Hard X-ray self-seeding set-up and results at SACLA

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Outline

- Introduction to SACLA
- System configuration
- Commissioning results
- Sensitivity for accelerator
- Summary

Japanese X-ray FEL facility, SACLA

(Spring-8 Angstrom Compact free electron LAser)

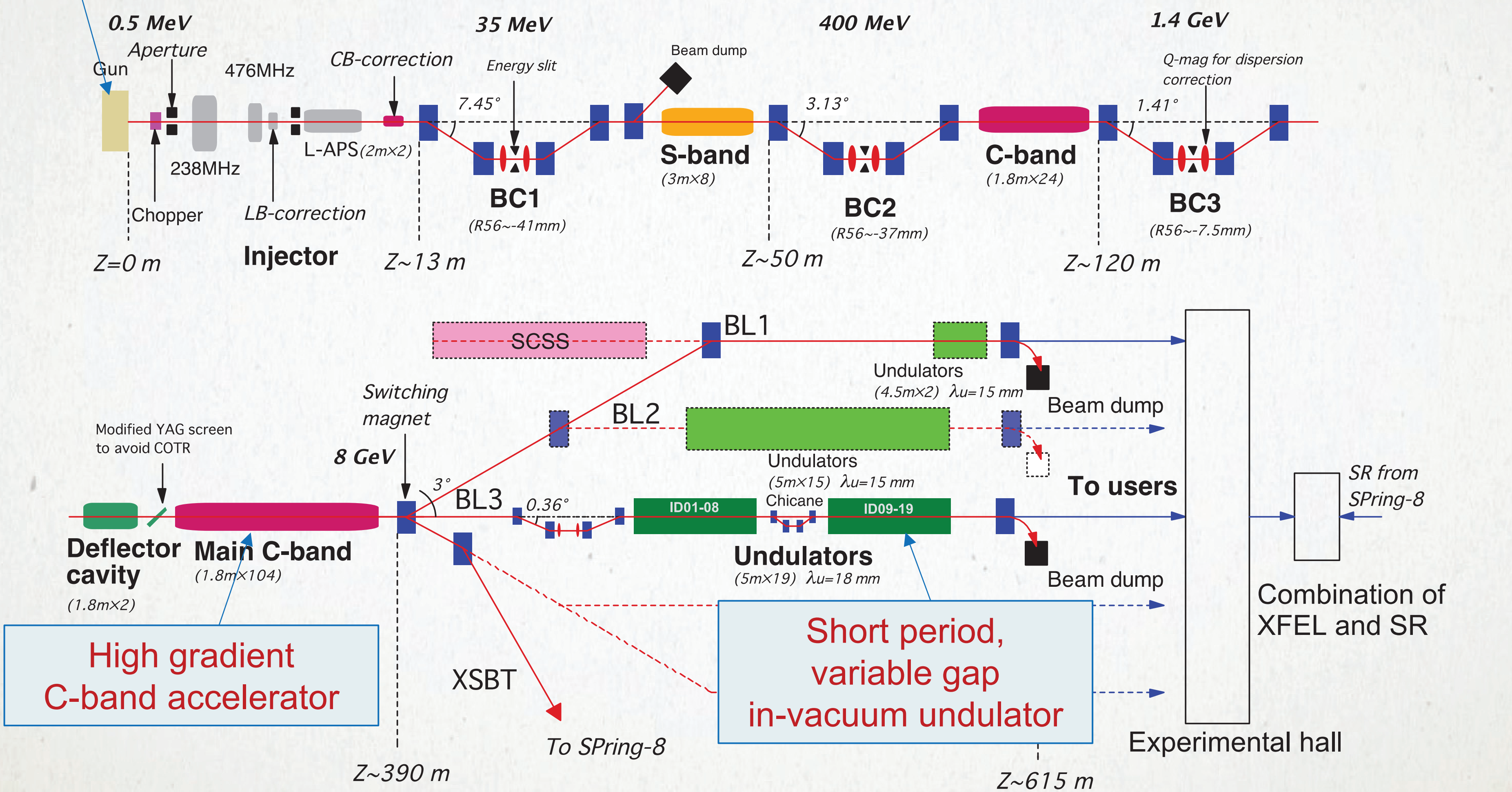
Construction: FY2006~2010
First lasing: June 7, 2011
User Operation: March 2012~
User time: > 3151 h/year (FY2012)
Number of users: 732 (FY2012)

Schematic of SACLA

Accelerator performance
Beam energy: 8.5 GeV max.
Energy stability: ~1×10^{-4} rms.
Bunch charge: ~0.3 nC
Rep, rate: 60 pps max.

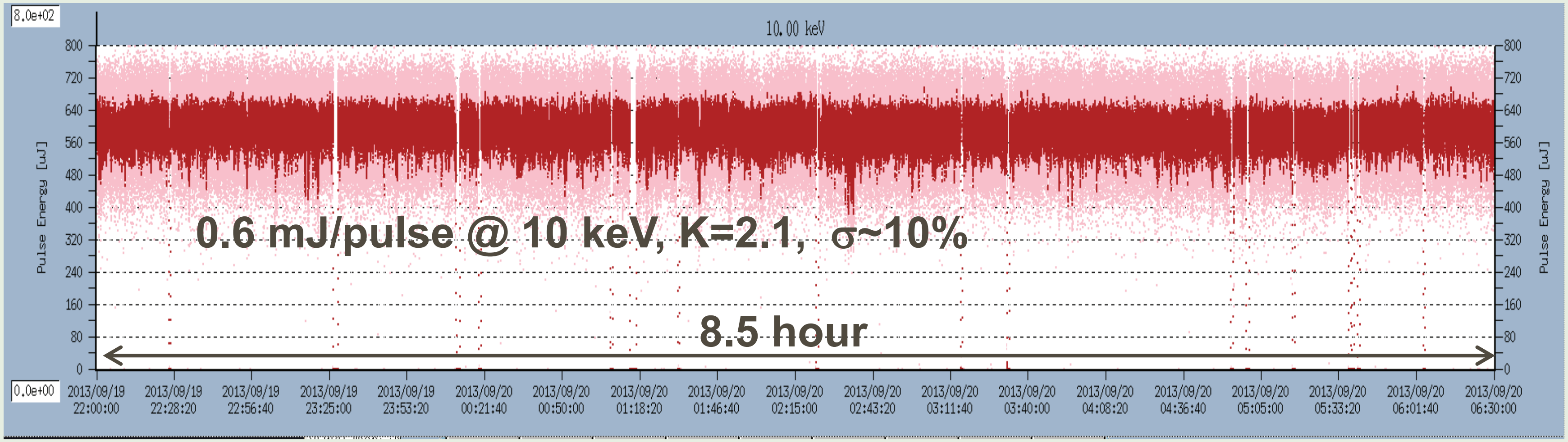
Low emittance thermionic gun

3 stage bunch compression to obtain several kA

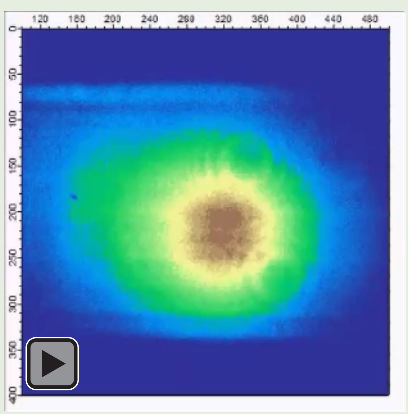


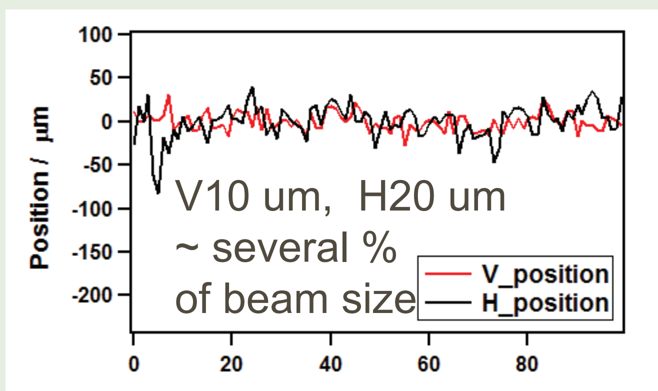
SACLA performance

SASE Intensity stability

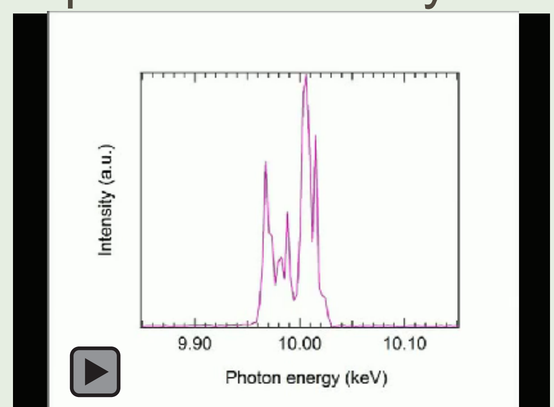


Pointing stability at experimental hutch 1





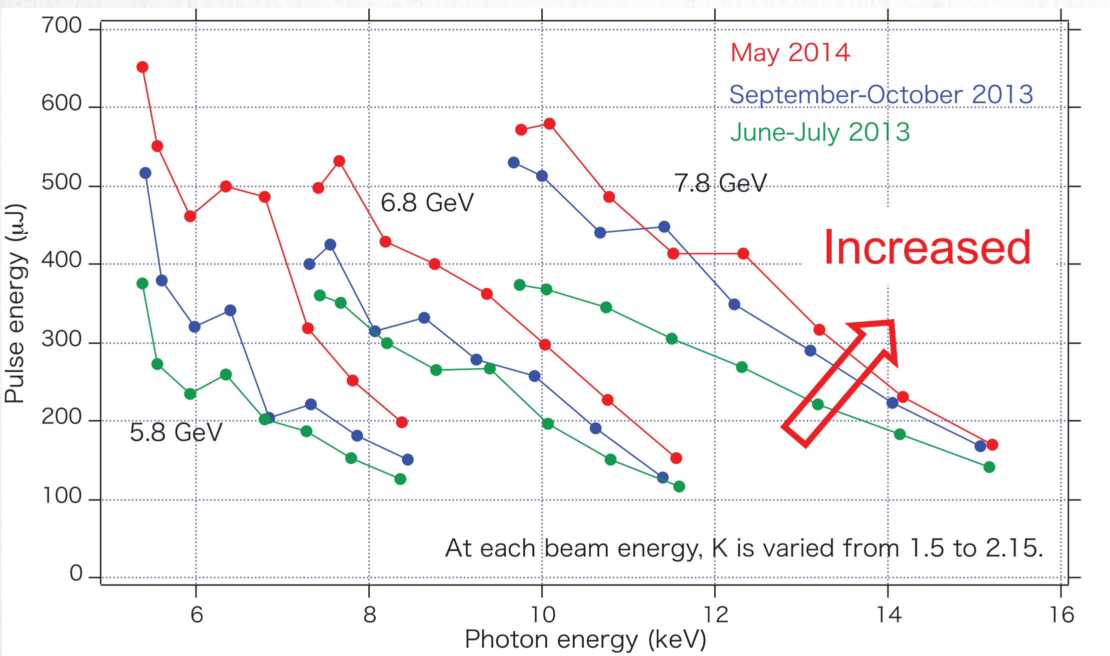
Spectrum stability



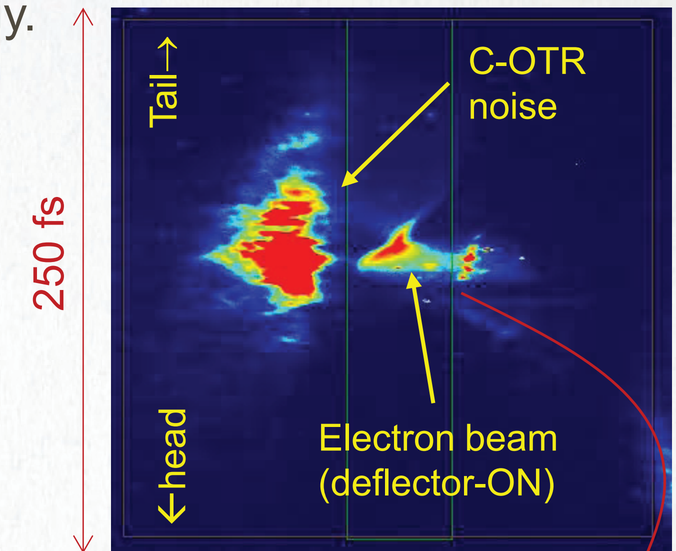
Pulse energy increase from 2013 to 2014

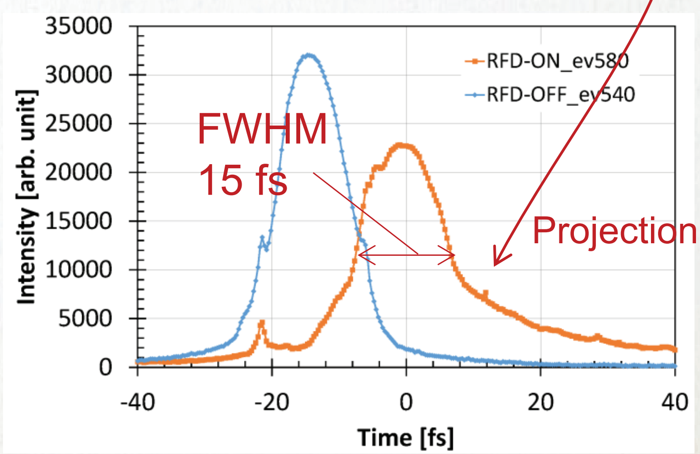
- Recent operation tends to stronger bunching and higher peak currents to maximize the pulse energy.
- Typical electron bunch length <15 fs (FWHM), measured using transverse deflector.

(with resolution ~12 fs, due to the beam size)

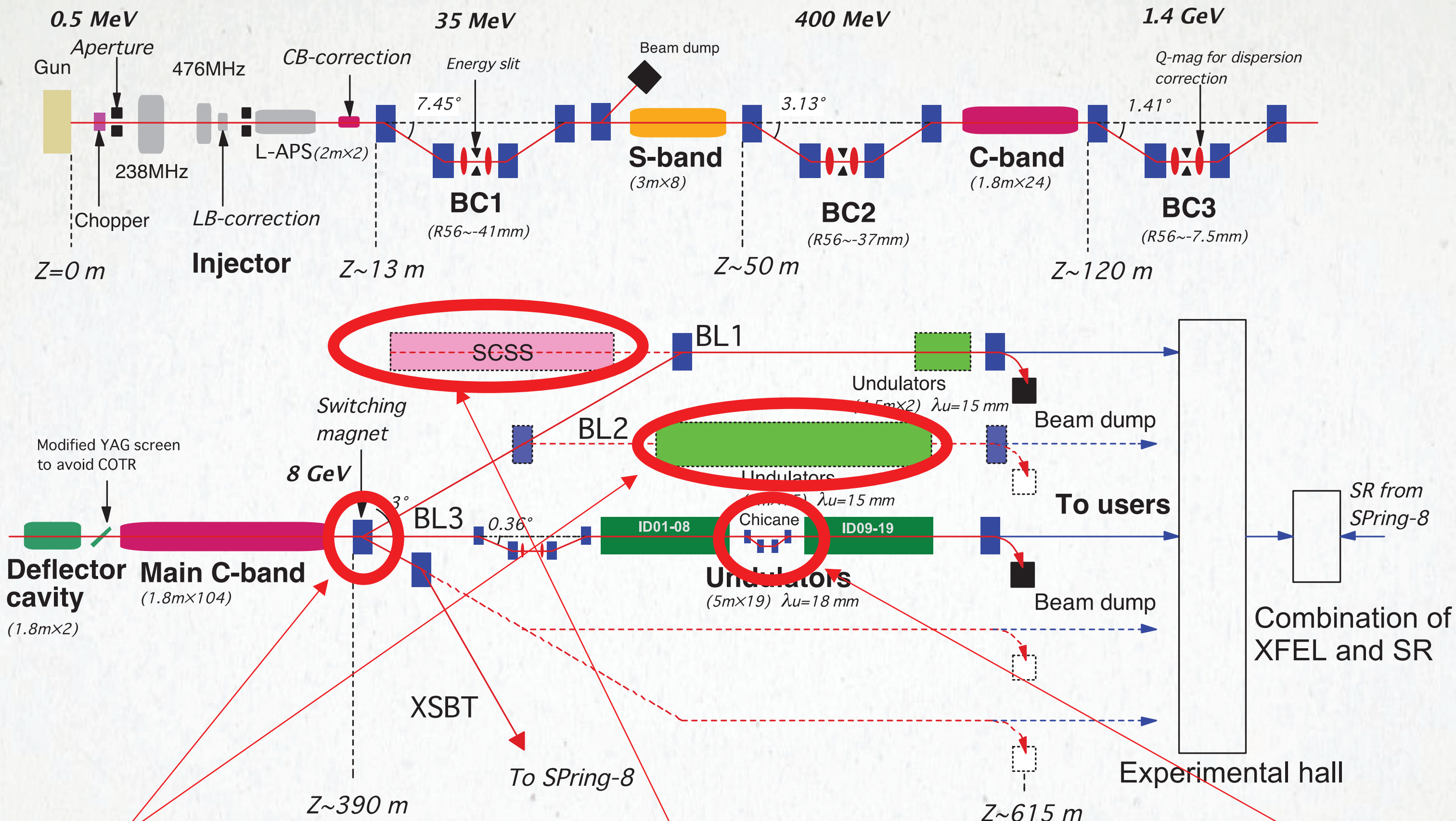


Electron temporal profile streaked by transverse deflector





Ongoing upgrade plans since 2012



2nd undulator beamline
Multi-beamline operation
with fast switching magnet
T.Hara, poster MOP022

SCSS test accelerator
(2005~2013)
→ EUV-FEL facility
400 MeV or more

Hard X-ray self-seeding
using forward Bragg diffraction.
Intense, single-mode XFEL for user experiments

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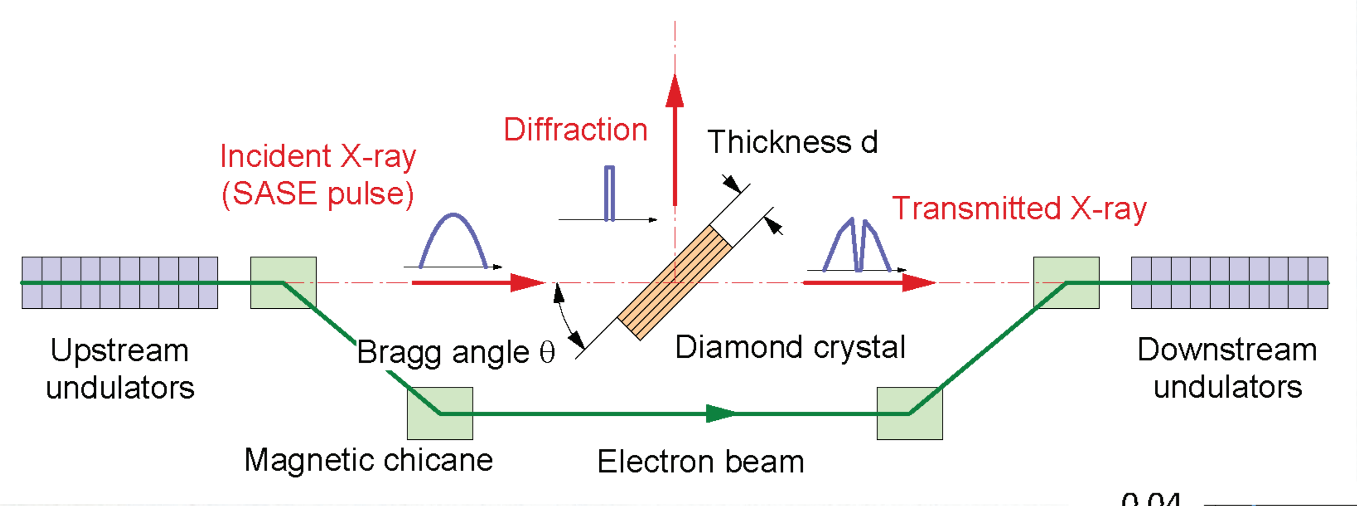
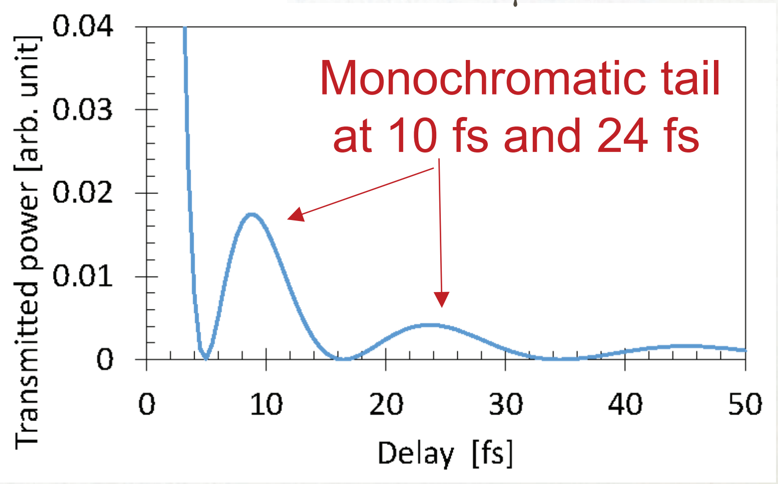
Self-seeding using a forward Bragg diffraction (FBD)

- Proposed at DESY G.Geloni, V. Kocharyan & E. Saldin, J. Mod. Opt. 58, 1391 (2011)
- First demonstrated at LCLS J. Amann, et. Al., Nat. Photonics 6, 693 (2012)

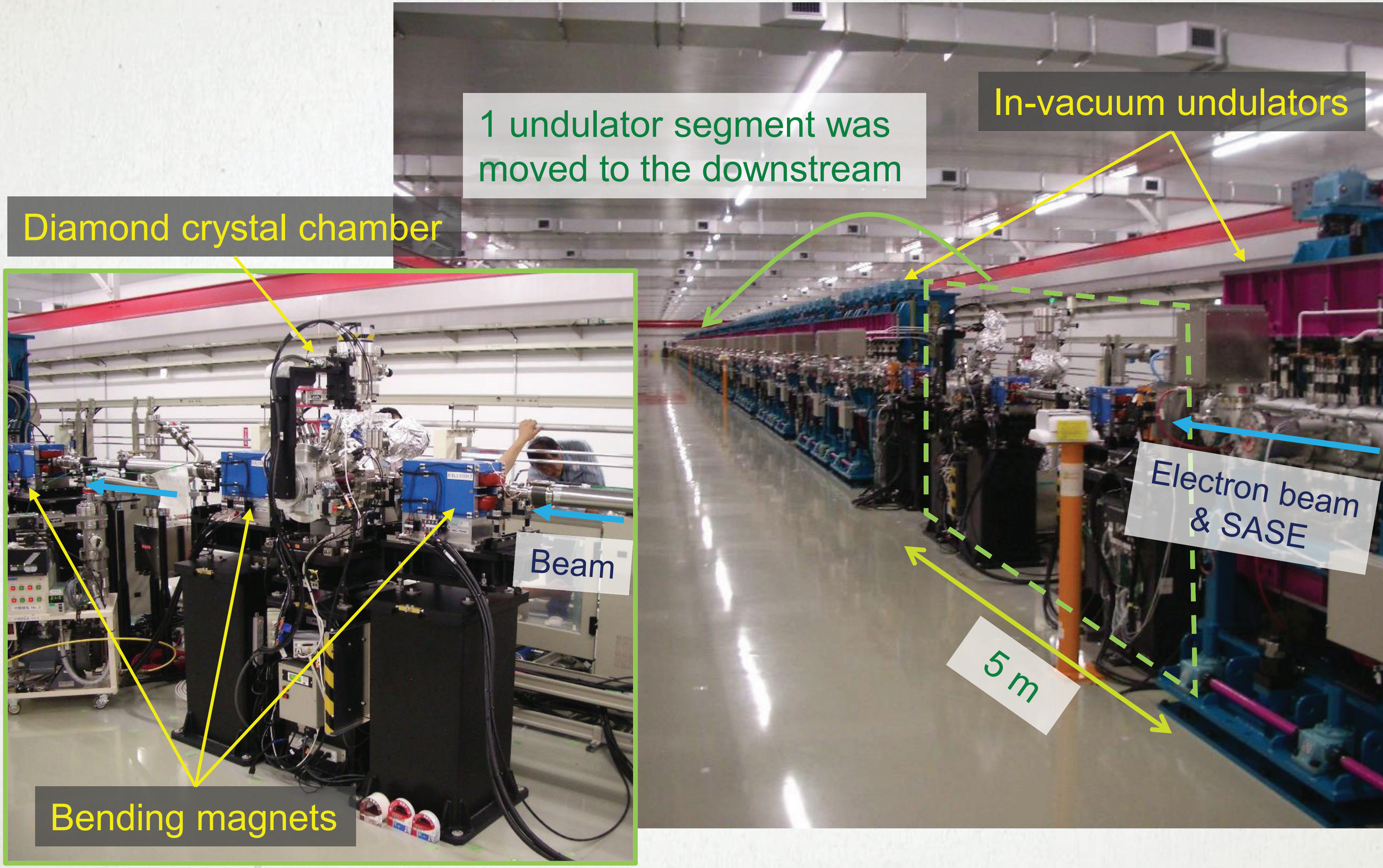


Numerical calculation of FBD radiation envelope for 10 keV pulse,
C(400) plane ,
t=180 μm



- FBD produce a monochromatic tail component in a transmitted X-ray pulse.
- Compact chicane gives delay to overlap.

Magnetic chicane (50 fs max.) in BL3 beamline



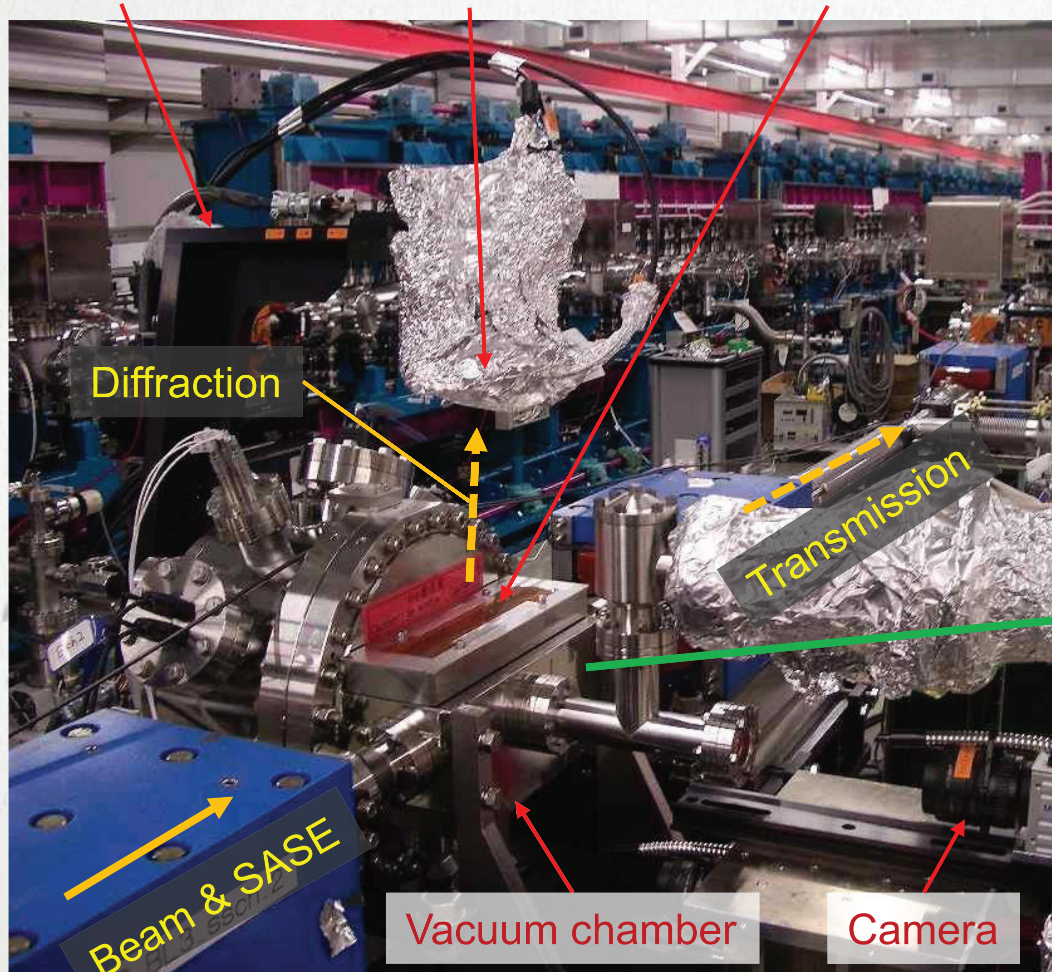
Diamond crystal chamber

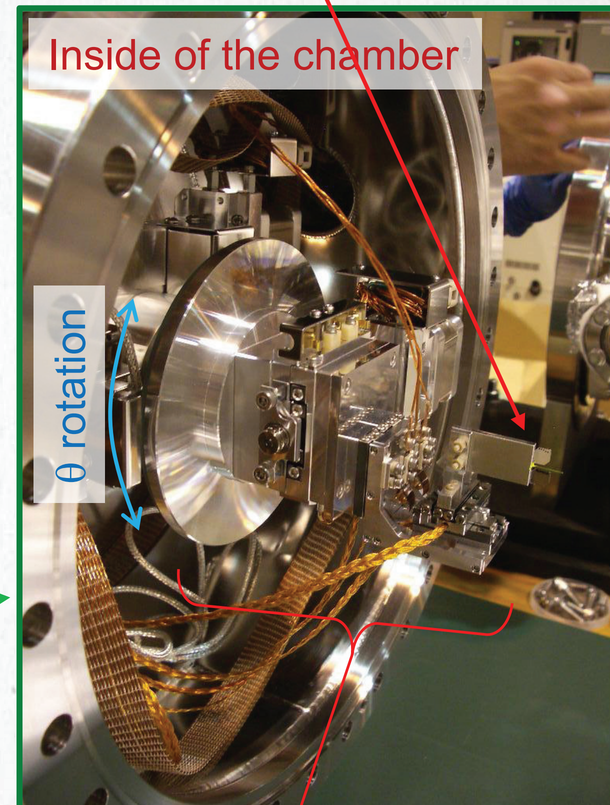
2θ rotation arm

Diffraction monitor (Photo-diode & CCD)

Be window

Diamond single crystals
$180\ \mu m \times 6.5mm \times 6mm$





Multi-axis stage (x,y,z,Ry,θ)
for remote control

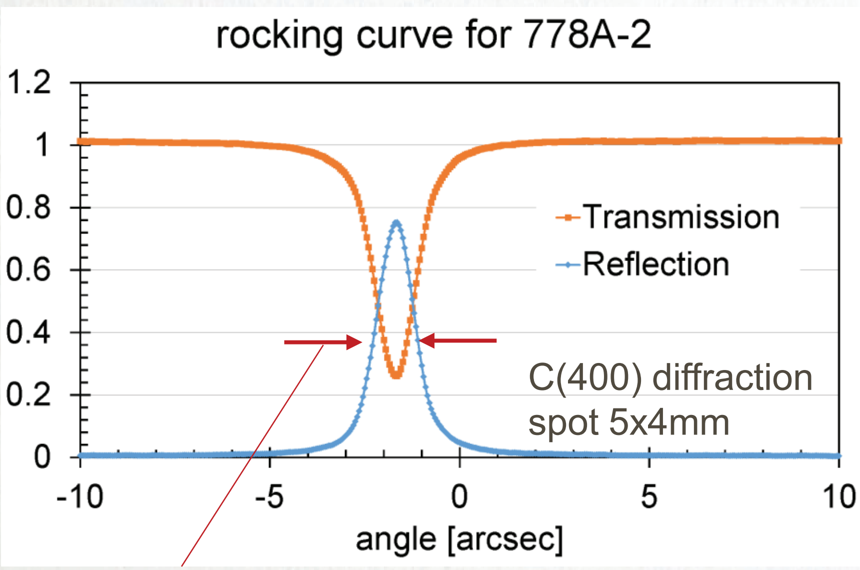
Diamond single crystal

- Polished to obtain nominal thickness of 180 μm.
- Quality was checked by X-ray rocking curve measurement at SPring-8 BL29 (1 km beamline).
- For a backup, 2 crystals were attached on the holder.

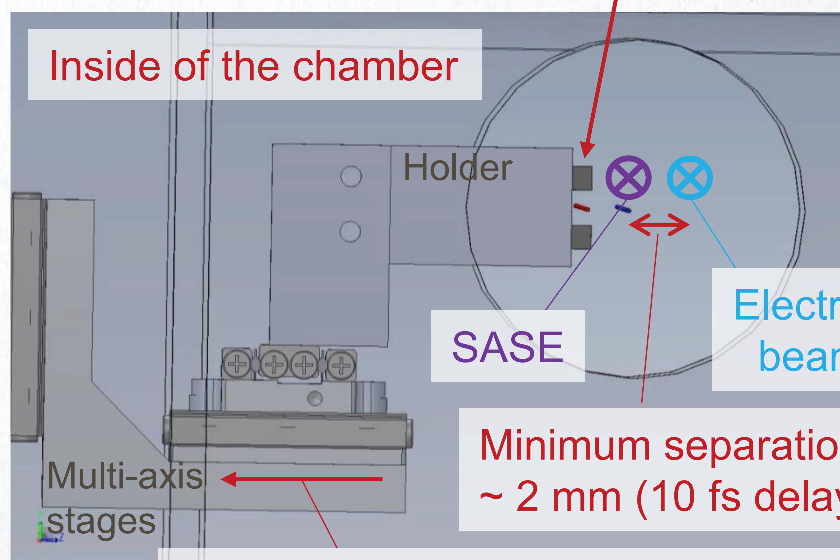
Diamond single crystal
(Sumitomo SEI-type-IIa)

6.5 mm

6 mm



Meas. 1.2 arcsec (FWHM)
Calc. 0.7 arcsec

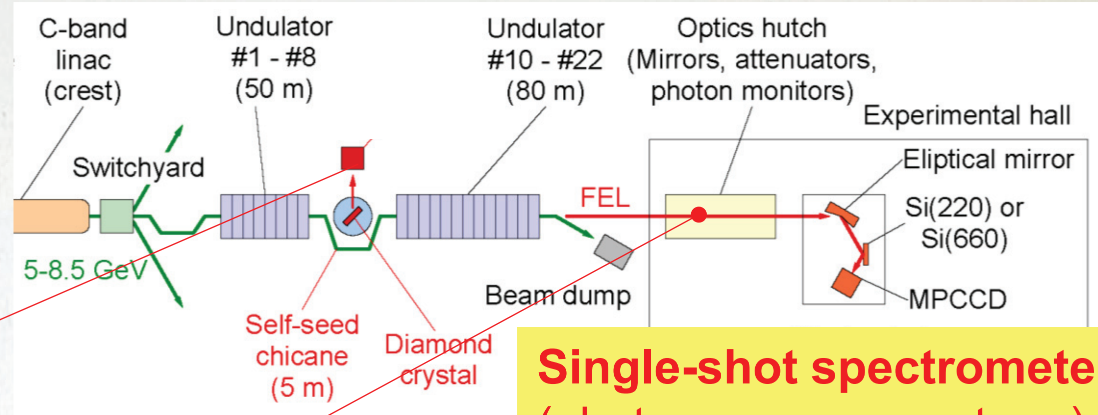


Minimum separation
~ 2 mm (10 fs delay)

Crystal is usually 10 mm retracted
for the SASE operation

Photon monitors

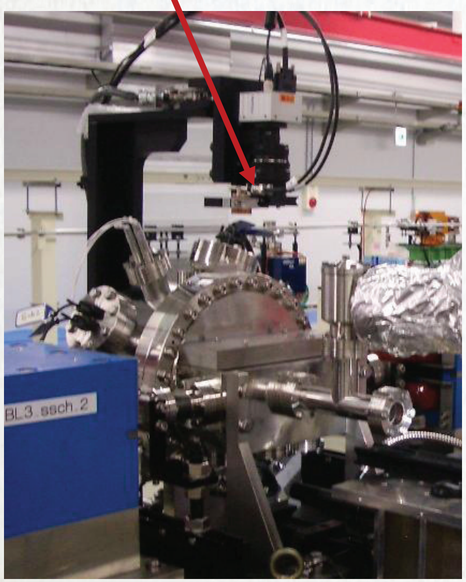
Accelerator
e- beam →

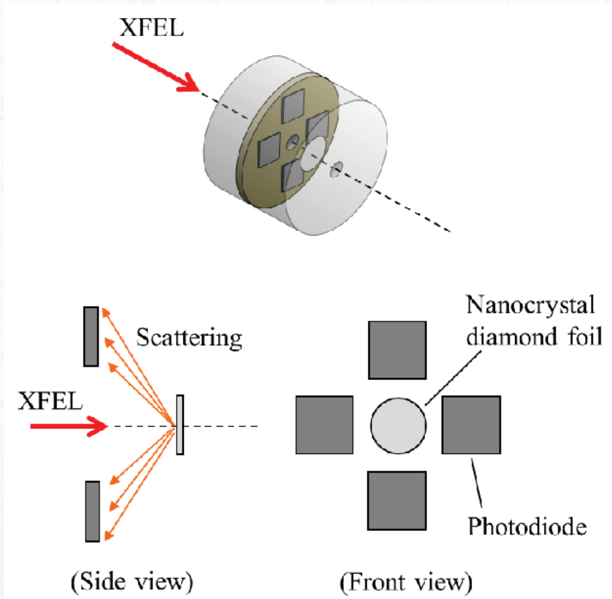


Single-shot spectrometer
(photon energy spectrum)

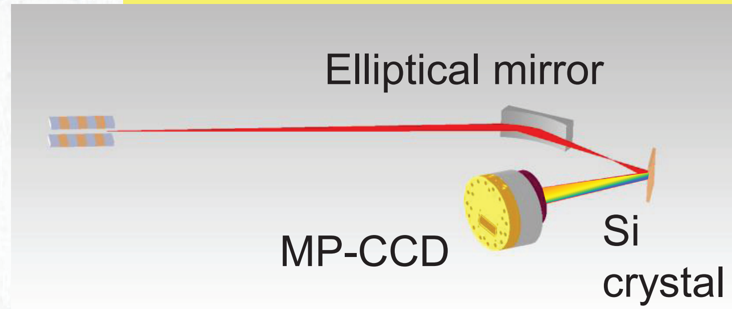
Photo-diode
(Diffraction monitor)

Intensity monitor
(Pulse energy, pointing)





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



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

Wide range mode: Si (220)
- Range 70 eV
- Resolution 0.8 eV/pixel

High resolution mode: Si (660)
- Range 6 eV
- Resolution 0.07 eV/pixel

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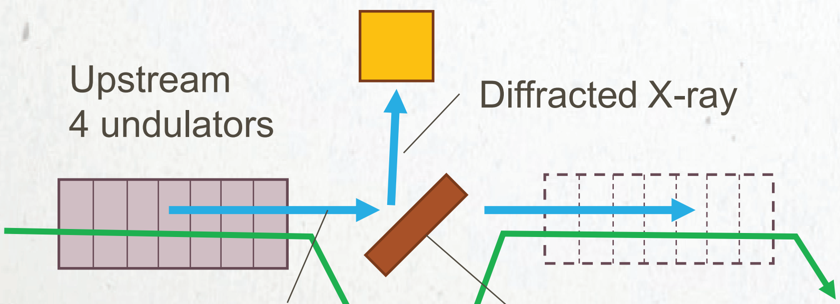
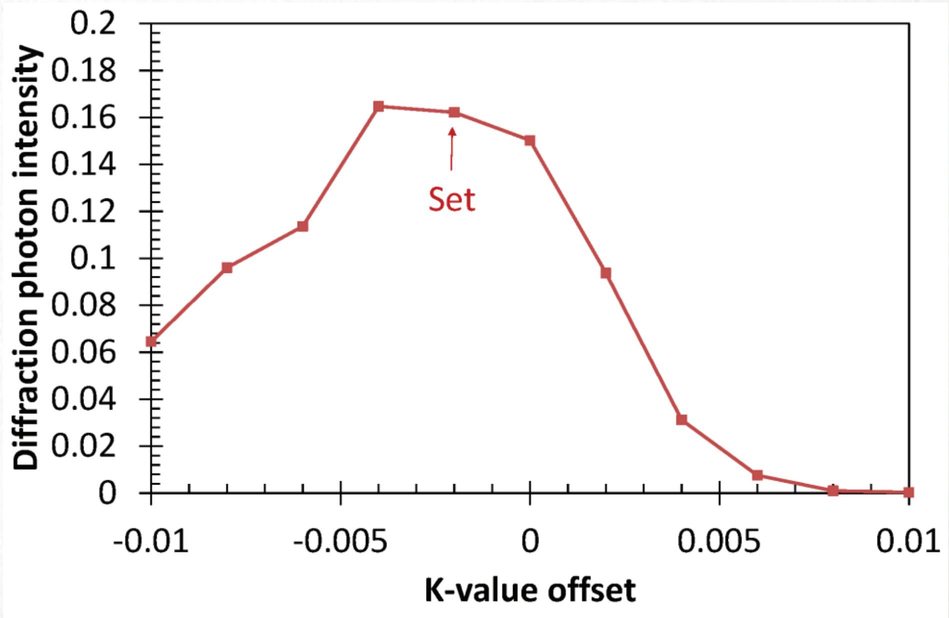
Recent commissioning results in June 23 2014

Beam energy 7.8 GeV
Beam charge 340 pC
Undulator K-value 2.1
Photon energy 10 keV
Pulse repetition 10 pps

Adjustment of the SASE photon energy

- We set the Bragg angle to θ = 44 degree in C(400) diffraction for 10 keV
- We used 4 undulators in the upstream. (~ 30 μJ/pulse)
- In order to adjust central photon energy of SASE to the Bragg diffraction, we scanned K-value (= photon energy) to maximize diffraction intensity.

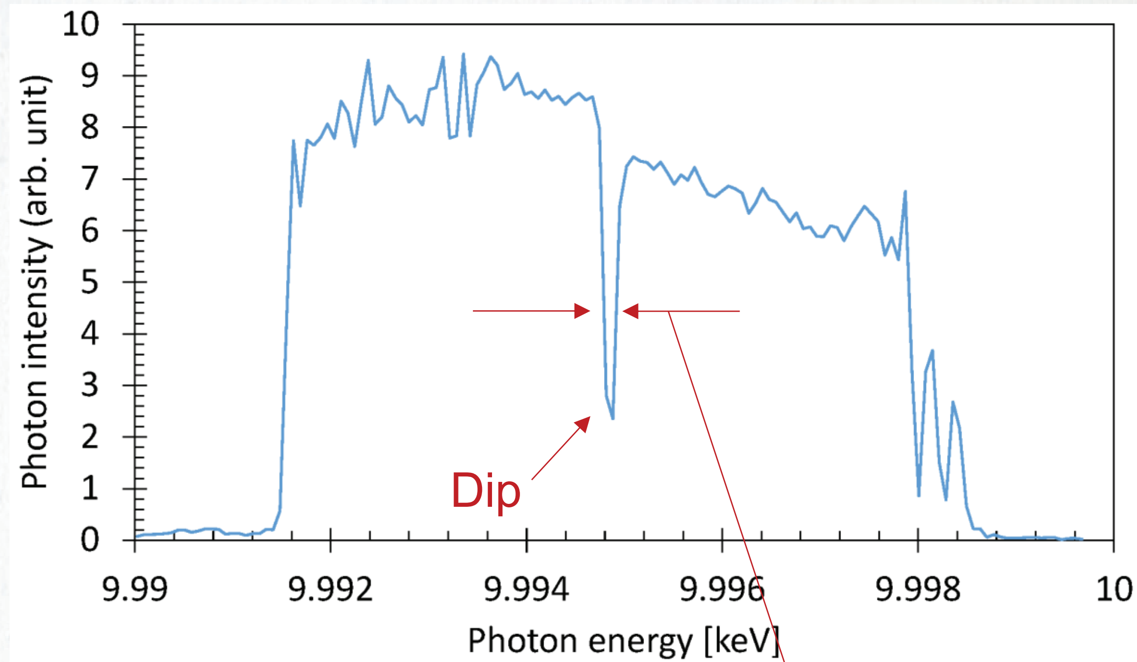


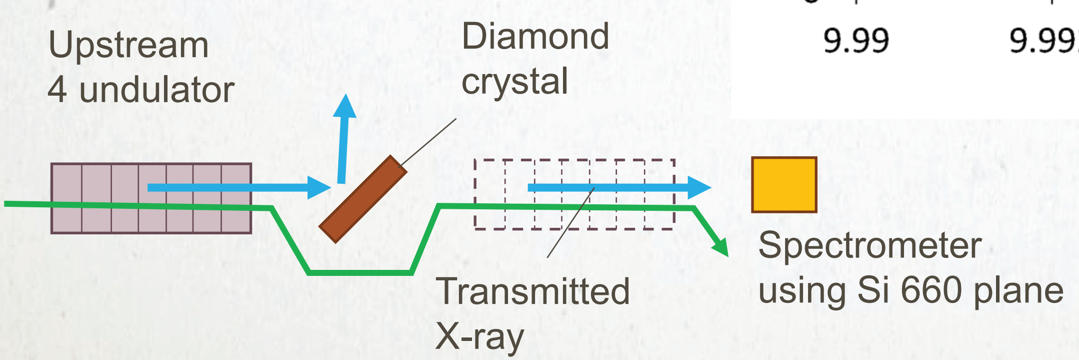


Spectrum of the transmitted SASE radiation

- We observed clear dip due to the Bragg diffraction
- The diamond crystal has a good quality, without degradation

Spectrum of 100 shot integration



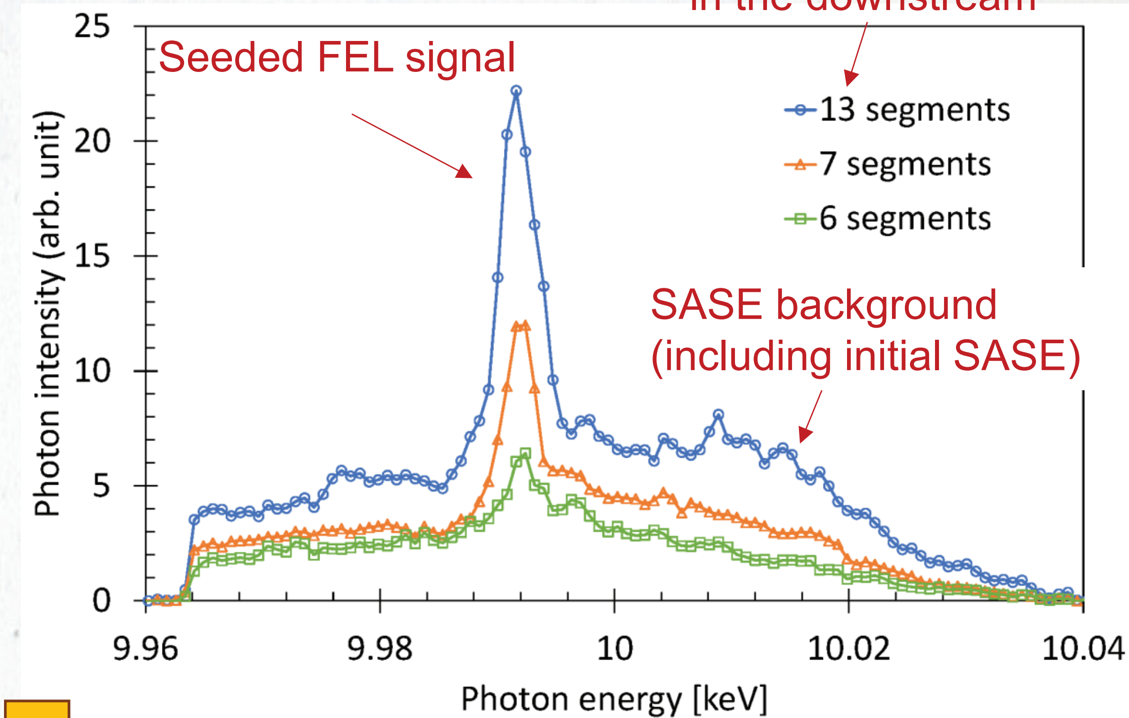


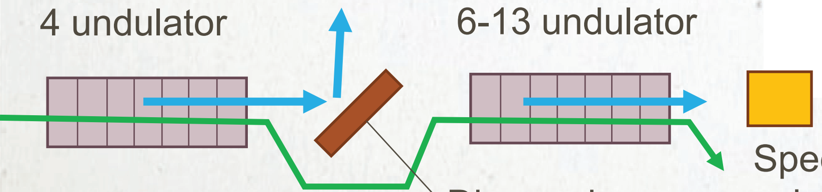
Width ~ 0.1 eV (2 pixel of CCD)
Comparable to the resolution of the high resolution mode.

Close the gap of downstream undulators

- Monochromatic peak due to the seeding was observed.
- We closed more undulators, seeded FEL increased.

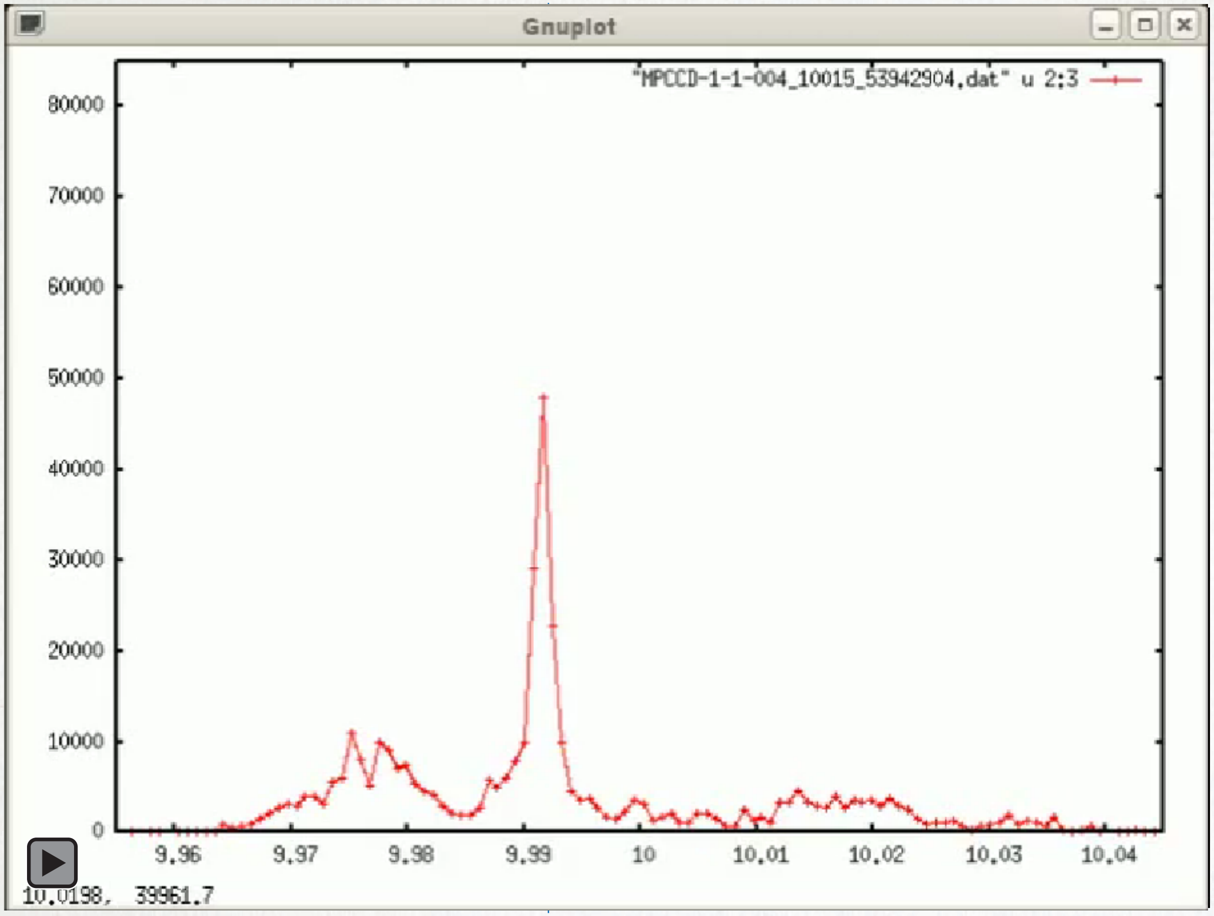
Photon energy spectrum of 100 shot integration





Wide range mode

Example of the single-shot spectrum



9.992 keV

With 13 undulators,
20 fs delay at chicane

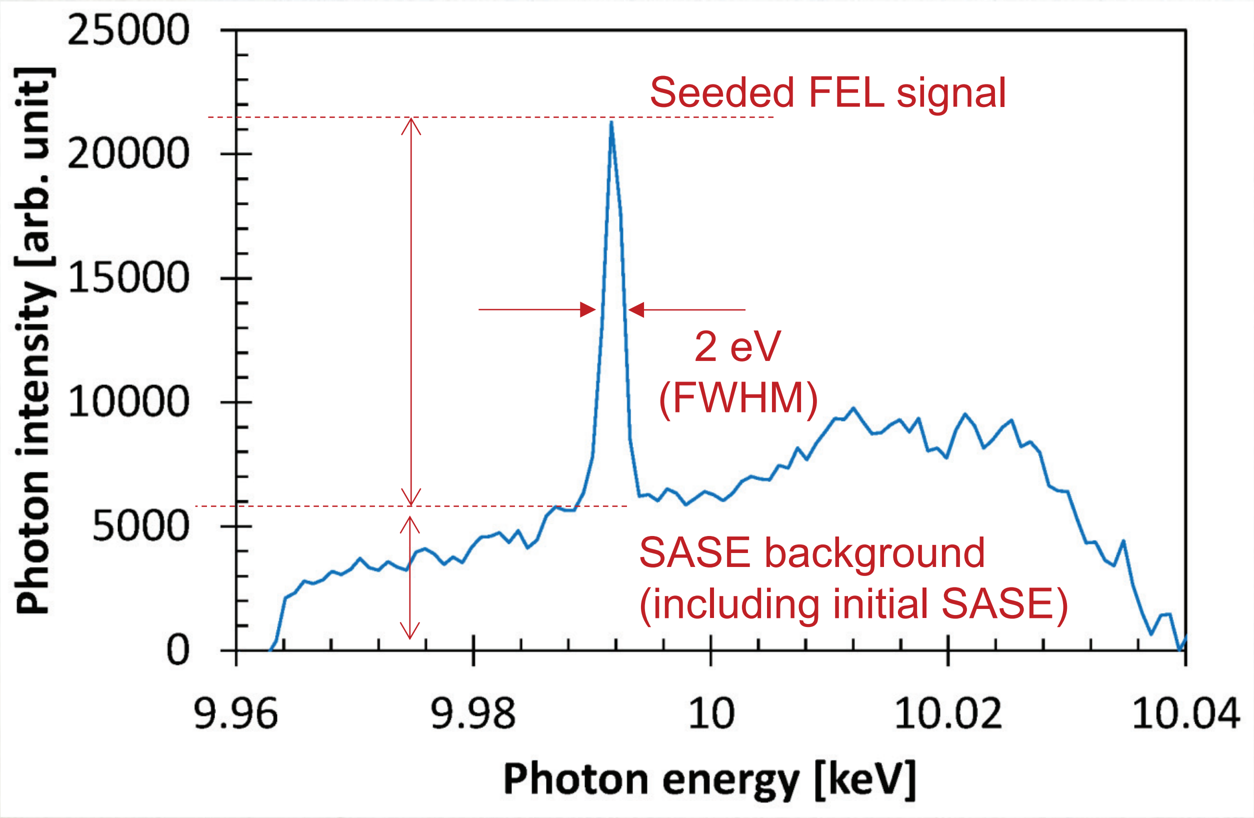
Spectrometer:
Wide range mode
(Si 220 plane)

Roughly half of the spectra had a peak at 9.992±0.001 keV.

Spectral width: ~ 2 eV.

100 shot integrated spectrum

- Peak intensity: 4 times higher than SASE background
- Spectral width: 2 eV (FWHM), which is 1/15 of SASE
- Self seeding drastically enhanced the monochromatic photon intensity and spectral narrowing as expected.



With
Upstream 4 undulators
Downstream 13 undulators
20 fs delay at chicane

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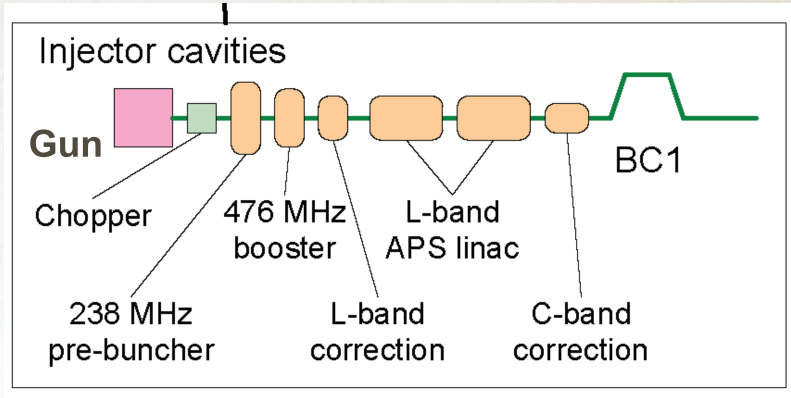
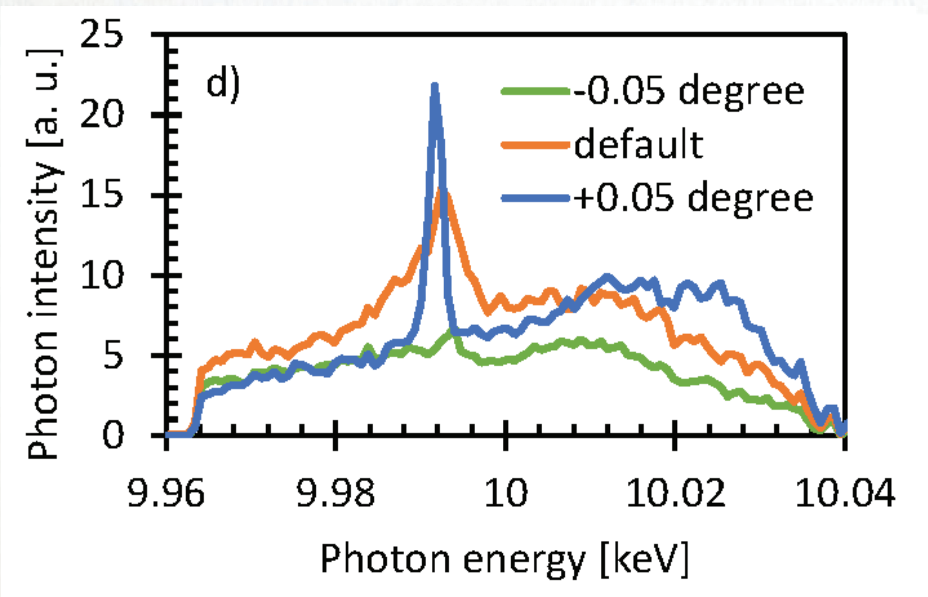
Sensitivity for RF phase

- Seeding seems quite sensitive to the RF phase of the accelerator cavities.
- We scanned the RF phase, and defined the "RF phase tolerances" for **50% decrease** of the intensity.

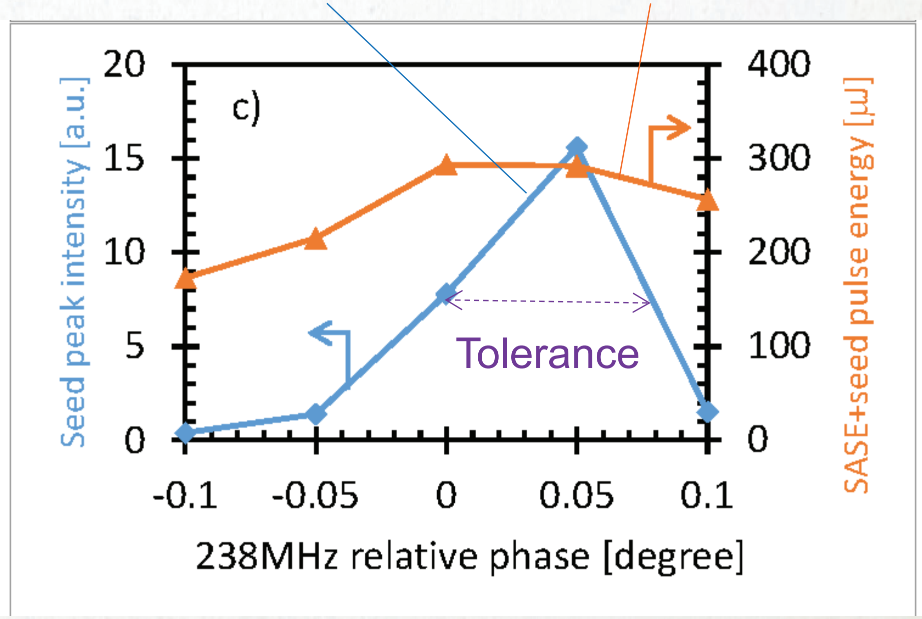


Spectral change for different RF phase of 238MHz pre-buncher.



Seeded peak intensity

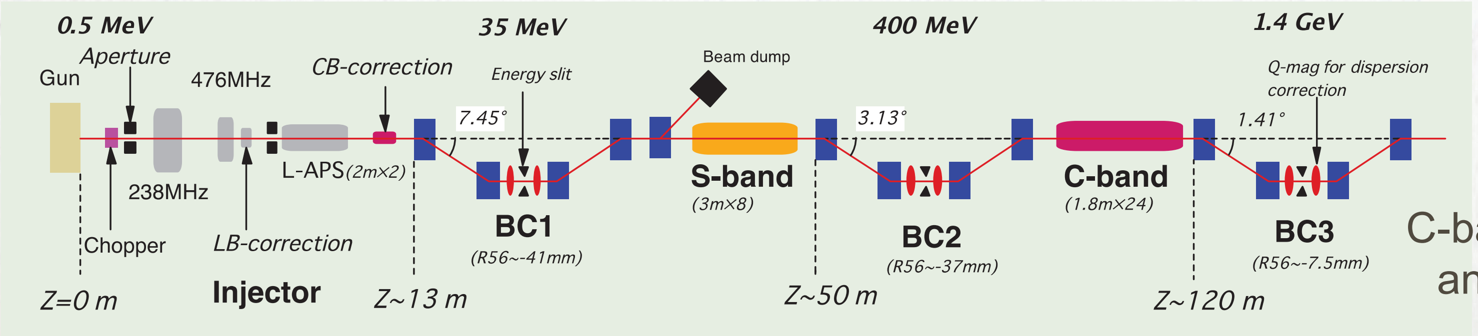
Pulse energy (mainly SASE)



Tolerances for RF phase change

- Seeding is more sensitive for RF phase variation than SASE.
- Optimum phase for the seeding is sometimes slightly different from that for SASE.

Accelerator cavities	Tolerance for seeding	Tolerance for SASE
238 MHz pre-buncher	**±0.05° (600 fs)**	±0.1°
476 MHz booster	±0.1° (600 fs)	±0.3°
L-band APS-type linac	**±0.05° (100 fs)**	±0.08°
C-band correction cavity	±0.3° (150 fs)	±0.5°
S-band linac	±0.5° (500 fs)	±0.5°
C-band linac (before BC3)	**±0.2° (100 fs)**	±0.3°



Next tasks… long-term stability and reproducibility

- So far we optimized and stabilized the beam parameters for SASE.
- But, the seeded FEL signal was sometimes fluctuated, although SASE intensity was not changed.
- We consider seeding is more sensitive to the internal distribution in the bunch (peak current, energy chirp, …) than SASE.
- Our in-line beam monitors (RF-BPM, CT, CSR,…) measure collective information of the bunch, and our beam-based feedback did not care about the internal distribution.

- We plan to optimize the beam condition for the seeding…..
  - Relaxation of bunching and lower peak current
  - Reduction of energy chirp

Summary

- Self-seeded XFEL with forward Bragg diffraction has been implemented in SACLA.
- Monochromatic X-ray due to the seeding was observed at 10 keV.
- Averaged intensity of the monochromatic X-ray was 4 times higher than SASE.
- Spectral width was about 2 eV in FWHM, which is one order narrower than SASE.

- Seeding is more sensitive to the accelerator variation than SASE.
- We plan further study and optimization of the operational conditions, in order to generate the seeded FEL stably for a future practical use.

Acknowledgement

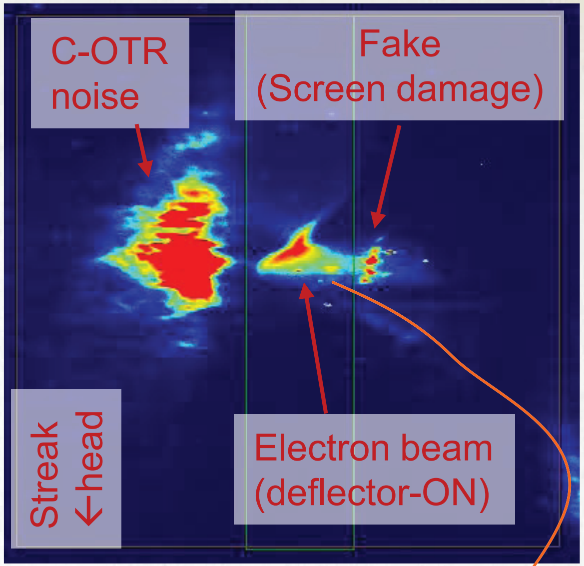
We thank to …

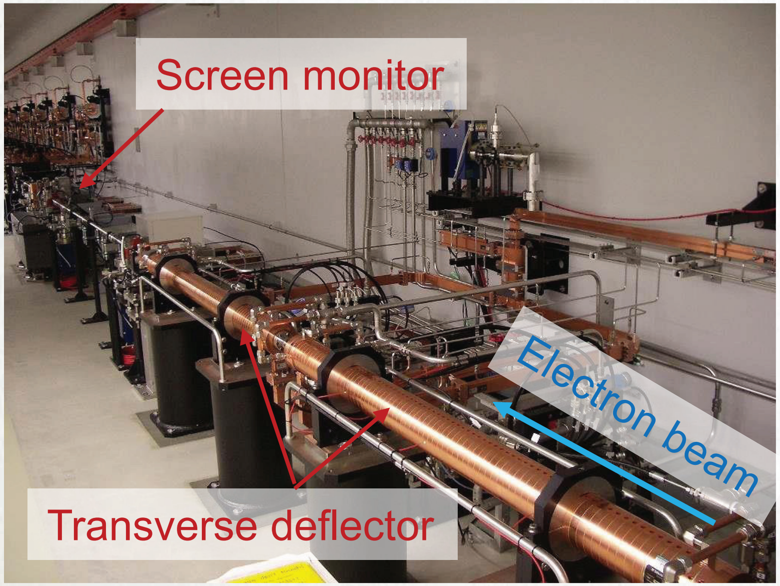
- Dr. J. Hastings (SLAC), Dr. G. Geloni (DESY), Dr. E. Allaria (Elettra), Dr. F. Loehl (PSI), and Dr. K. Ohmi (KEK), for joining our commissioning and discussion.
- All of SACLA staffs for construction, operation and maintenance.

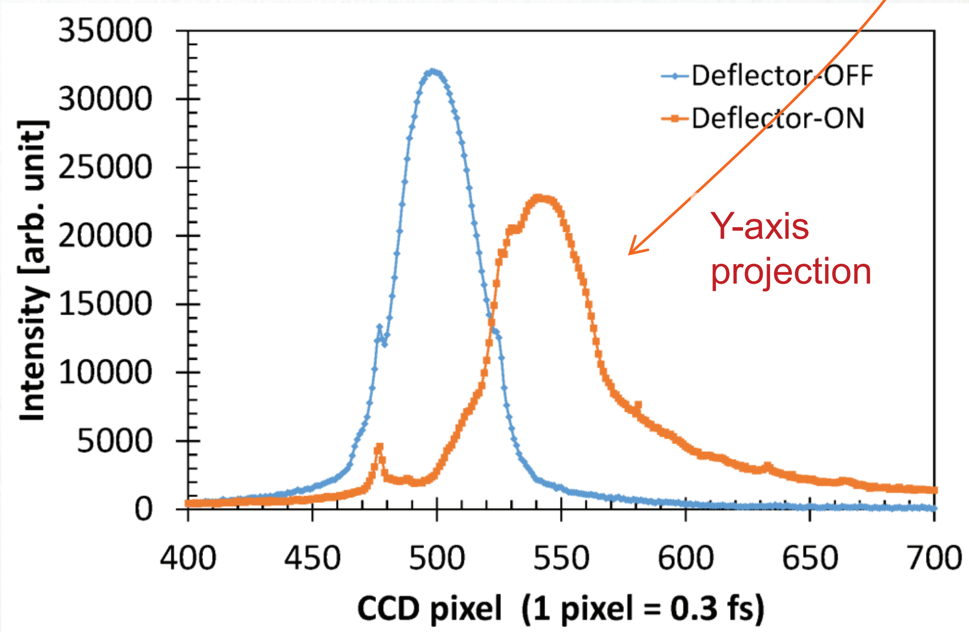
Backup slides

Typical bunch length

- Measured using transverse deflector after BC3.
- Deflector-OFF, vertical size = 37 pixel (FWHM)
- Deflector-ON, vertical size = 45 pixel (FWHM)
- $\sqrt{45^2 - 37^2}$ = 26 pixel → 8 fs (FWHM)



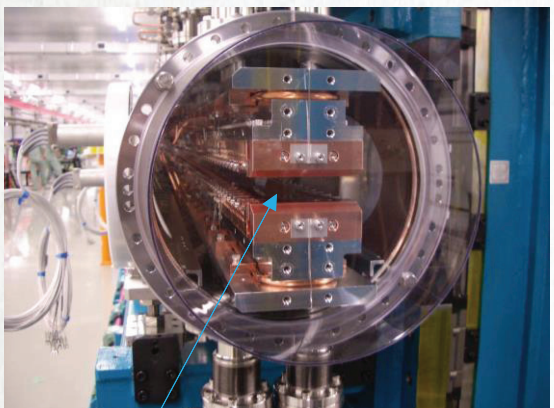


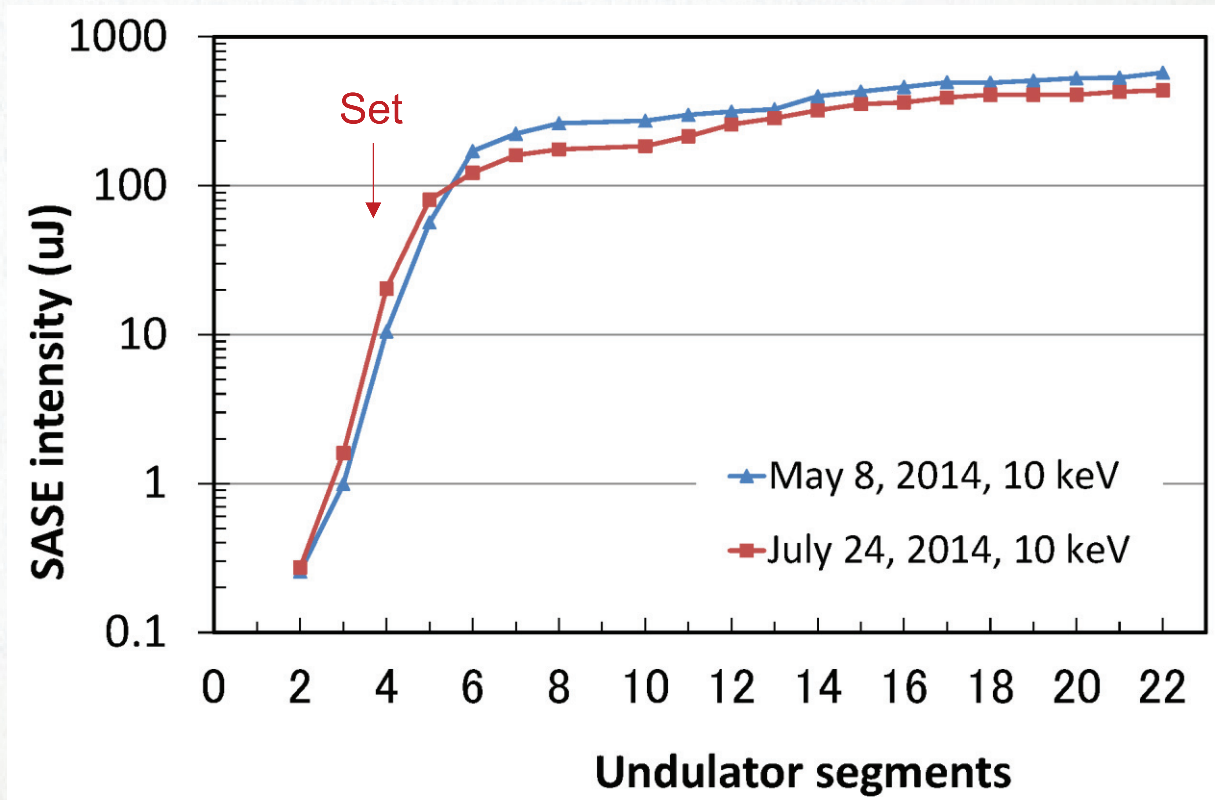


Gain curve and determination of upstream undulators

- We used 4 undulators (#4-8), just in the upstream of the chicane.
- SASE~30 μJ/pulse, in linear regime

Typical gain curves for 10 keV SASE

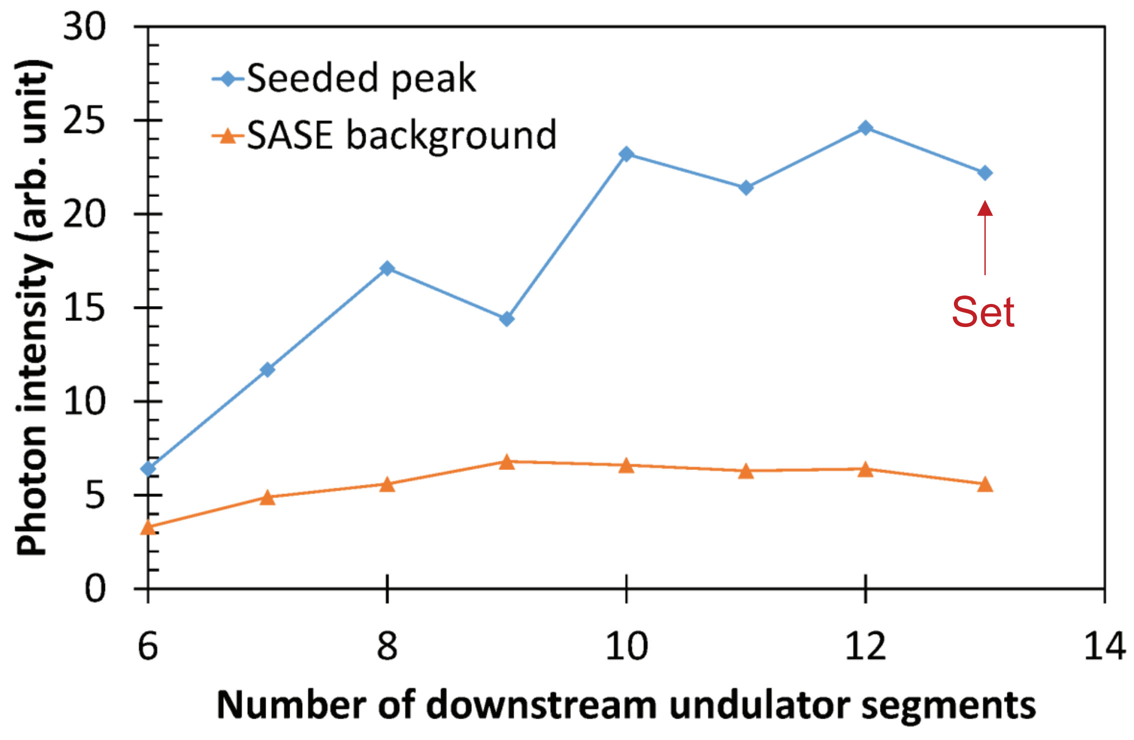




Gap 10 mm → 3.8 mm
K-value 0.6 → 2.1
(with taper -0.002/segment)

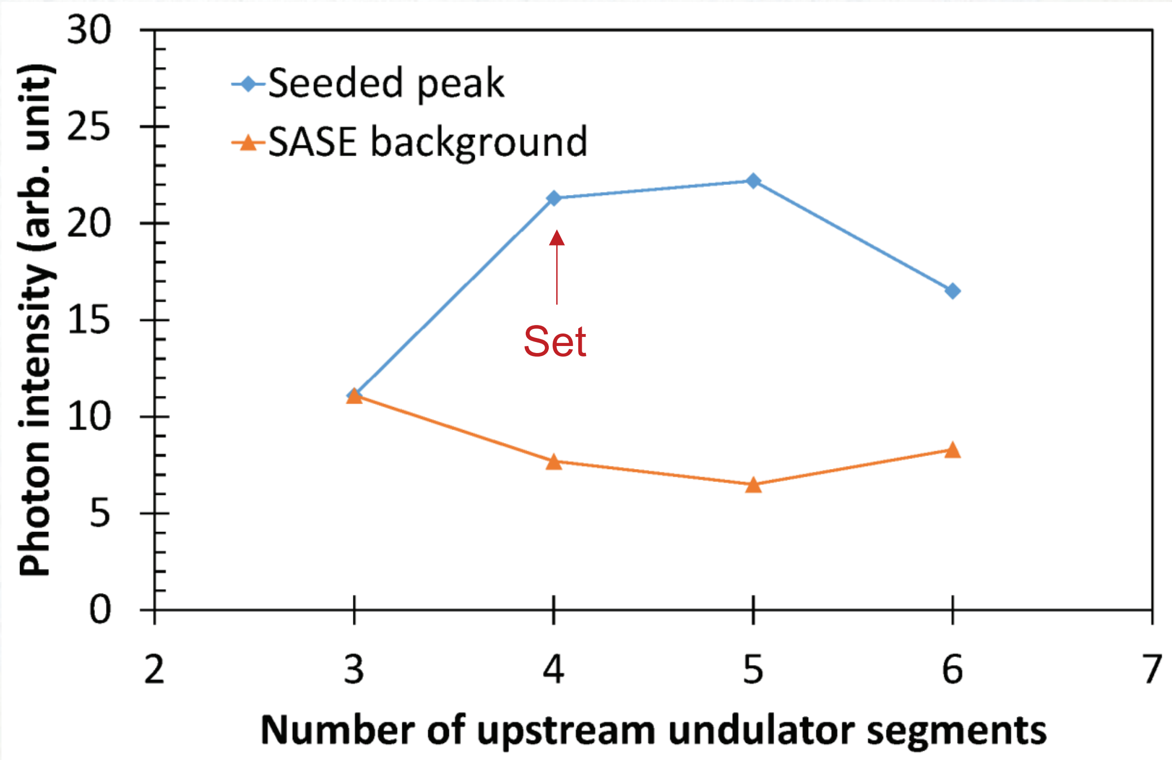
Number of downstream undulators

- SASE background was constant. (No amplification in downstream)
- Seeded FEL increased, until 10 undulators.
- Further optimization (K-value taper, …) might increase the seeded component?



Number of upstream undulators

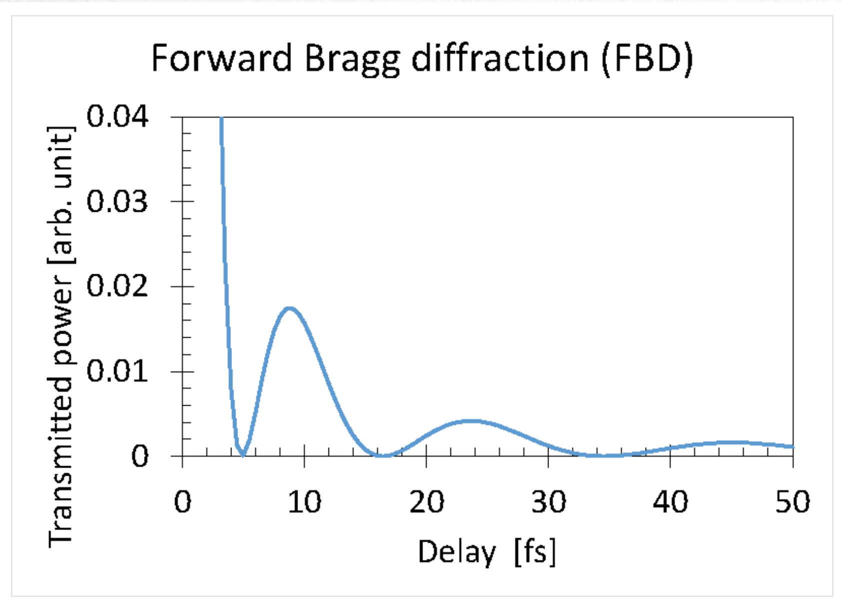
- 3 undulators (~1 μJ/pulse) : SASE was too weak for seeding.
- 6 undulators (~150 μJ/pulse) : Beam quality (energy spread) was deteriorated.



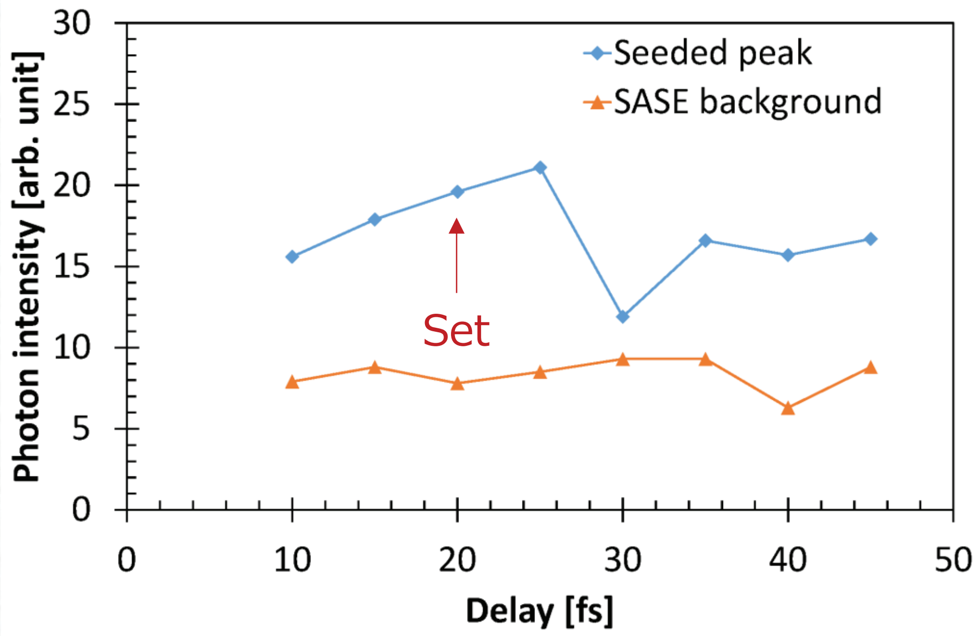
Delay time in the chicane

- Enhancement was observed around 24 fs and 45 fs, as expected.

Numerical calculation



Measurement



Peak intensity and photon energy

- “Seeded” rate was 42 event /100 shots
- For “seeded” events, fluctuation of peak intensity ~ 31% (RMS)
- Fluctuation of photon energy ~ 0.9 eV, comparable to the resolution.