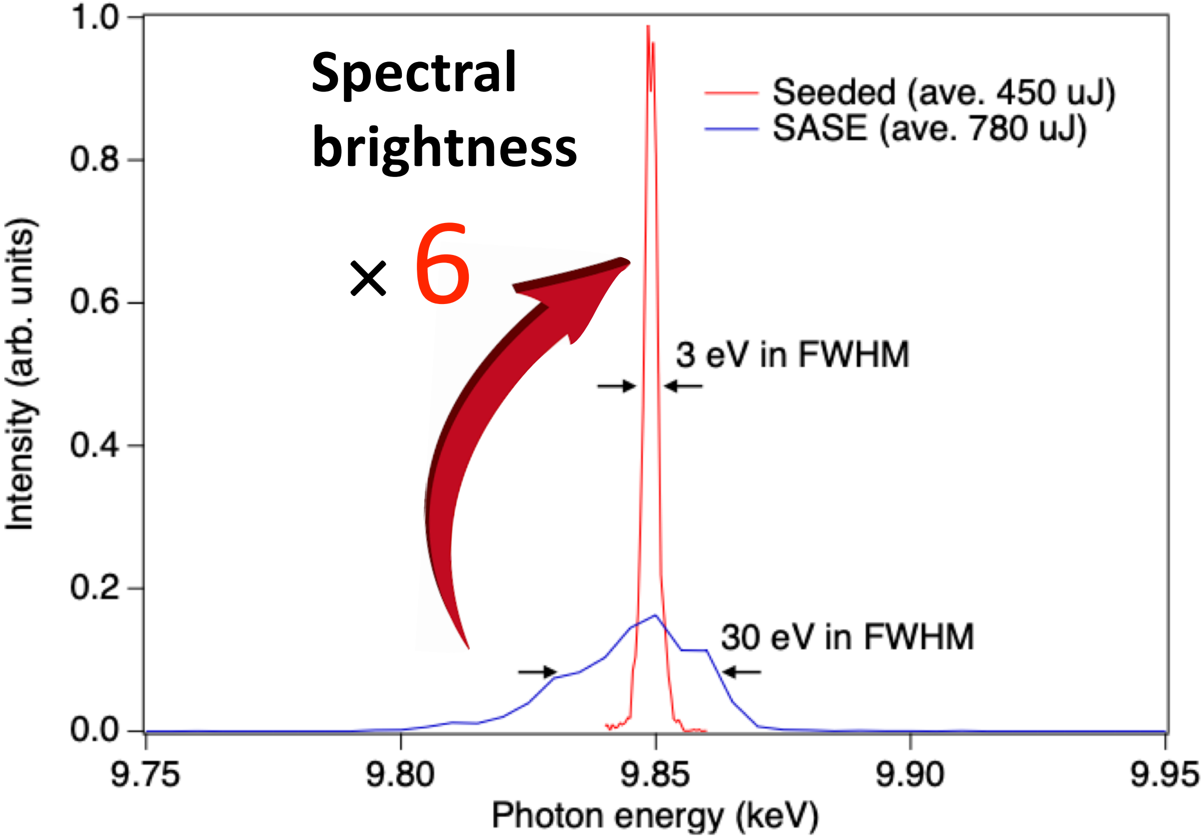
Average spectrum of SASE-XFEL (all IDs).

Averaged spectrum of self-seeded XFEL

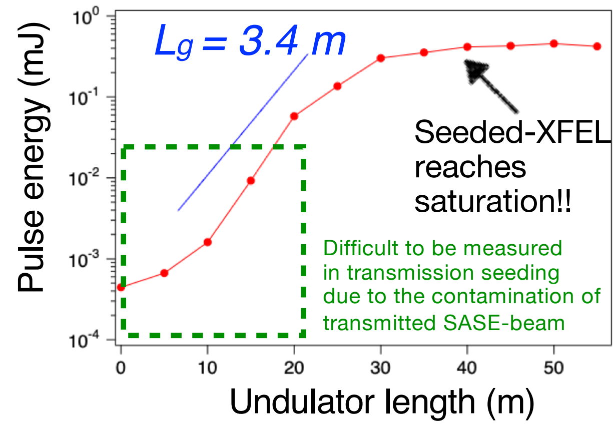
nature photonics LETTERS
https://doi.org/10.1038/s41566-019-0365-y

Generation of narrow-band X-ray free-electron laser via reflection self-seeding

Ichiro Inoue[1,3*], Taito Osaka[1,3], Toru Hara[1], Takashi Tanaka[1], Takahiro Inagaki[1], Toru Fukui[1], Shunji Goto[1,2], Yuichi Inubushi[1,2], Hiroaki Kimura[1,2], Ryota Kinjo[1], Haruhiko Ohashi[1,2], Kazuaki Togawa[1], Kensuke Tono[1,2], Mitsuhiro Yamaga[1,2], Hitoshi Tanaka[1], Tetsuya Ishikawa[1] and Makina Yabashi[1,2]



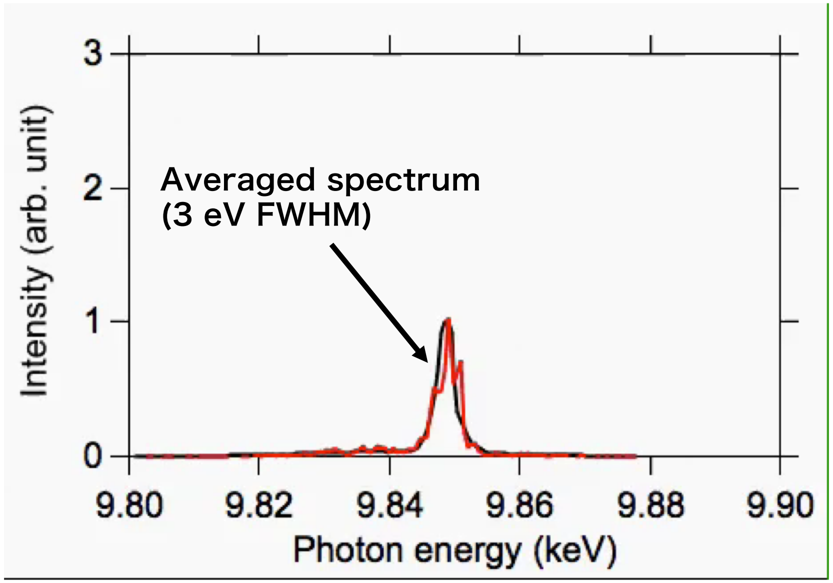
Gain curve of seeded-XFEL beam



Gain length (L_g = 3.4 m) was comparable to that of normal SASE mode (L_g = 2.3 m).

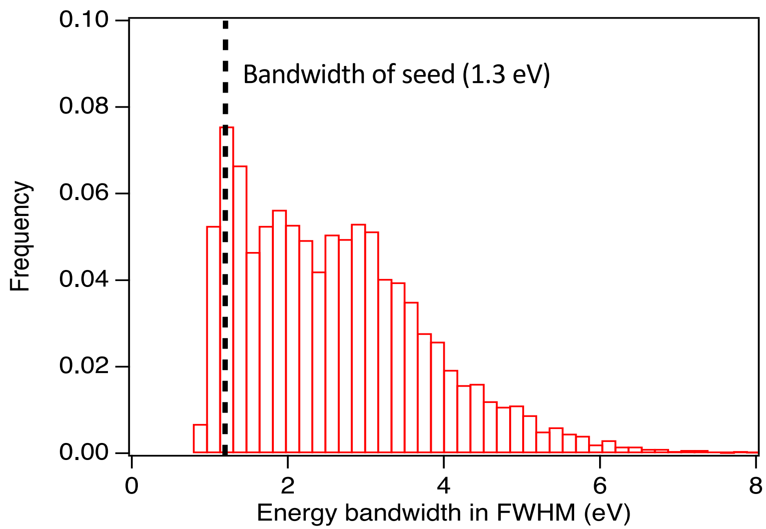
I. Inoue et al., *Nature Photon.* (2019).

Single-shot spectrum of seeded-XFEL beam

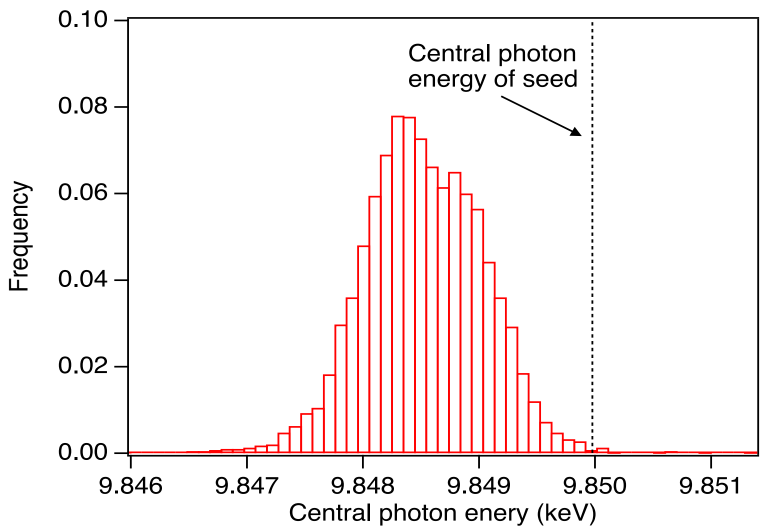


Central photon energy of the seeded-XFEL is slightly lower than that of seed.

Bandwidth of the seeded-XFEL is larger than that of seed.



Histogram of bandwidth

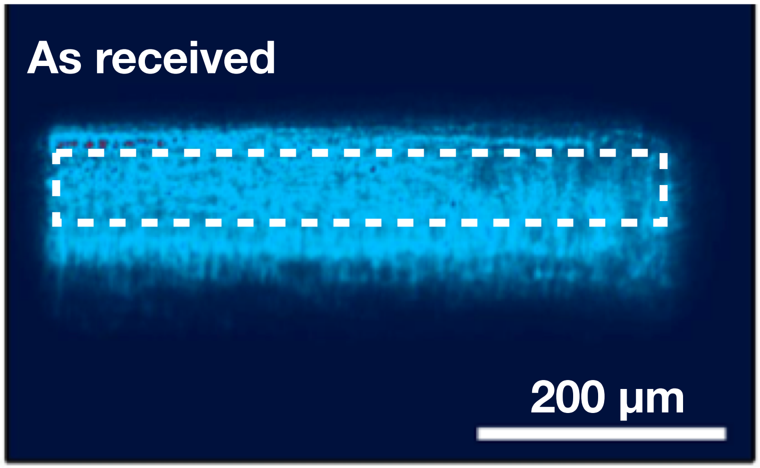


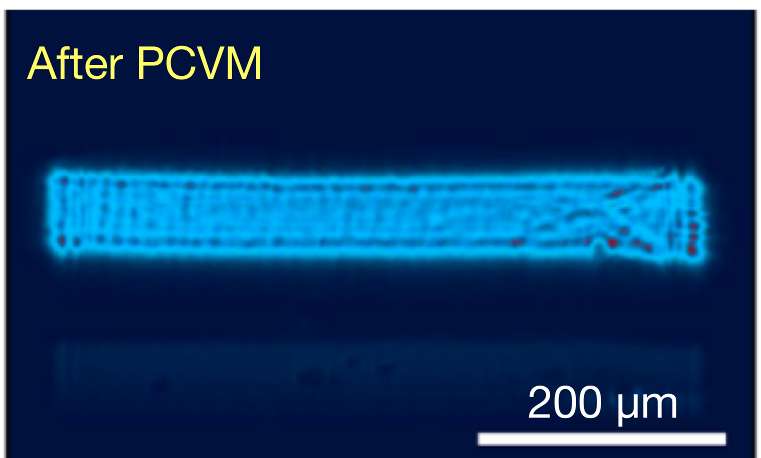
Histogram of central photon energy

I. Inoue et al., *Nature Photon.* (2019).

Towards narrower and brighter seeded-XFELs

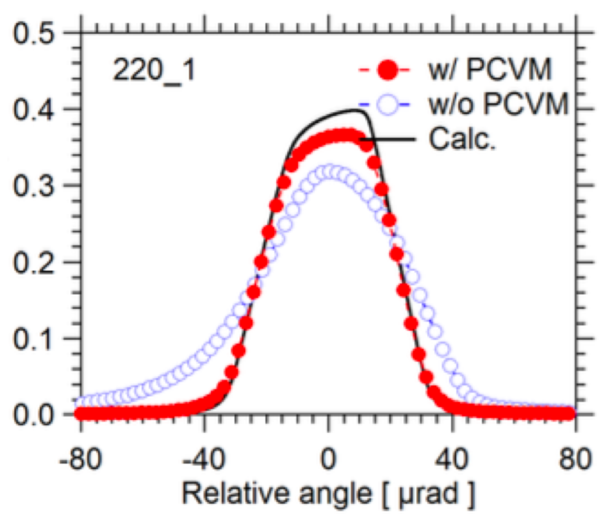
- Smaller energy chirp in the electron beam.
- Narrower bandwidth of the seed → use of higher order diffraction (Si 220).





Diffraction in higher order indices is more sensitive to lattice strain, which results in distorted wavefront.

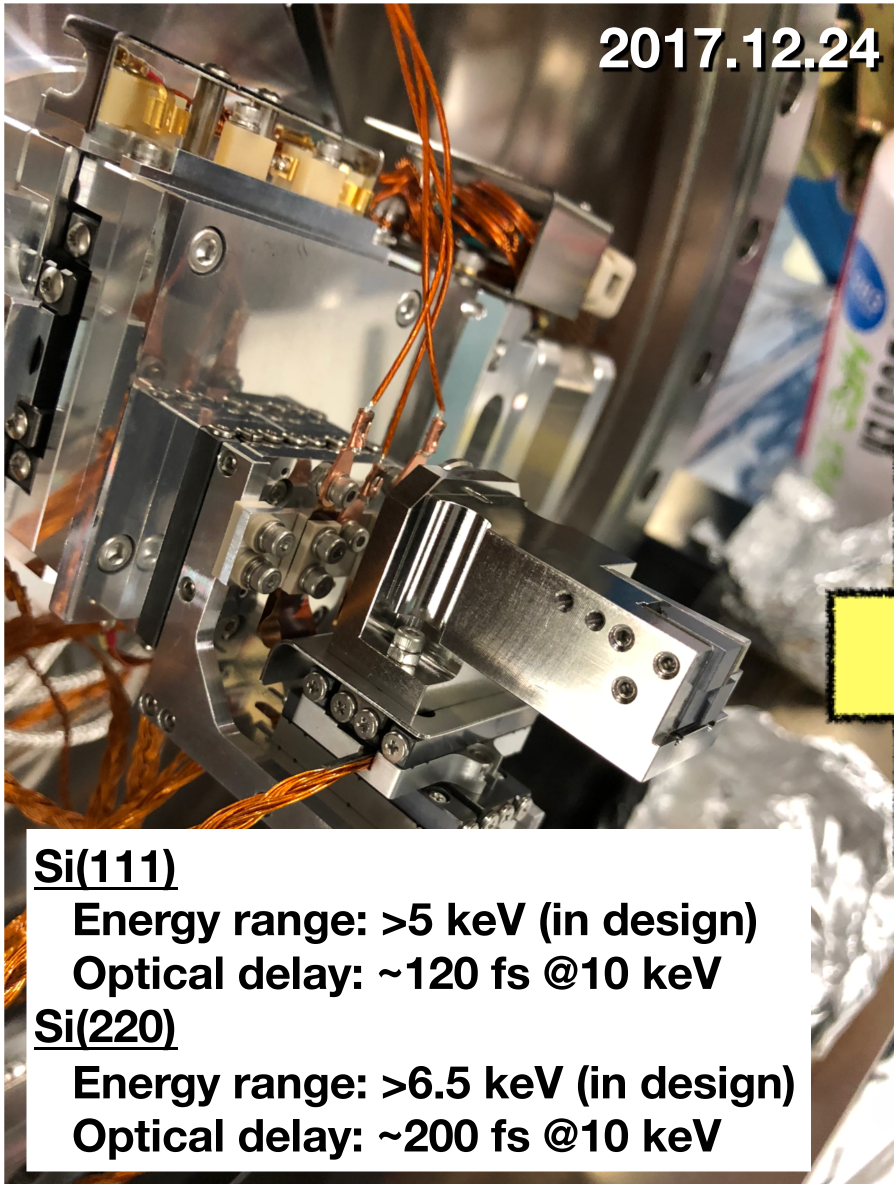
Si(220) crystal treated with a plasma etching technique (PCVM).
→ Nearly ideal reflection profile and rocking curve.



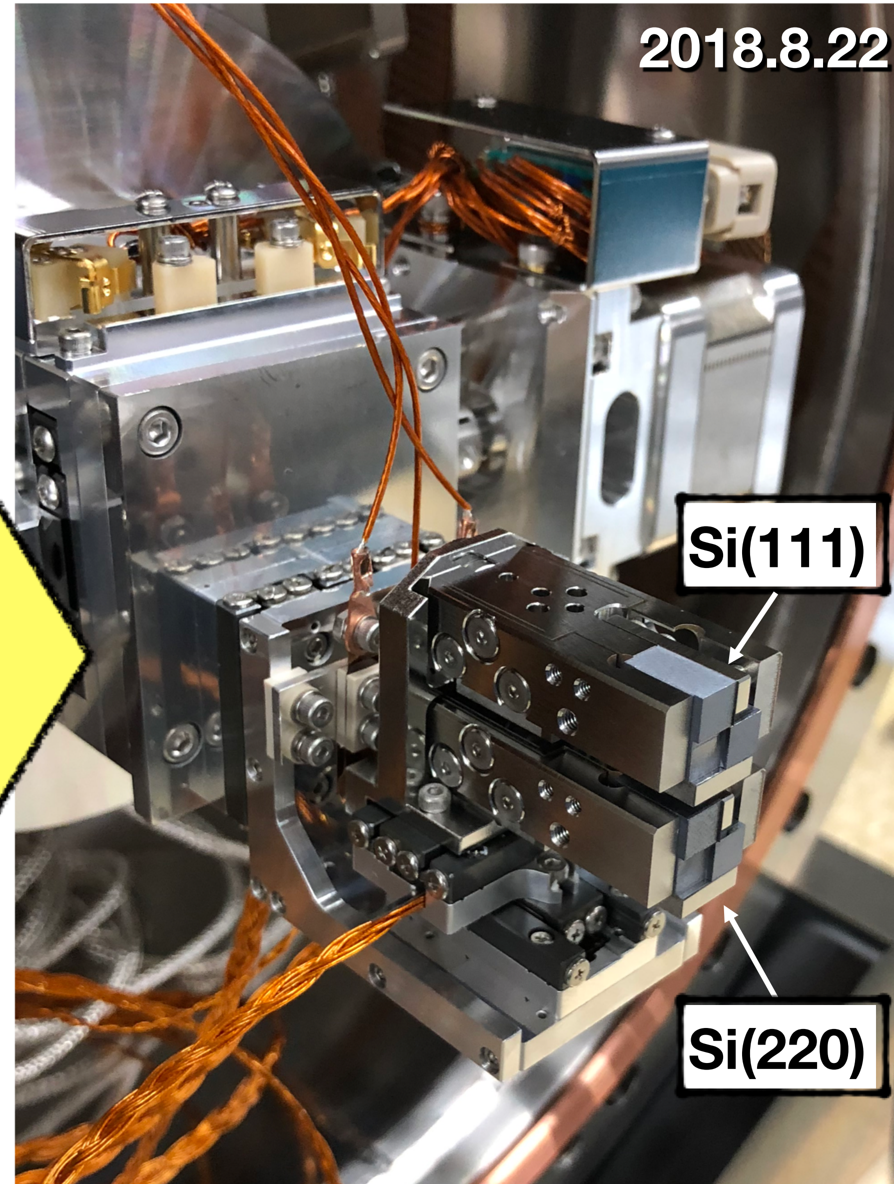
Takashi Hirano (Osaka U)

Rocking curve measured with 10 keV synchrotron radiation monochromatized by Si(111) DCM.

Installation of Si(220) crystal



Si(111)
Energy range: >5 keV (in design)
Optical delay: ~120 fs @10 keV
Si(220)
Energy range: >6.5 keV (in design)
Optical delay: ~200 fs @10 keV

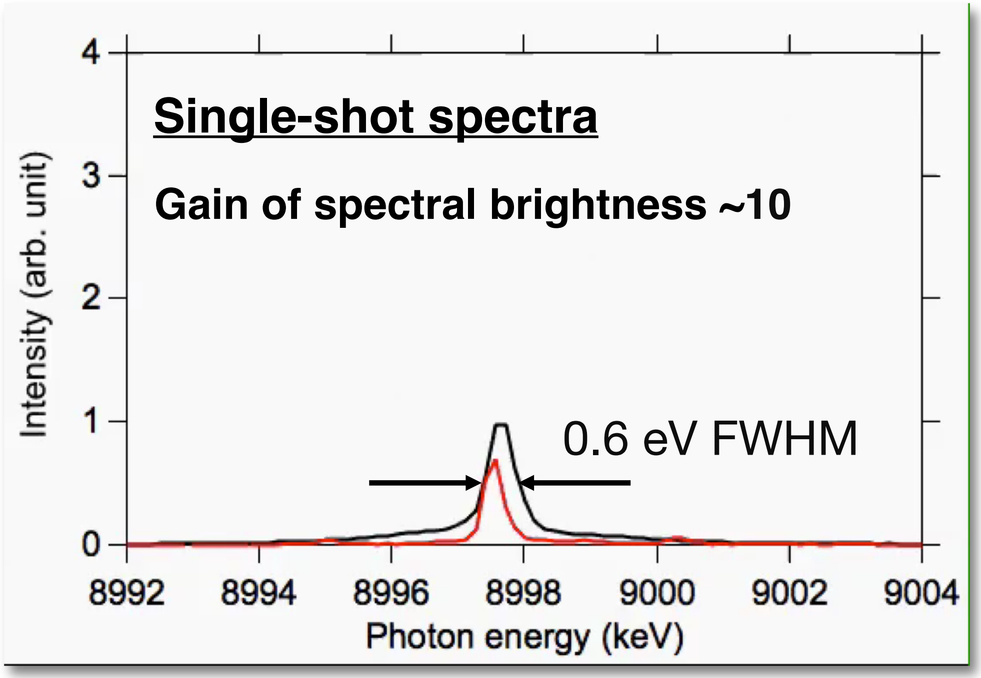


Seeded-XFELs generated with Si (220) crystal

Typical gain of spectral brightness by Si (220) seeding with respect to normal SASE is ~7.

cf. typical gain with Si (111) seeding: ~6

If the electron beam condition is good (unfortunately not always available), the bandwidths of seeded-XFEL and seed becomes almost equal.

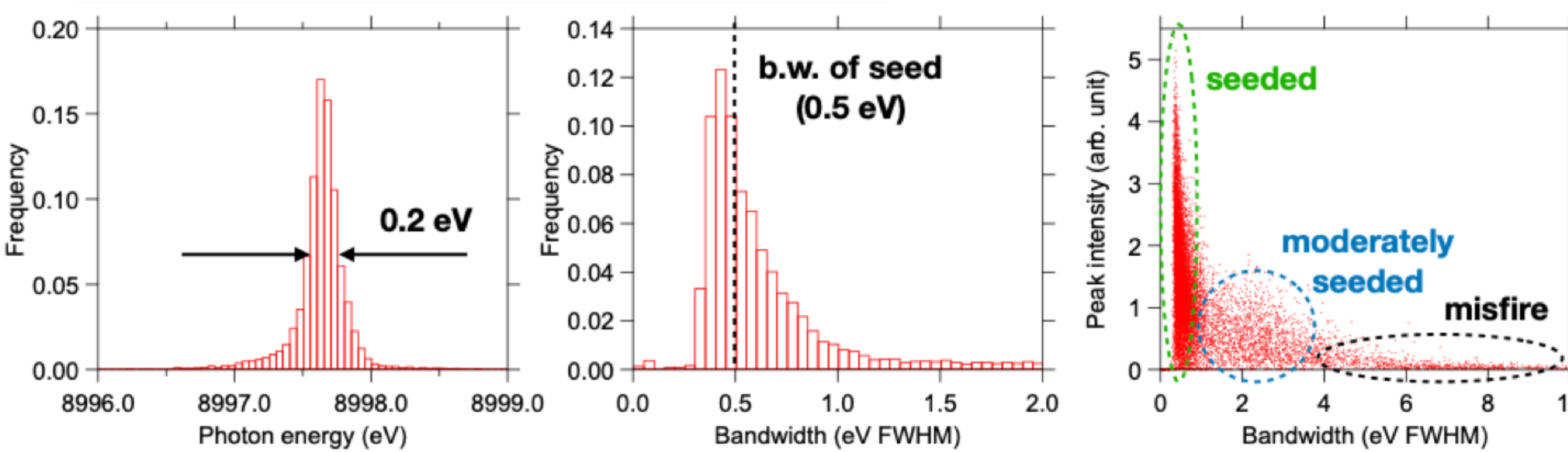


Average bandwidth (0.6 eV) is similar to that of the seed (0.5 eV).

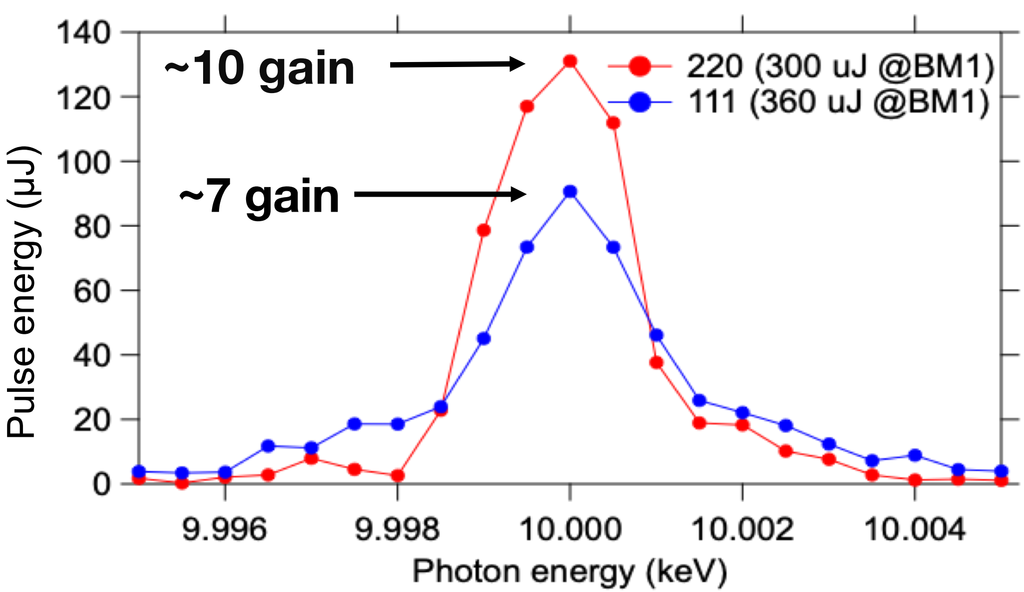
XFEL pulse duration of SACLA is 6 fs
→ Self-seeded XFEL pulse reaches close to Fourier limit.

T. Osaka et al., *in preparation.*

Seeded-XFELs generated with Si (220) crystal



Statistics of Si(220) self seeding.



Comparison of averaged spectra of Si(220) and Si(111) measured on the same day.

Early user experiments (10 users since June 2018)

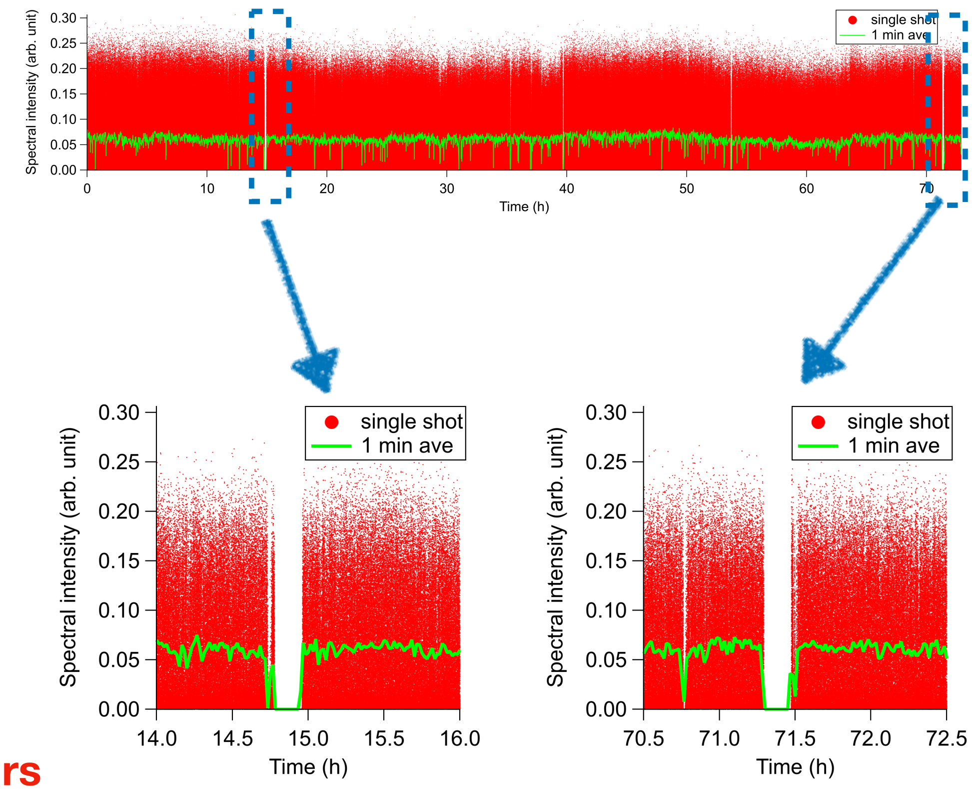
Typical tuning time

1. Tune normal SASE with full IDs including spectrum & optical axis. **~2 h**
2. Open the downstream IDs & adjust μCC. **1~2 h**
3. Close the downstream IDs & adjust the optical axis. **~0.5 h**
4. Set delay and offset for e⁻ beam to design values, then adjust the optical axis of SASE to the seed position. **~0.5 h**
5. Optimize some parameters of the downstream IDs by monitoring the pulse energies after the Si(111) DCM (e⁻ beam offset both in Ver. & Hor., K value, taper of IDs, delay etc). **3~4 h**

Just observing the seeded XFEL: ~4 hours
Operation with optimized conditions: ~8 hours
Not short but straightforward.
(All procedures can be completed by operators without the help of scientists.)

Long term stability

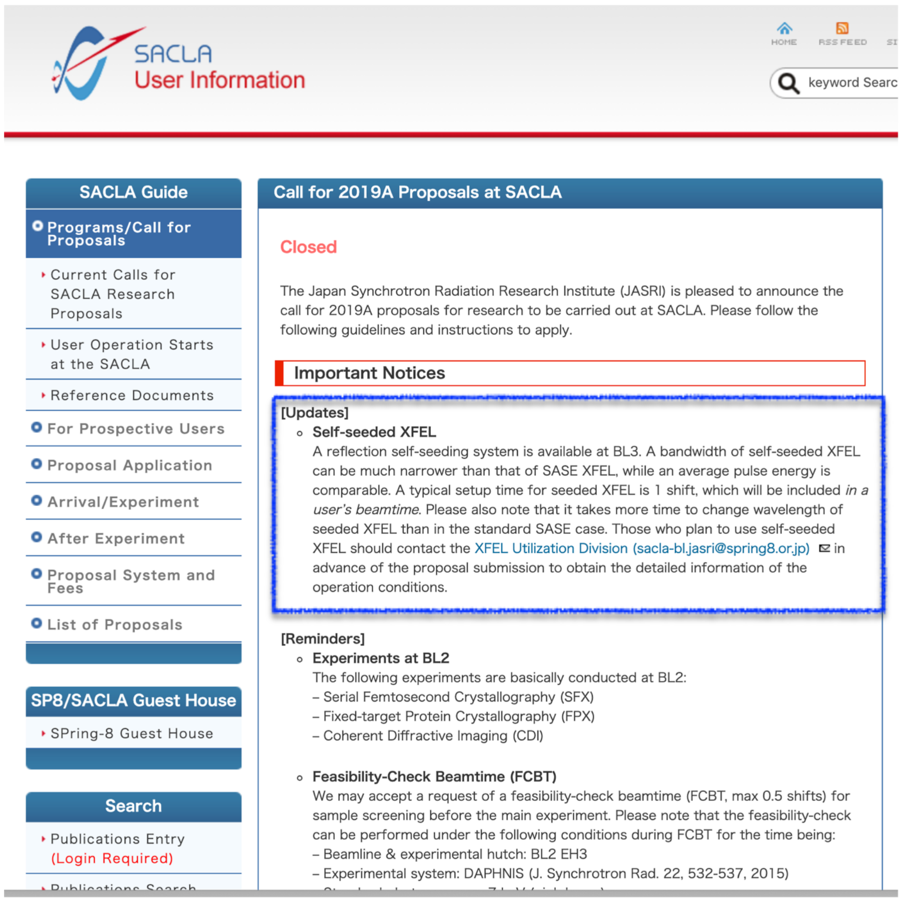
XFEL intensity after Si (111) DCM during the user experiments (Dec. 2018).



The same spectral brightness had been maintained for 3 days (typical beam time for a single user).

Self-seeding is officially released for user experiments

Since April 2019, self-seeded operation has been officially released for user experiments.



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Call for 2019A Proposals at SACLA

Closed

The Japan Synchrotron Radiation Research Institute (JASRI) is pleased to announce the call for 2019A proposals for research to be carried out at SACLA. Please follow the guidelines and instructions to apply.

Important Notices

[Updates]

- **Self-seeded XFEL**
  A reflection self-seeding system is available at BL3. A bandwidth of self-seeded XFEL can be much narrower than that of SASE XFEL, while an average pulse energy is comparable. A typical setup time for seeded XFEL is 1 shift, which will be included *in a user's beamtime.* Please also note that it takes more time to change wavelength of seeded XFEL than in the standard SASE case. Those who plan to use self-seeded XFEL should contact the XFEL Utilization Division (sacla-bl.jasri@spring8.or.jp) in advance of the proposal submission to obtain the detailed information of the operation conditions.

[Reminders]

- **Experiments at BL2**
  The following experiments are basically conducted at BL2:
  – Serial Femtosecond Crystallography (SFX)
  – Fixed-target Protein Crystallography (FPX)
  – Coherent Diffractive Imaging (CDI)
- **Feasibility-Check Beamtime (FCBT)**
  We may accept a request of a feasibility-check beamtime (FCBT, max 0.5 shifts) for sample screening before the main experiment. Please note that the feasibility-check can be performed under the following conditions during FCBT for the time being:
  – Beamline & experimental hutch: BL2 EH3
  – Experimental system: DAPHNIS (J. Synchrotron Rad. 22, 532-537, 2015)

25% of scheduled experiments of SACLA BL3 ask for self-seeded XFEL operation.

Homepage of call for 2019A Proposals at SACLA (http://sacla.xfel.jp/?page_id=12475&lang=en)

Summary

- Reflection type self-seeding with a micro-channel-cut crystal was implemented at SACLA BL3.
- Spectral brightness increases by 7~10 compared to a SASE + monochromator case.
- Self-seeded operation has been released to user experiments since April 2019.
- Typical tuning time of self-seeded operation is about 8 hours and the condition is maintained over 3 days.
- Self-seeded operation works well around 10 keV, but further study is still necessary for low energies (4~6 keV).