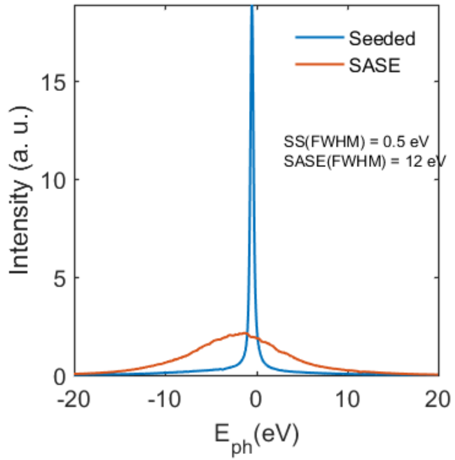
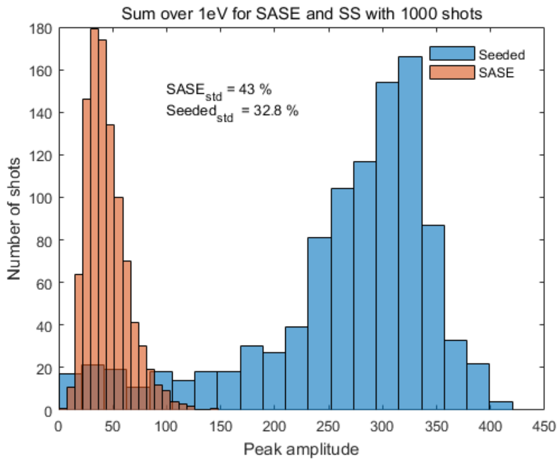
FEL2019, Hamburg





Hard X-Ray Self-Seeding at PAL-XFEL

Chang-Ki Min

on behalf of the PAL-XFEL self-seeding & operation team

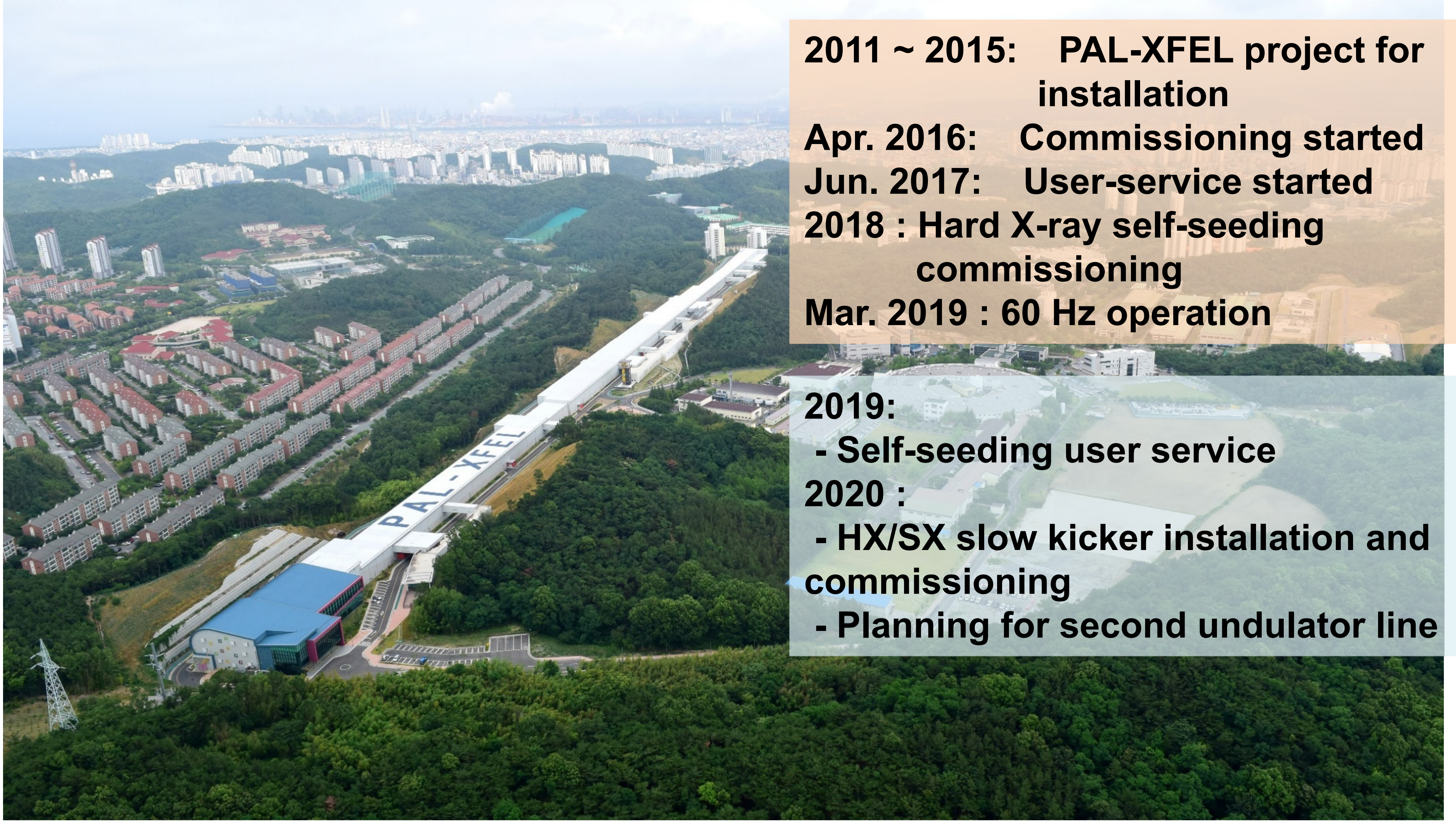
PAL 포항가속기연구소
POHANG ACCELERATOR LABORATORY

Outlines

- Recent updates of PAL-XFEL

- Hard X-ray Self-seeding
  - ❖ Commissioning results from 3.5 keV to 14.4 keV
  - ❖ Improved seeding with laser heater
  - ❖ User-service plan


PAL-XFEL
PLS-II
PAL-XFEL



2011 ~ 2015: PAL-XFEL project for installation

Apr. 2016: Commissioning started

Jun. 2017: User-service started

2018 : Hard X-ray self-seeding commissioning

Mar. 2019 : 60 Hz operation

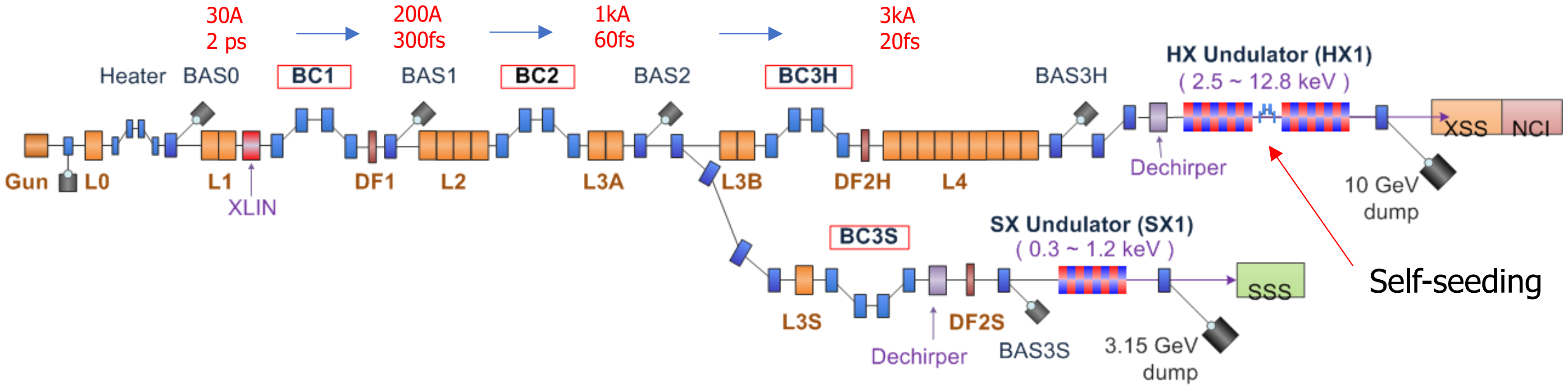
2019:

- Self-seeding user service

2020 :

- HX/SX slow kicker installation and commissioning
- Planning for second undulator line

PAL-XFEL Parameters



Main parameters

e^- Energy	11 GeV
e^- Bunch charge	150 - 220 pC
Slice emittance	< 0.4 mm mrad
Peak current	> 3 kA
Repetition rate	60 Hz
FEL photon energy	2 ~ 14.5 keV (HX) 0.25 ~ 1.25 keV (SX)
FEL intensity	> 1 mJ (HX), > 0.2 mJ (SX)
duration	5 – 35 fs
SX line switching	DC magnet (to be changed to Kicker by 2020)

Undulator Line	HX1	SX1
Photon energy [keV]	2.0 ~ 14.5	0.25 ~ 1.25
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	energy	gap
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0
No. of undulators	20	7

Operation parameters

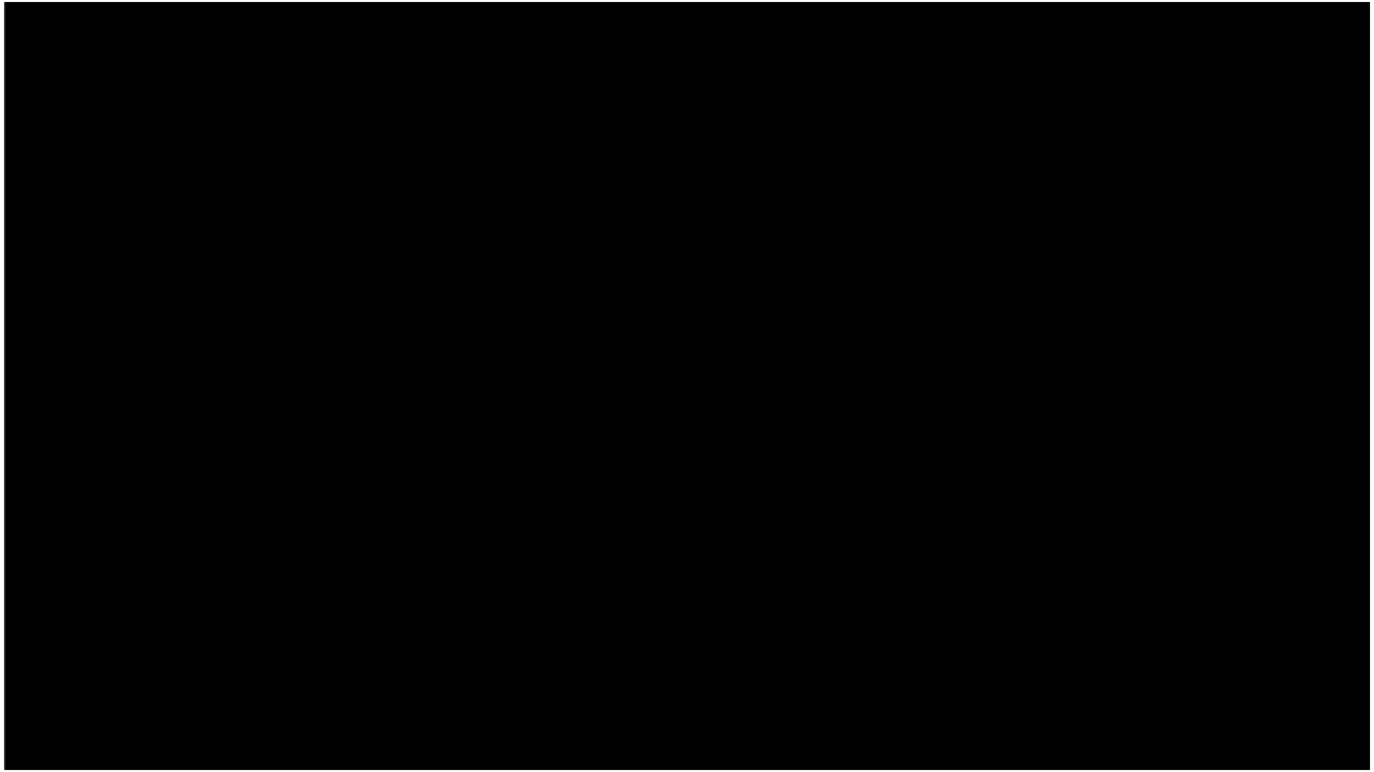
- Gun 33.7
- L1 -10.5
- X-linearizer -180.0
- L2 -19.6
- L3 -3.0
- L4 -2.0
- BC1 4.97° (-66.7 mm)
- BC2 3.3° (-46.9 mm)
- BC3 1.6° (-11.6 mm)

※ **3-BC improves FEL power stability and phase tolerance by reducing CSR.**

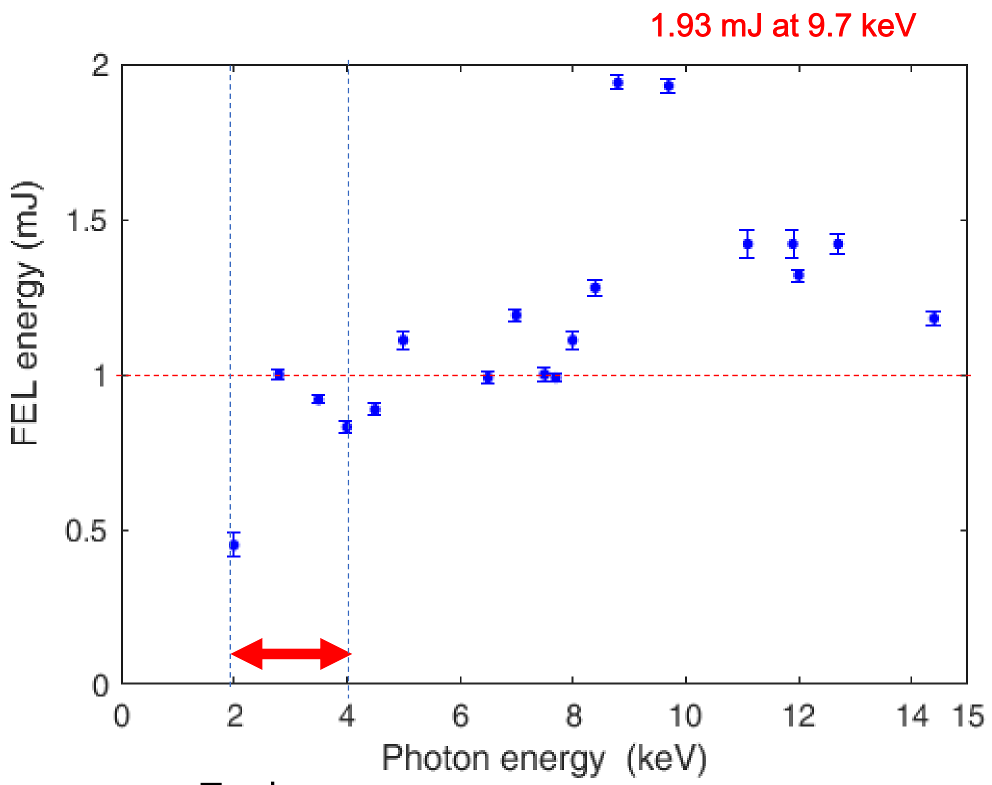
14.4 keV FEL (1 mJ, 20 Nov. 2018)

E-beam at the beam dump

FEL beam at the YAG screen, 40 meter downstream of last undulator

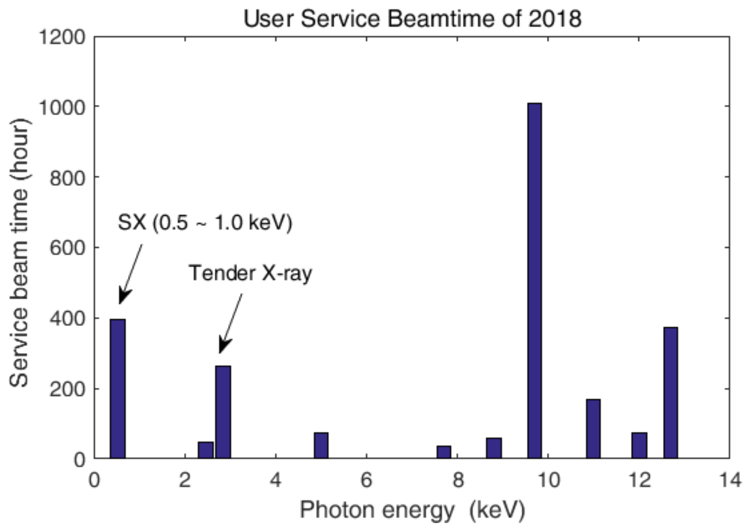


Hard X-ray FEL Intensity



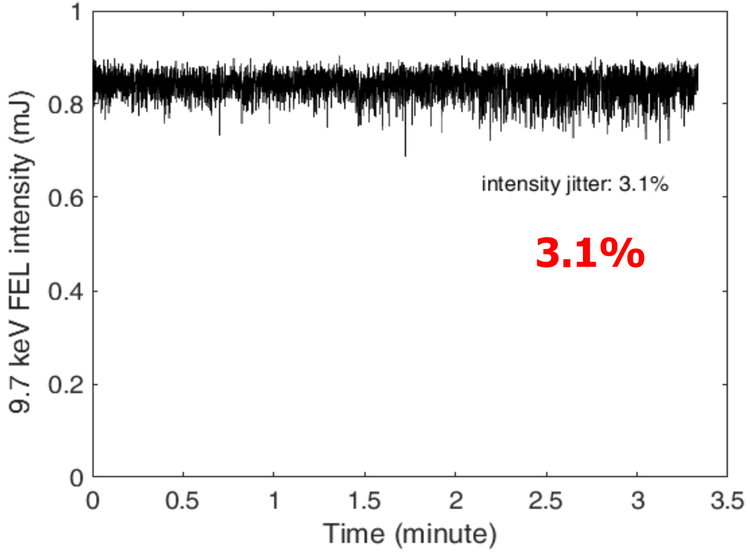
Tender x-ray

- Access to the tender X-ray range (2.0 ~ 4 keV) presently is only available at PAL-XFEL
- This regime allows access to the Ru L edge and the M edges of the 4d transition metals.

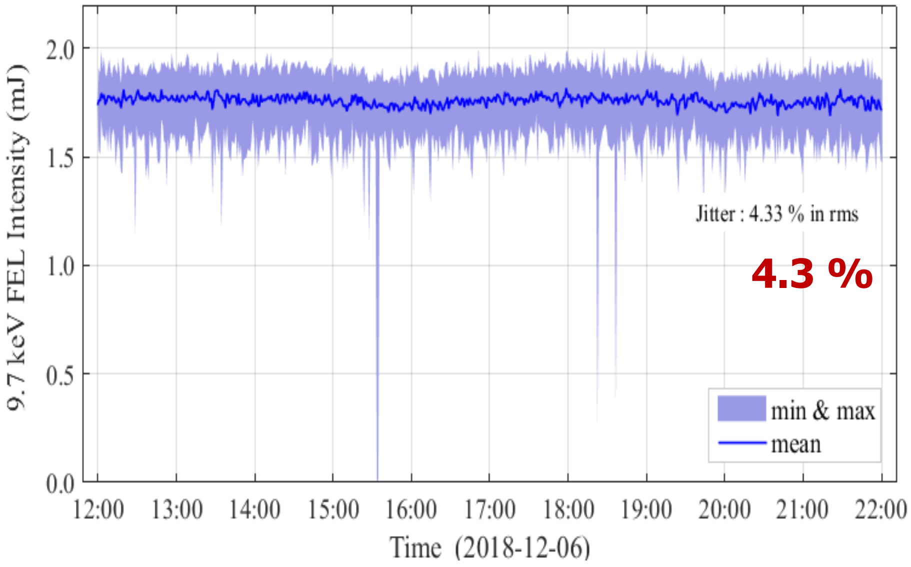


FEL intensity stability (9.7 keV FEL)

Short-term (3 min.)



Long-term (10 hour)



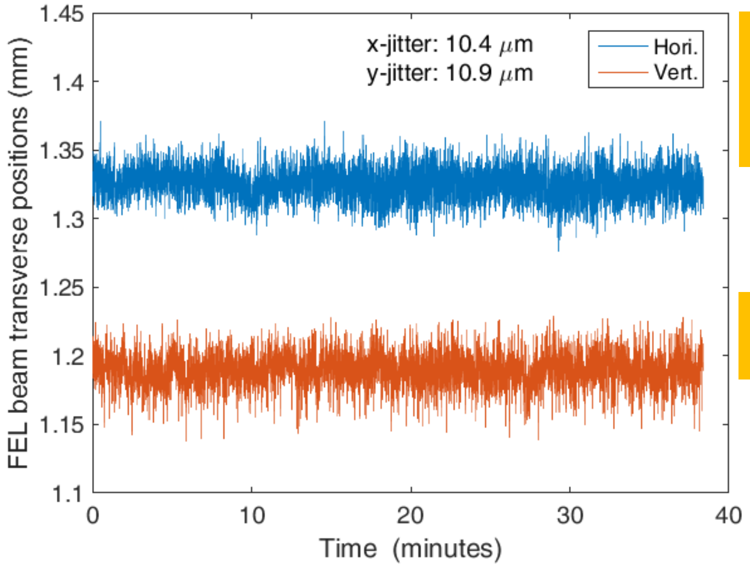
Fluctuations of the radiation pulse energy at the end of the exponential gain regime

$$\frac{\Delta W}{W} \sim \frac{1}{\sqrt{M_L}}$$

- FEL beam pulse duration 24.7±0.7 fs (FWHM)
- M_L ($\approx {}^{24.7}/_{0.22}$) 112
- FEL fluctuation at gain regime 9.5%
- Fluctuations after saturation 3.2% (~ 9.5 / 3)

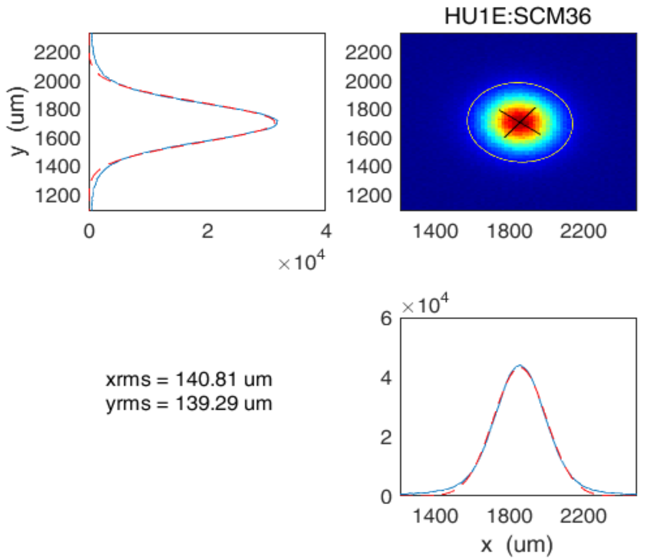
FEL Beam Pointing Jitter

(measured at an YAG-screen, 40-m downstream from last undulator)



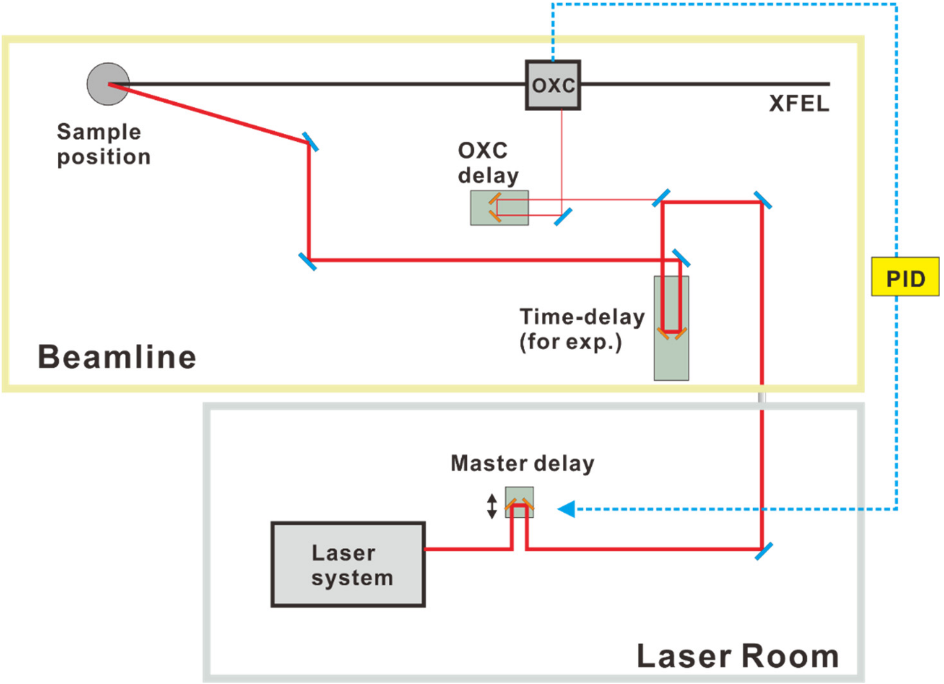
7.4 % of photon beam size

7.8 %

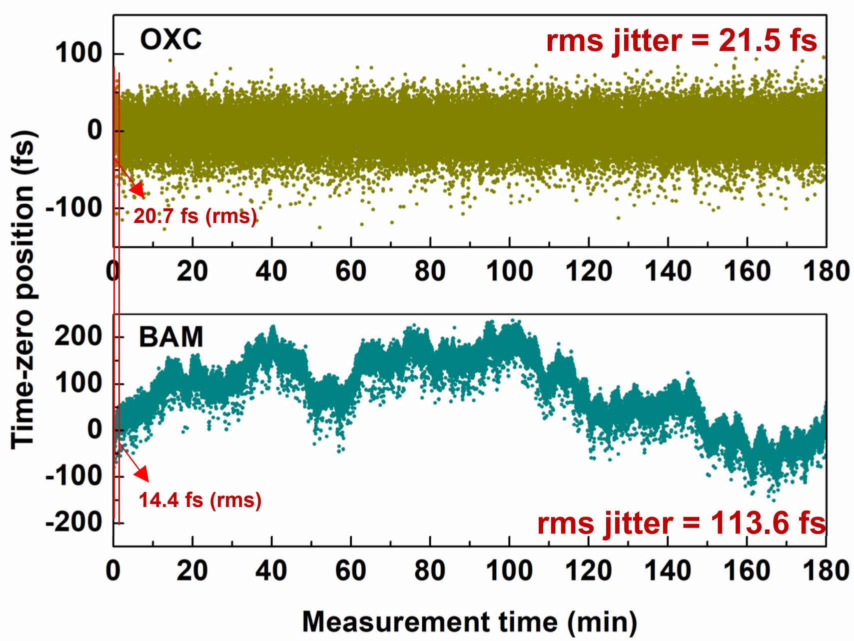


- FEL beam divergence angle: 1.6 μrad
- **Pointing jitter: 0.14 μrad in rms**

Slow drift correction of reference timing

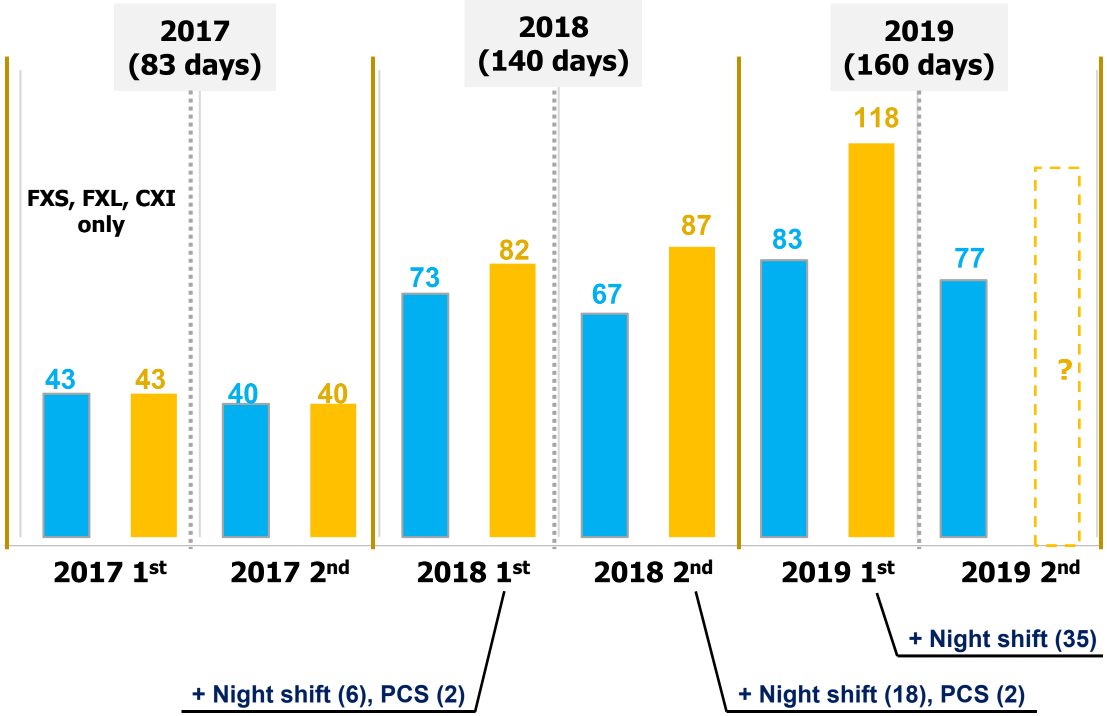


Stability for 3 hours

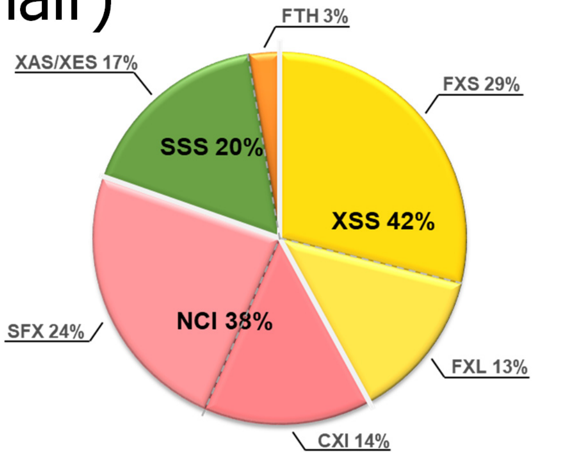


Beamtime statistics (2017 – 2019, 1st half)

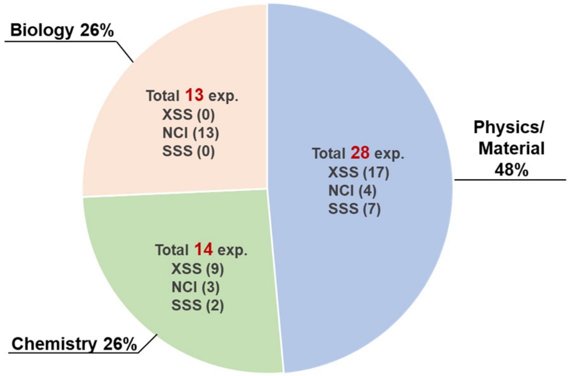
- User beamtime (Days)
- Number of beamtime shifts (12 h/shift)



By Beamline (XSS, NCI, SSS)



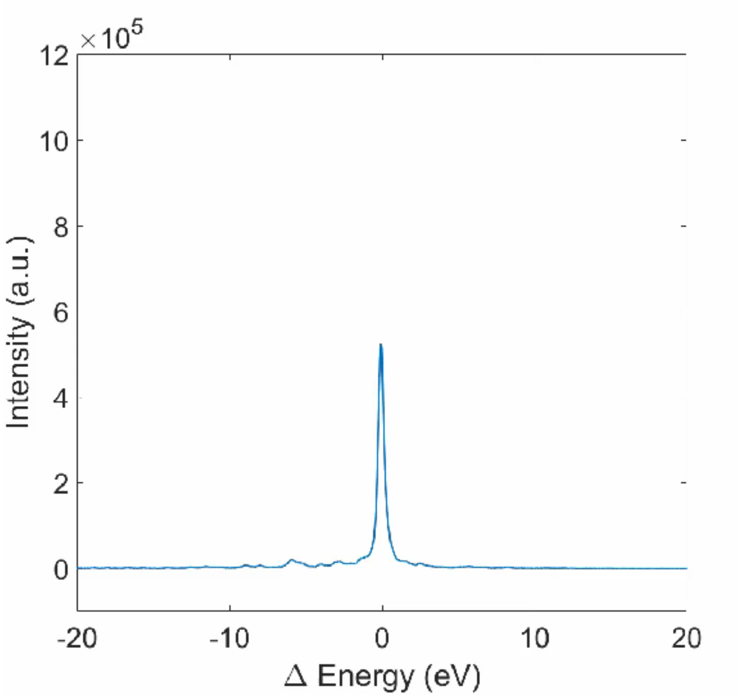
By Science fields



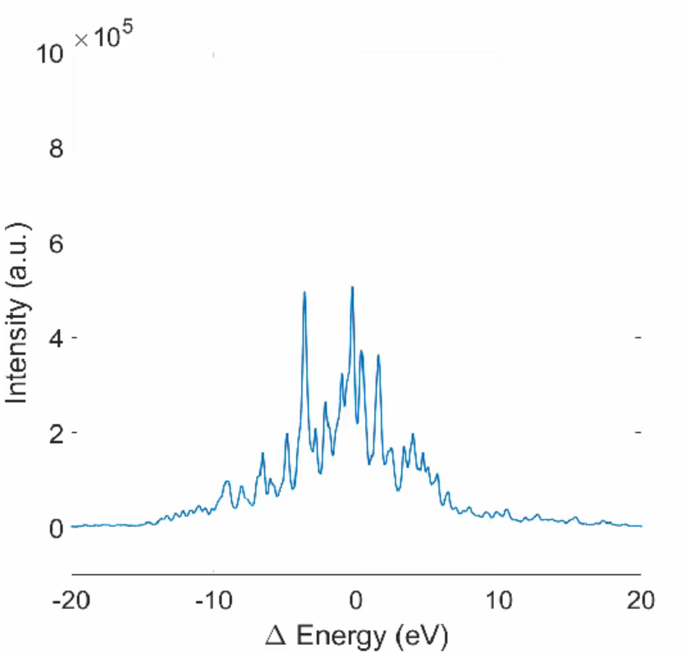
Self-Seeding Test (Aug 13, 2019)

- 200 pC charge, C100 (100um), Crystal plane [1,1,5]

SASE at 9.7 keV (1.1 mJ)

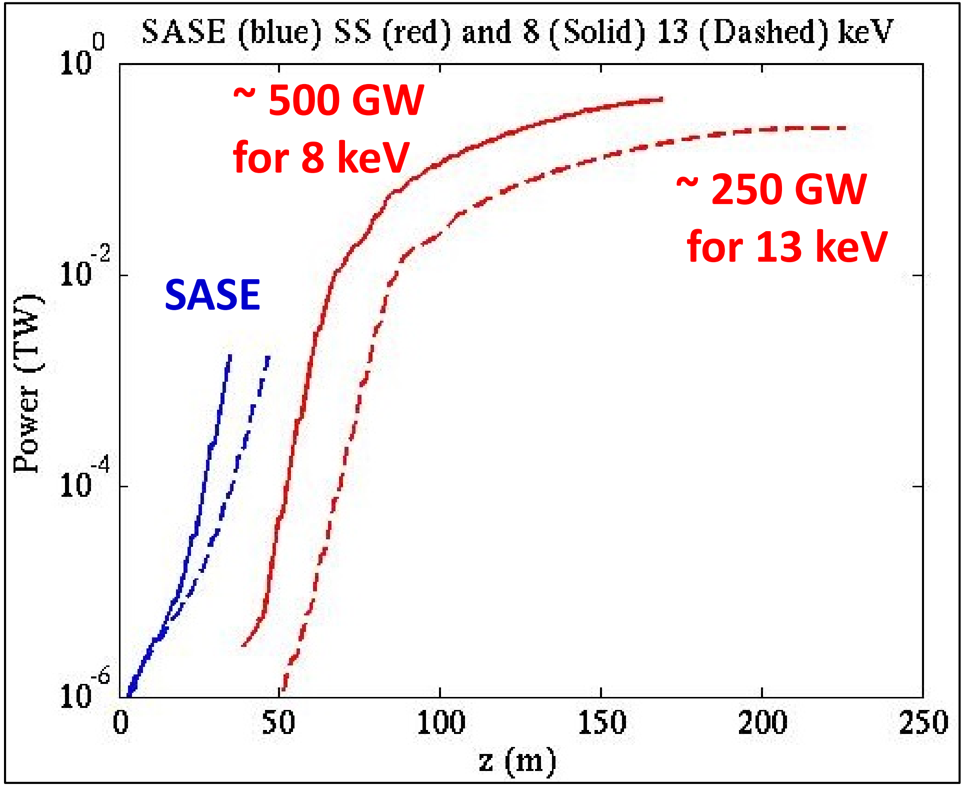


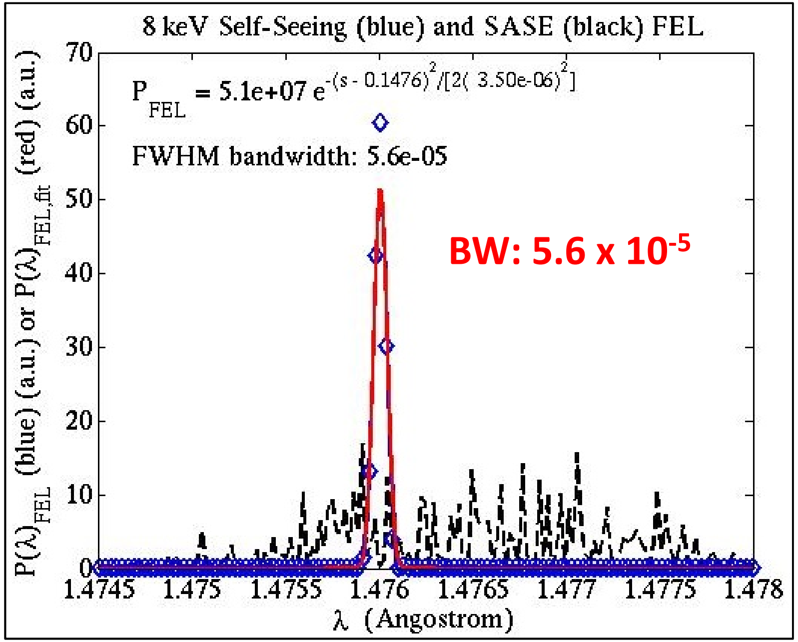
Self-seeding at 9.7 keV (400 uJ)



Motivation of self-seeding, TW single mode FEL

Self-seeding + undulator tapering





Simulation, Ju-Hao Wu(SLAC)

PAL-XFEL Hard X-ray self-seeding(HXSS) collaboration

- ANL
  Yuri Shvyd'ko, Deming Shu, Kwang-Je Kim

- TISNCM
  Vladimir Blank, Sergei Terentyev

- SLAC
  Franz-Josef Decker, Alberto Lutman, Ju-Hao Wu

- DESY
  Svitozar Serkerz, Gianluca Geloni

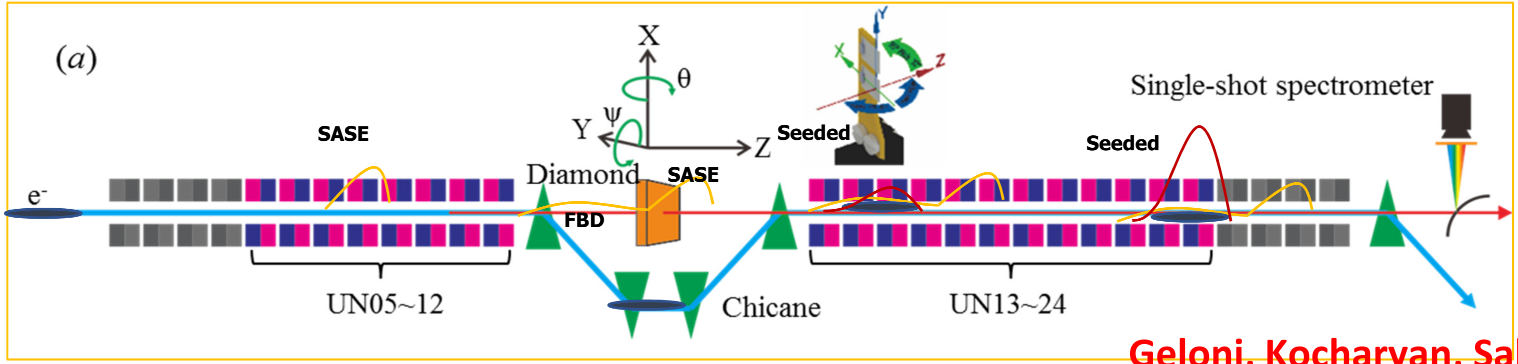
- PAL-XFEL
  Chang-Ki Min, Inhyuk Nam, Haeryong Yang, Gyujin Kim, Chi Hyun Shim, Jun Ho Ko, Hoon Heo, Myunghoon Cho, Bonggi Oh, Young Jin Suh, Min Jae Kim, Donghyun Na, Changbum Kim, Heung-Sik Kang. Beamline support for single-shot spectrometer.

PAL-XFEL HXSS project history

- Collaboration with APS/USA and TISNCM/Russia since 2014
  - Design of Diamond crystal monochromator by APS
  - Diamond crystals fabricated by TISNCM, Russia are checked at APS for its property
  - Engineering design by PAL staff and fabrication by Korean company
  - Feb. 2018: Installation of HXSS
- Commissioning of PAL-XEL HXSS
  - <u>May 2018</u>: Low bunch charge 40 pC for 8.4 keV, crystal offset calibration with undulator radiation
  - <u>Oct. 2018</u>: Nominal bunch charge 180 pC for 7,8. keV, crystal offset calibration with crossing points of self-seeding (Collaboration with LCLS)
  - <u>Nov. 2018</u>: Seeding for 3.5 keV with 30 um crystal and 14.4 keV (Collaboration with LCLS)
  - <u>Aug. 2019</u>: Seeding performance improved with laser heater (After discussion with DESY, SwissXFEL)
  - <u>Late 2019</u>: Test experiments planned

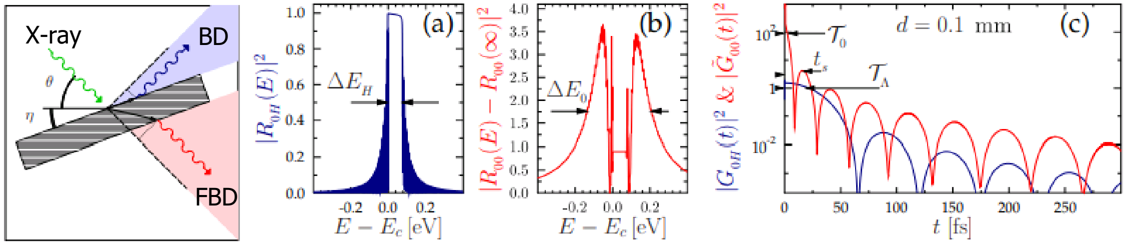
Hard X-ray Self-seeding

- Schematic of hard x-ray self-seeding with a diamond crystal



Geloni, Kocharyan, Saldin (*DESY*)

- Forward Bragg diffraction theory



Bragg diffraction

Actual forward Bragg diffraction

FBD time response

Lindberg, R. & Shvyd'ko, Y. V. Phys. Rev. ST Accel. Beams, **15**, 050706 (2012)

- FBD time response

$$|G_{00}(t)|^2 \propto \left[\frac{1}{2T_0}\frac{J_1\left(\sqrt{\frac{t}{T_0}}\right)}{\sqrt{\frac{t}{T_0}}}\right]^2$$

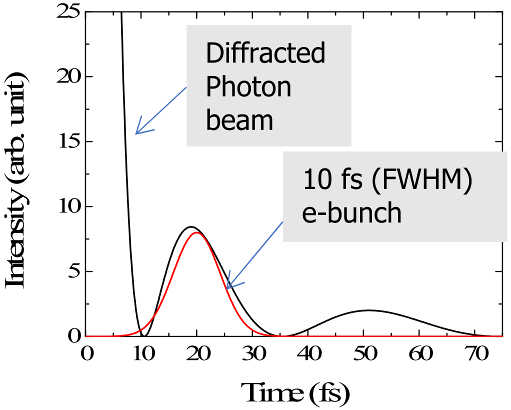
- Characteristic time: $T_0 = 2\Lambda_H^2 \sin\theta \,/(cd)$
- Extinction length: Λ_H
- Maximum of first trailing of the wake:

  $t_s \sim 26\, T_0$
- Duration of the wake: $t_d \sim 16\, T_0$
- Spectral FBD bandwidth: $\Delta E \sim \hbar/(\pi\, T_0)$

Self seeding crystals

Diamond (400) : Photon energy: 7~10 keV

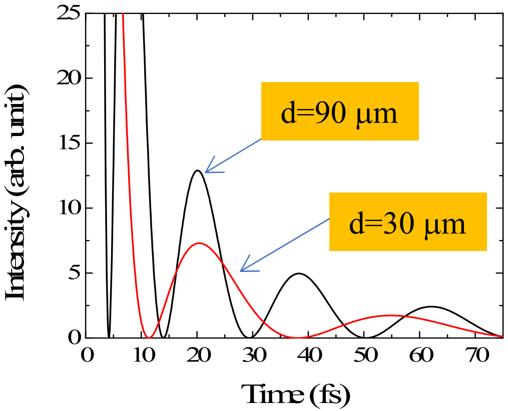
C(400), E_c=8.3 keV, η=0°, θ=56°



100 μm thickness, 2 pieces

Diamond (220) : Photon energy: 5~7 keV

C(220), E_c=5.0 keV, η=0°, θ=79.48°

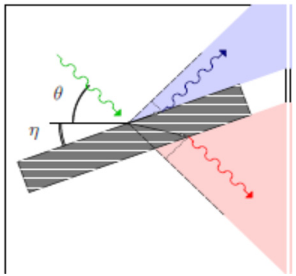


90 μm thickness, 1 piece

30 μm thickness, 1 piece

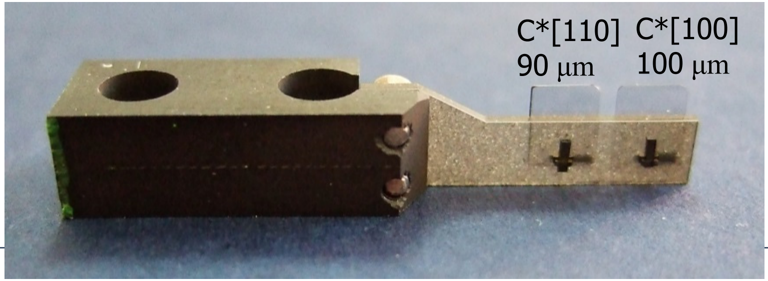
Diamond (111) : energy: 3.3~5 keV

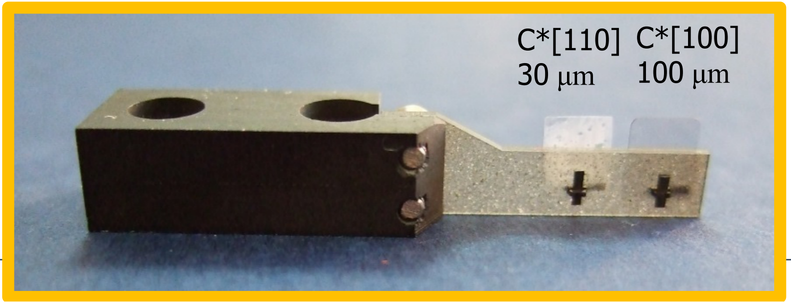
C(111), E_c=3.68 keV, η=35.3°, θ=54.7°



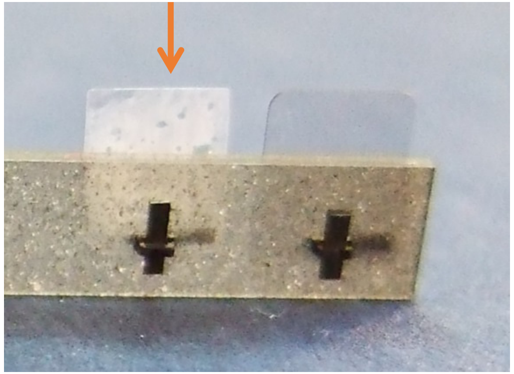
η: asymmetry angle between the crystal surface and the reflecting atomic planes

30 μm thickness

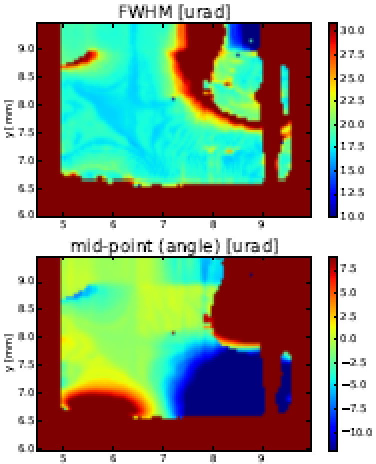




30 µm C*(110) crystal

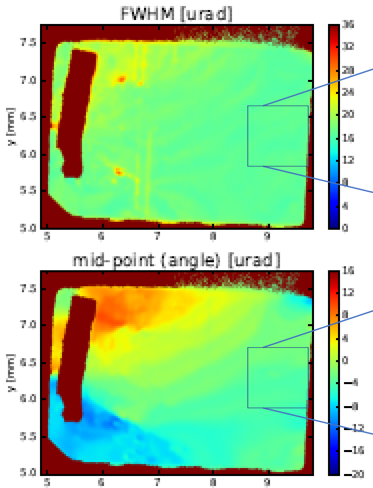


- Color change due to annealing process.
- Crystal quality is as good as other thick crystals
- Mounting strain: < 1.5 µrad (rms) → 0.02 eV rms (seeding condition) in 2 x 2 mm^2

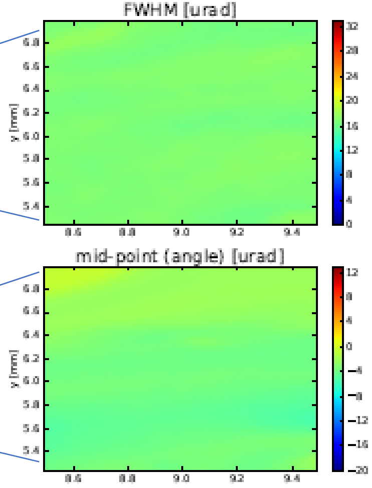


Annealed

Strain removed



Small portion (~ mm)

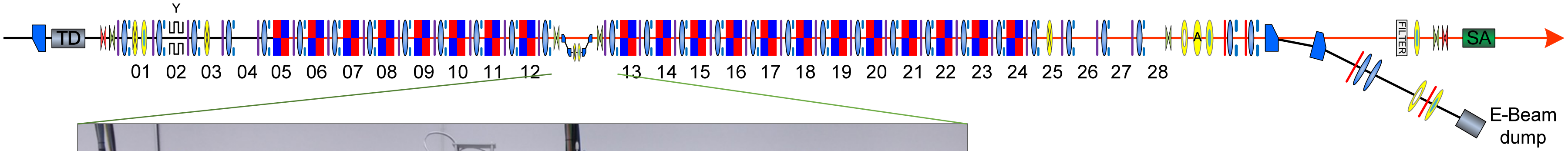


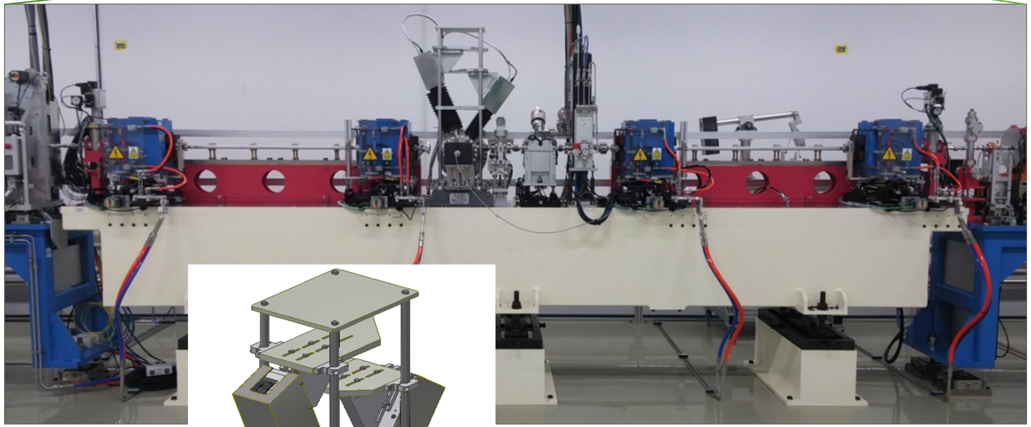
Shvyd'ko, Y. V. (ANL)

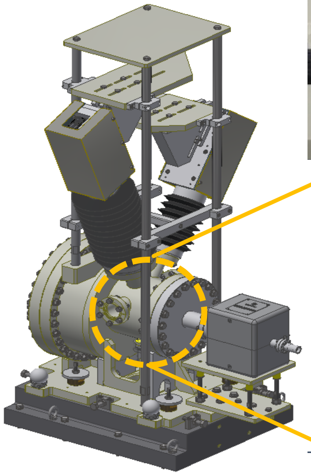
Self seeding system

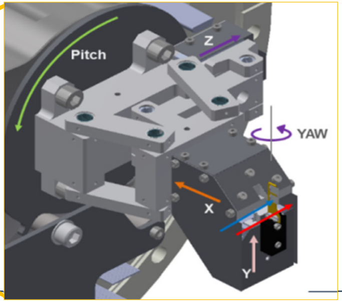
Hard X-ray Undulator (HX1)

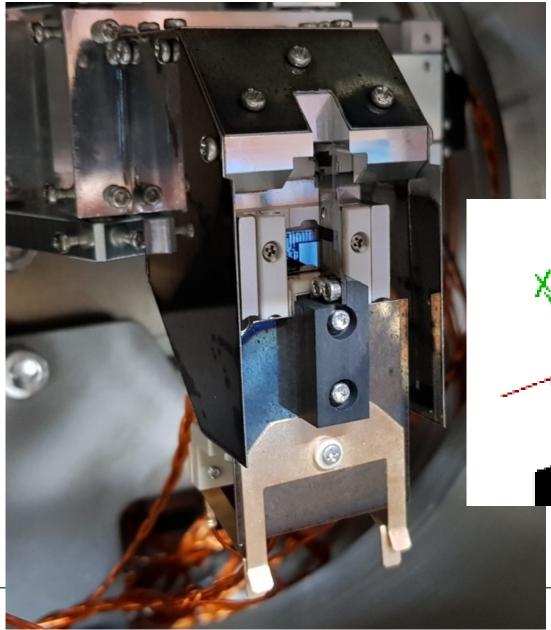
Undulator K = 1.87

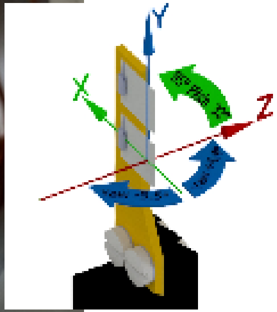




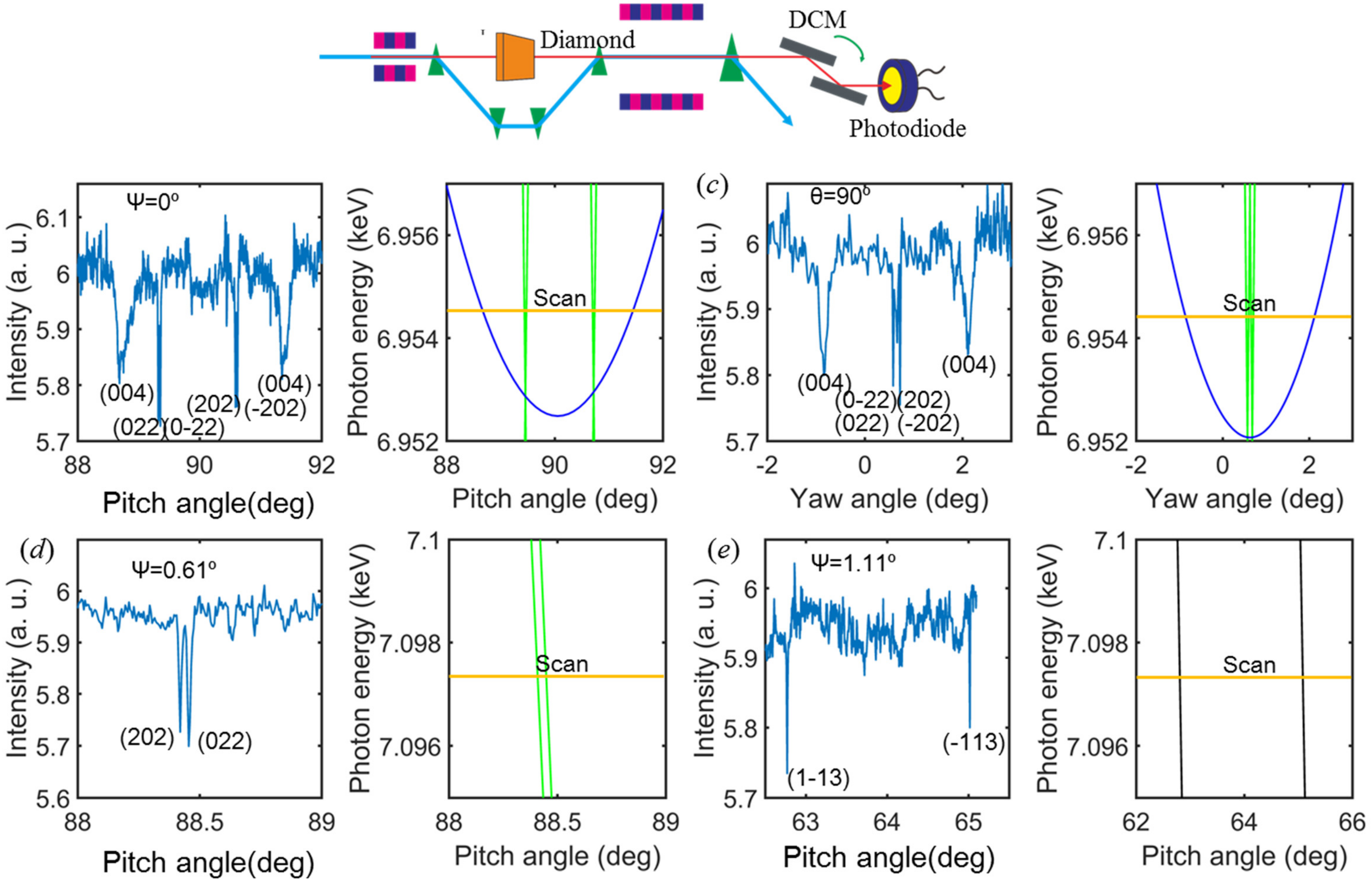




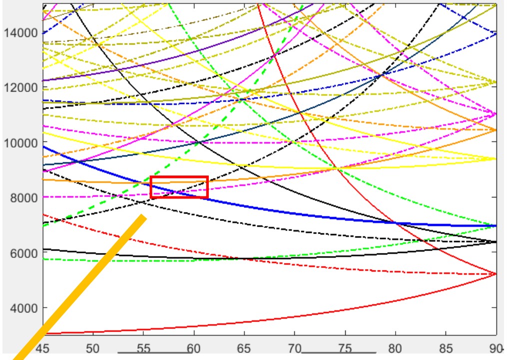




Crystal offset calibration using undulator radiation and DCM

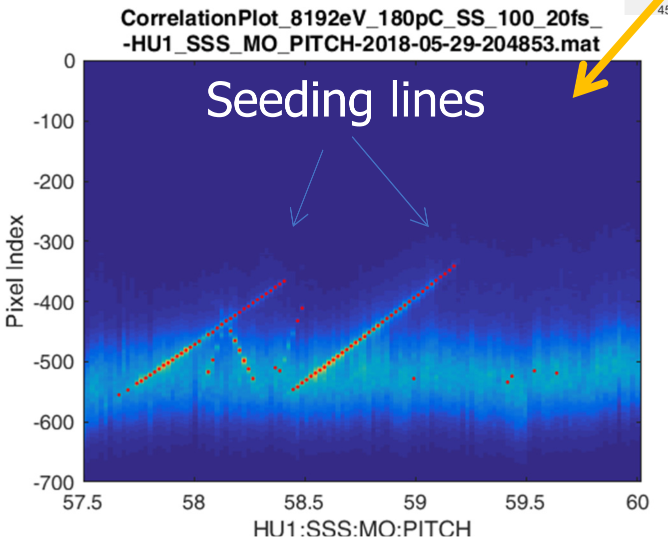


Crystal Calibration (searching lines for seeding, collaboration with LCLS)



Crystal angle offset
and motor axis offset

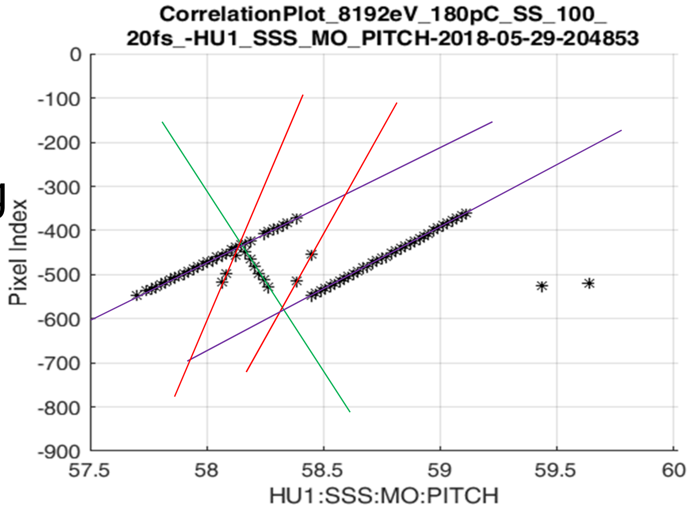
Fit



Photon energy (a.u.)

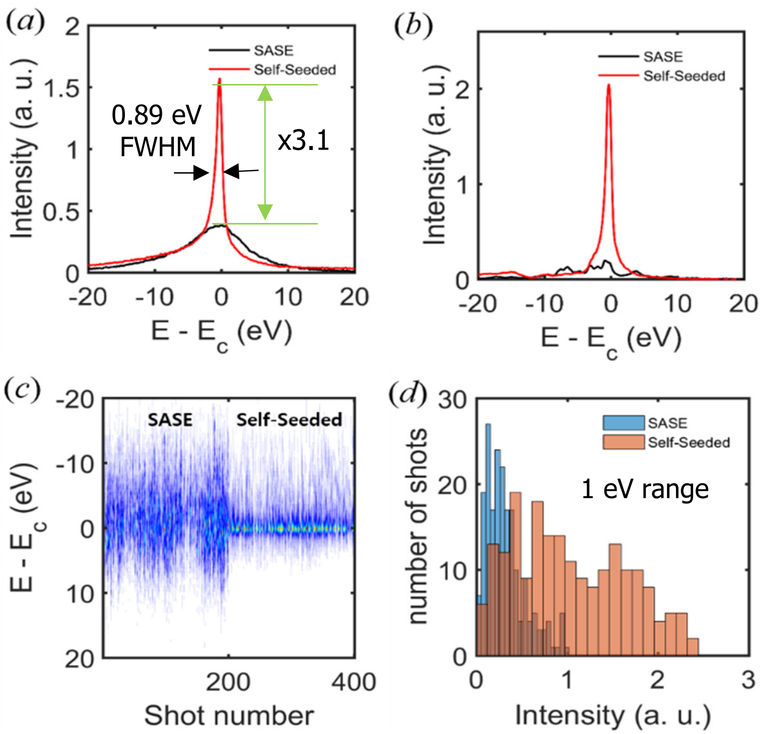
Pitch angle

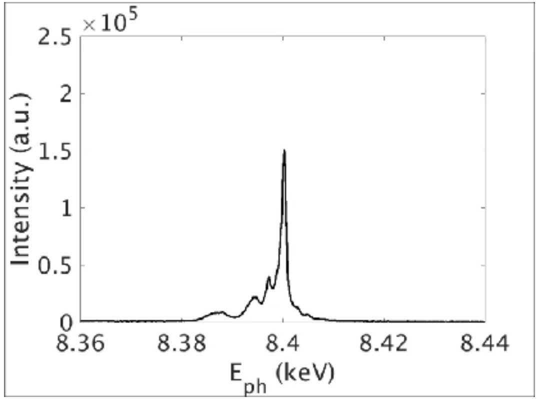
Find
Line crossing



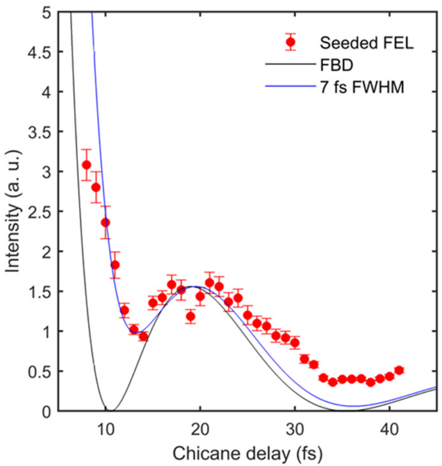
Self-seeding at 40 pC bunch charge

laser heater off, 8 fs delay, 8.3keV





FEL vs time delay

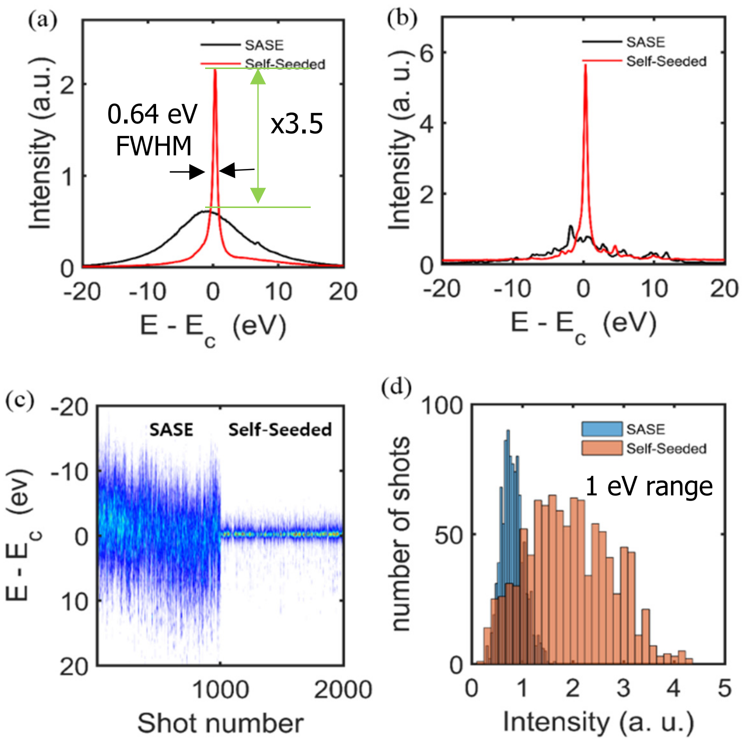


- Beam parameter
  - Charge: 40 pC
  - Peak current: ~2.3 kA
  - Emittance: ~0.3 mm-mrad
- Seeding
  - Pitch angle: 56.9 deg [400]
  - FEL energy: 40 μJ (seeded), 110 μJ (SASE)
  - BW (FWHM): 0.89 eV (seeded), 12 eV (SASE)
    (limited by Si (111) spectrometer resolution of ~0.8 eV)

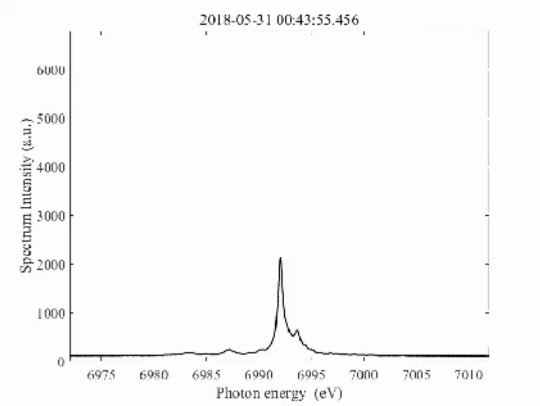
Si(111) single shot spectrometer used

Self-seeding at the nominal (~180 pC) bunch charge

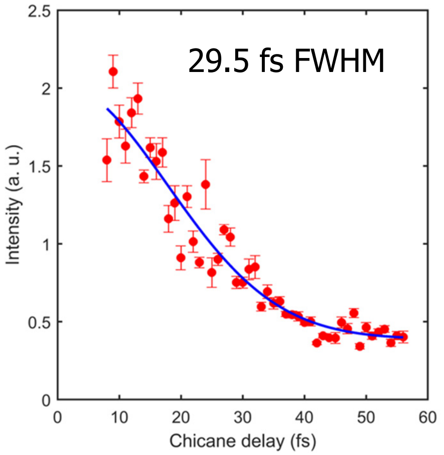
7keV at 60 fs delay



Si(111) single shot spectrometer used



SASE pulse length measurement



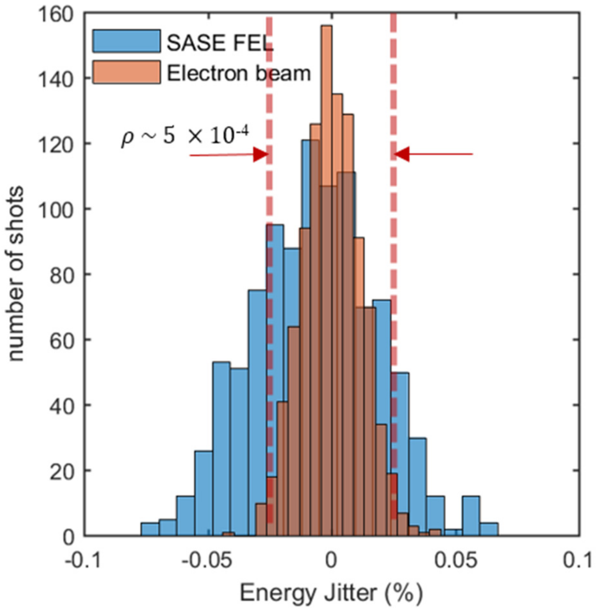
- Beam parameter
  - Charge: ~180 pC
  - Peak current: ~2.5 kA
  - Emittance: ~0.4 mm-mrad

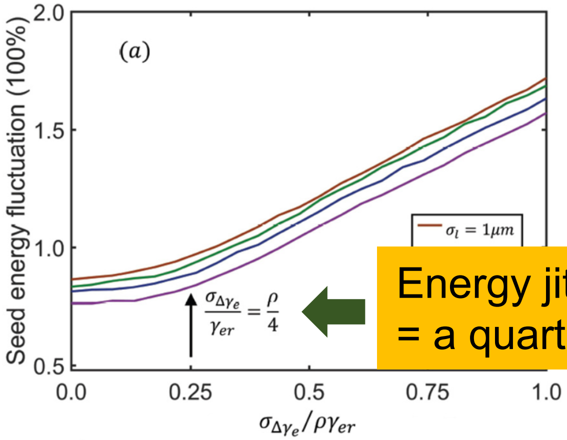
- Seeding
  - Pitch angle: 89.5 deg [400]
  - FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
  - BW (FWHM): 0.64 eV (seeded), 12 eV (SASE)
    (limited by Si (111) spectrometer resolution of ~0.6 eV)

Pulse intensity statistics and energy jitters

Photon and electron energy jitter

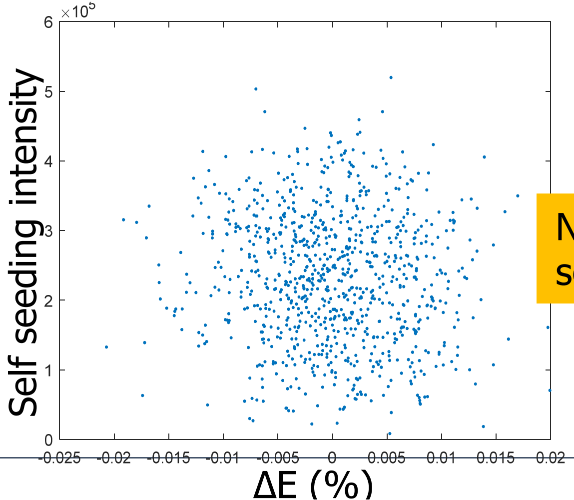
Electron jitter: 0.012% rms
Photon jitter: 0.025% rms





Yang et al. AIP Adv. 9, 035254 (2019)

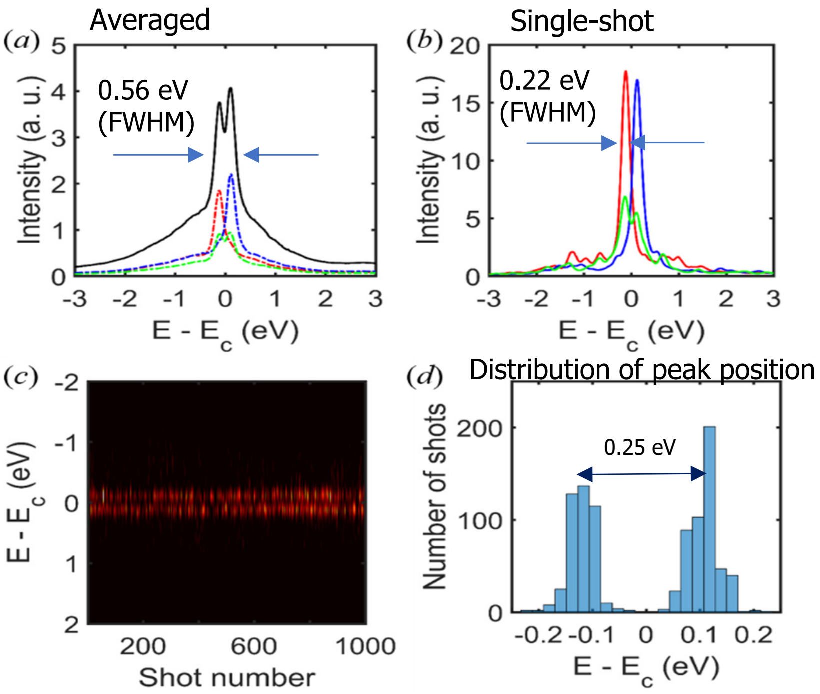
Energy jitter of e⁻ bunch = a quarter of FEL Pierce parameter



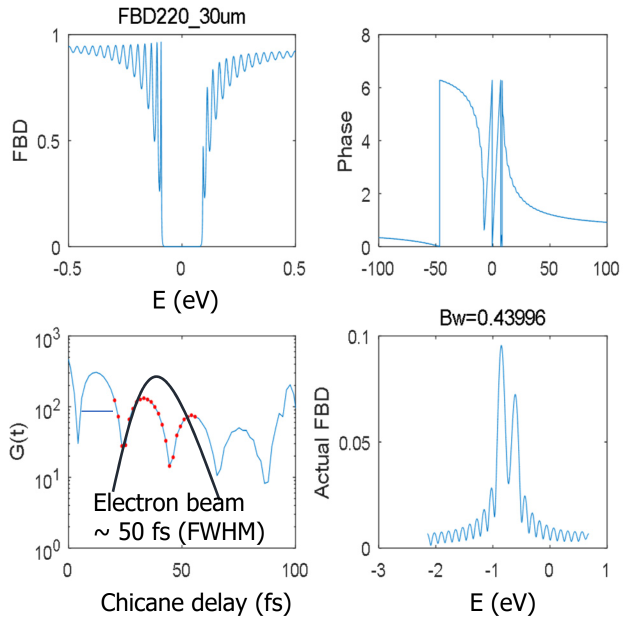
No correlation between seeded FEL and e⁻ energy

Self-seeding using 30 μm diamond crystal and Si(333) spectrometer

8.3 keV θ=36.5° [220] T_0 = 0.5 fs



- FBD Calculation

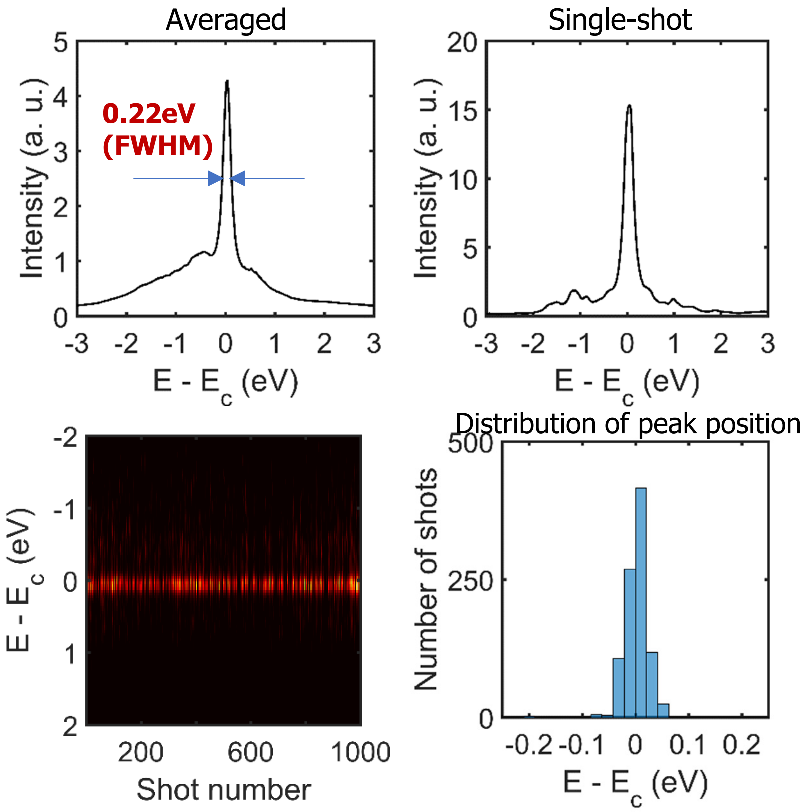


- Double color seeding was observed due to small T_0 , where the electron beam overlapped with many FBD wake trails

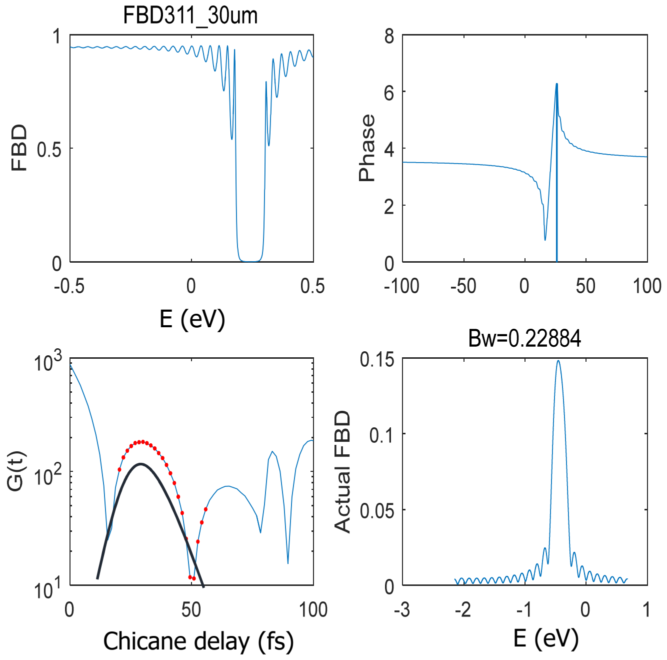
Si(333) single shot spectrometer with a resolution of ~ 0.2 eV

Self-seeding using 30 μm diamond crystal and Si(333) spectrometer

8.3 keV θ=43.9° [331] ***T_0* = 2.17 fs**

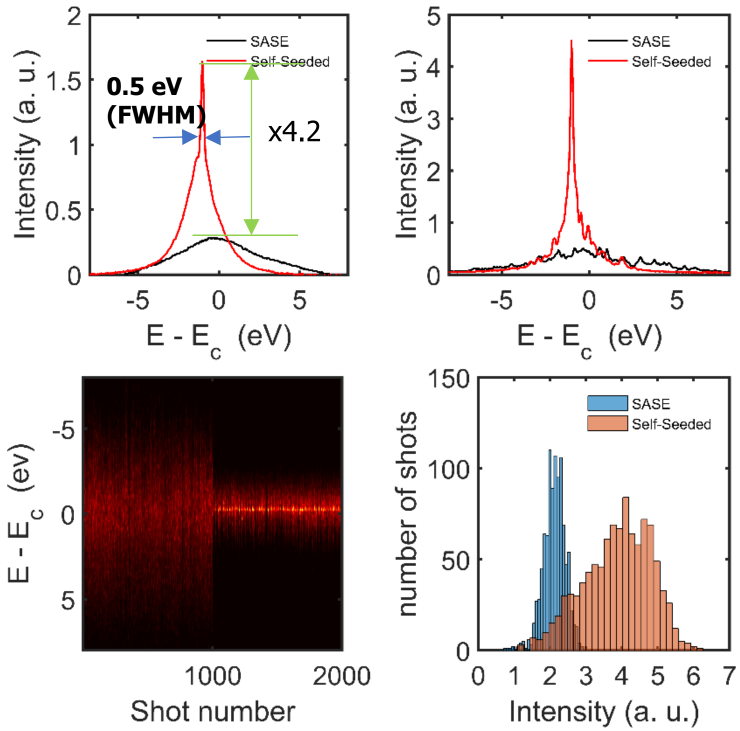


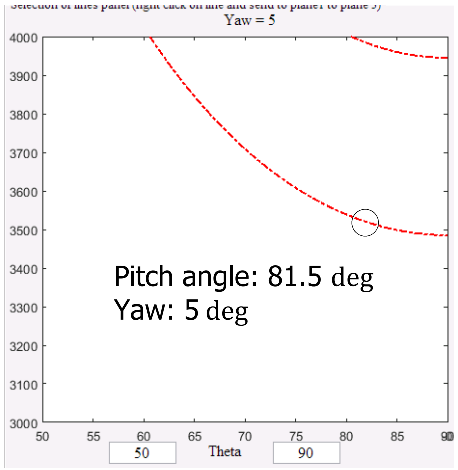
- FBD Calculation



Electron beam
~ 50 fs (FWHM)

Seeding at 3.5 keV with 30 μm crystal



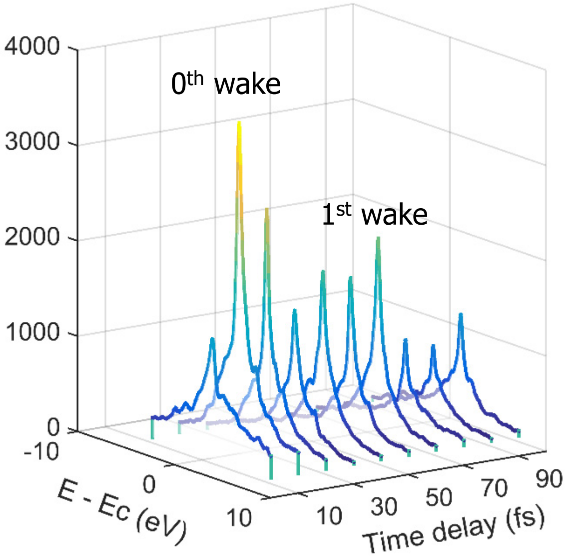


- Seeding
  - Seeding: 7 unds, Amplification: 12 unds
  - Pitch angle: 89.5 deg [11-1]
  - FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
  - BW (FWHM): 0.5 eV (seeded), 6.5 eV (SASE)

- Large SASE background exist due to electron energy chirp.
- Further optimization needed to decrease this SASE background

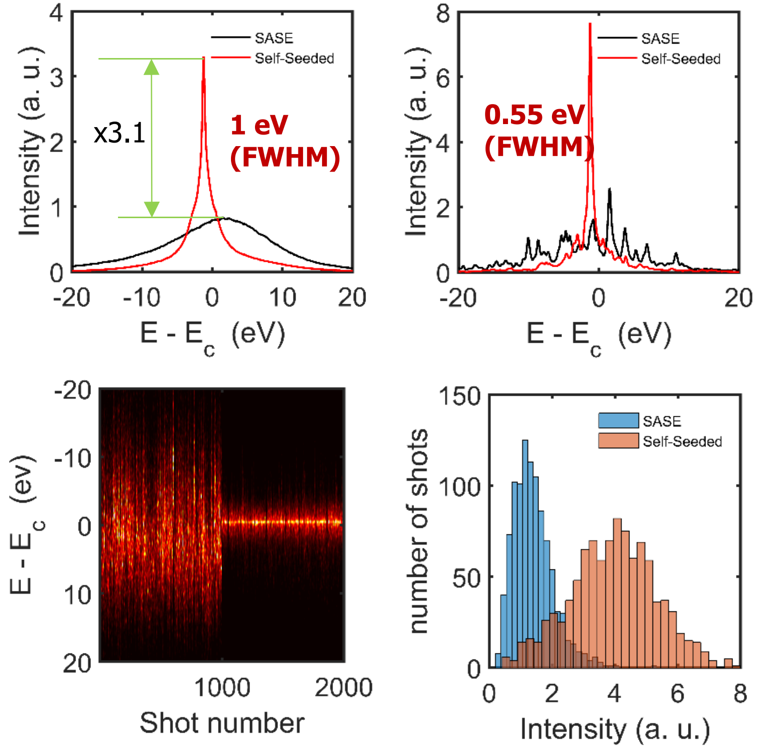
Seeding at 14.4 keV 100 μm crystal

- Seeding conditions
  - [hkl] = [440]
  - Pitch angle = 46.63 deg
  - $\Lambda_H = 6.41$
  - $T_0 = 1.8716$ fs
  - $\Delta E = 0.1$ eV
  - $t_s \sim 50$ fs
  - $t_d \sim 30$ fs



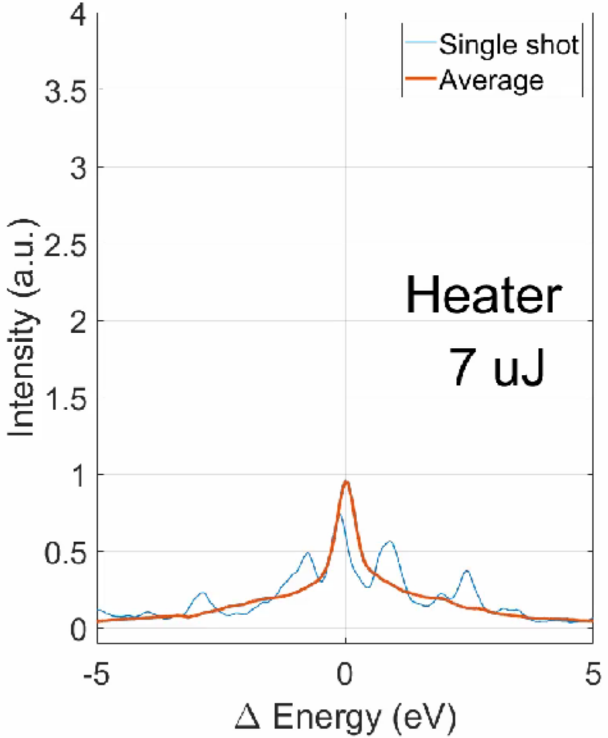
- Seeding results
- Time delay: 25 fs (0th wake of FBD)
  - FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
  - BW (FWHM): 1 eV (Averaged) / 0.55 eV (single-shot) (seeded),

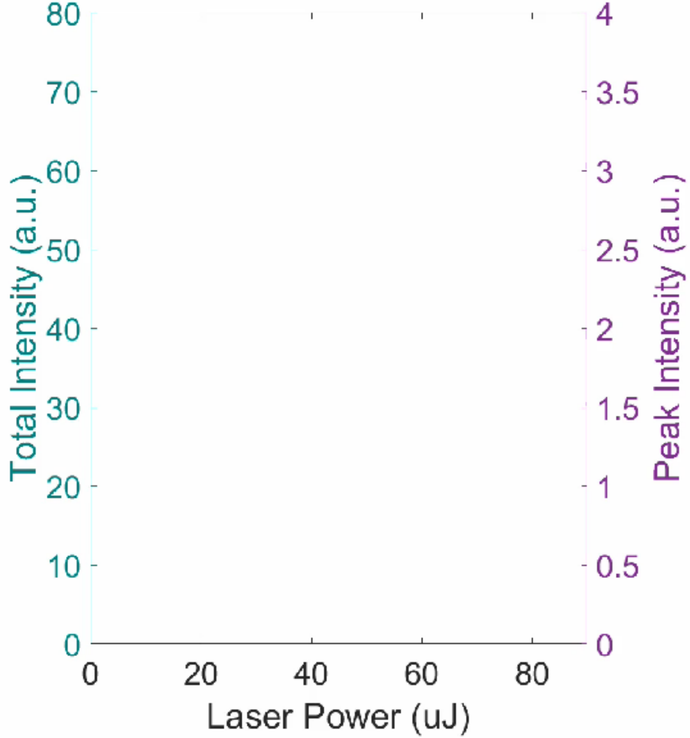
    18 eV (SASE)



Improved Seeding with laser heater

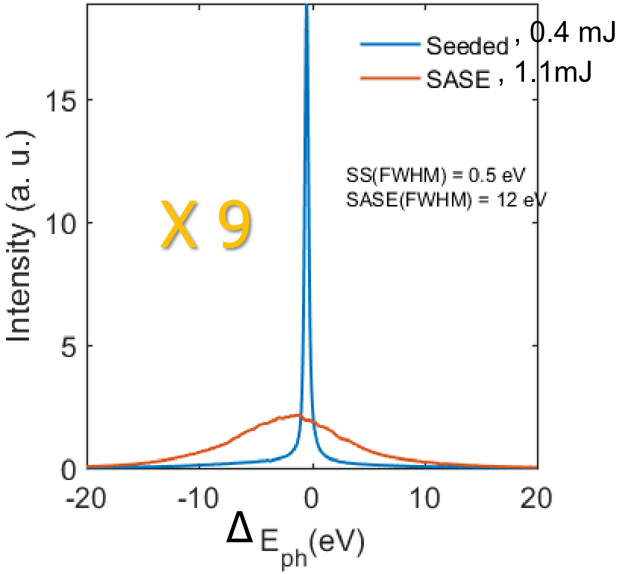
- 200 pC charge, C100 (100um), Crystal plane [1,1,5], 30 fs delay

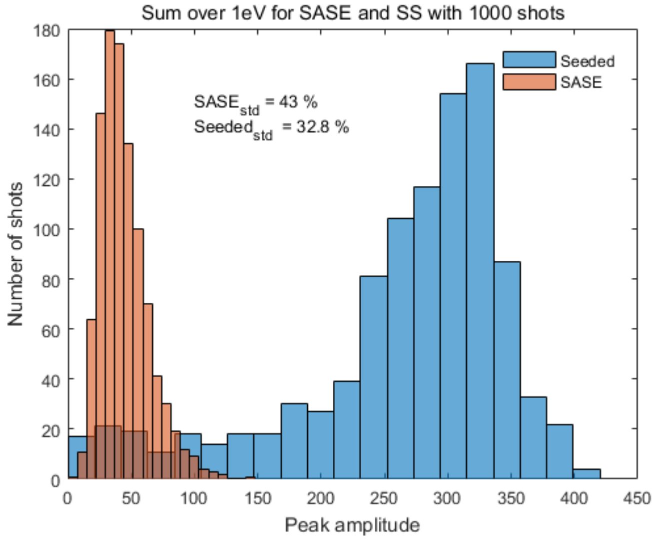




Improved Seeding with laser heater

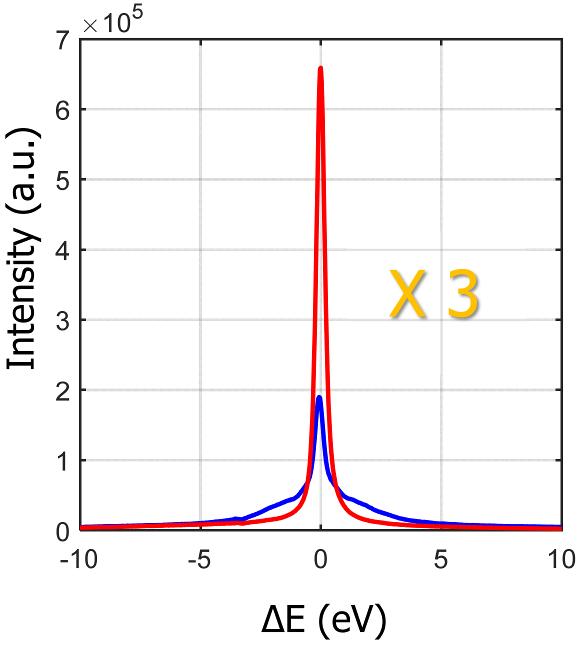
- 200 pC charge, C100 (100um), Crystal plane [1,1,5], T_0= 3.8 fs



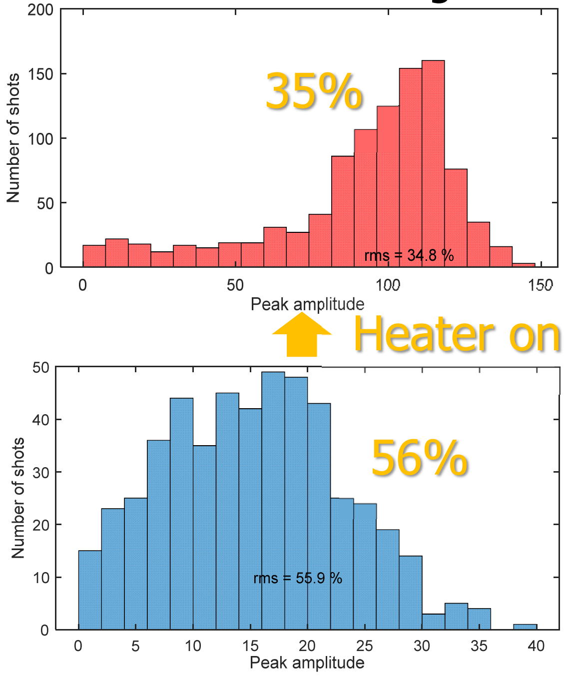


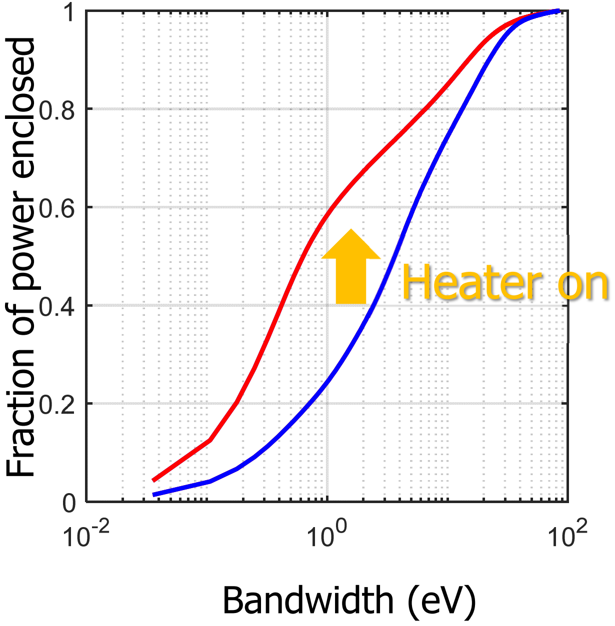
- Using self-seeding, the peak intensity is increased by ~9 times.
  (Sum over 1eV bandwidth is increased by ~6 times.)
- Shot-to-shot intensity fluctuation is improved from 43% RMS in SASE to 33% RMS in self-seeding.
- Pulsewidth 15 fs FWHM -> 3.6 fs FWHM (if transform limited, ΔνΔτ = 0.441)

Improved Seeding with laser heater



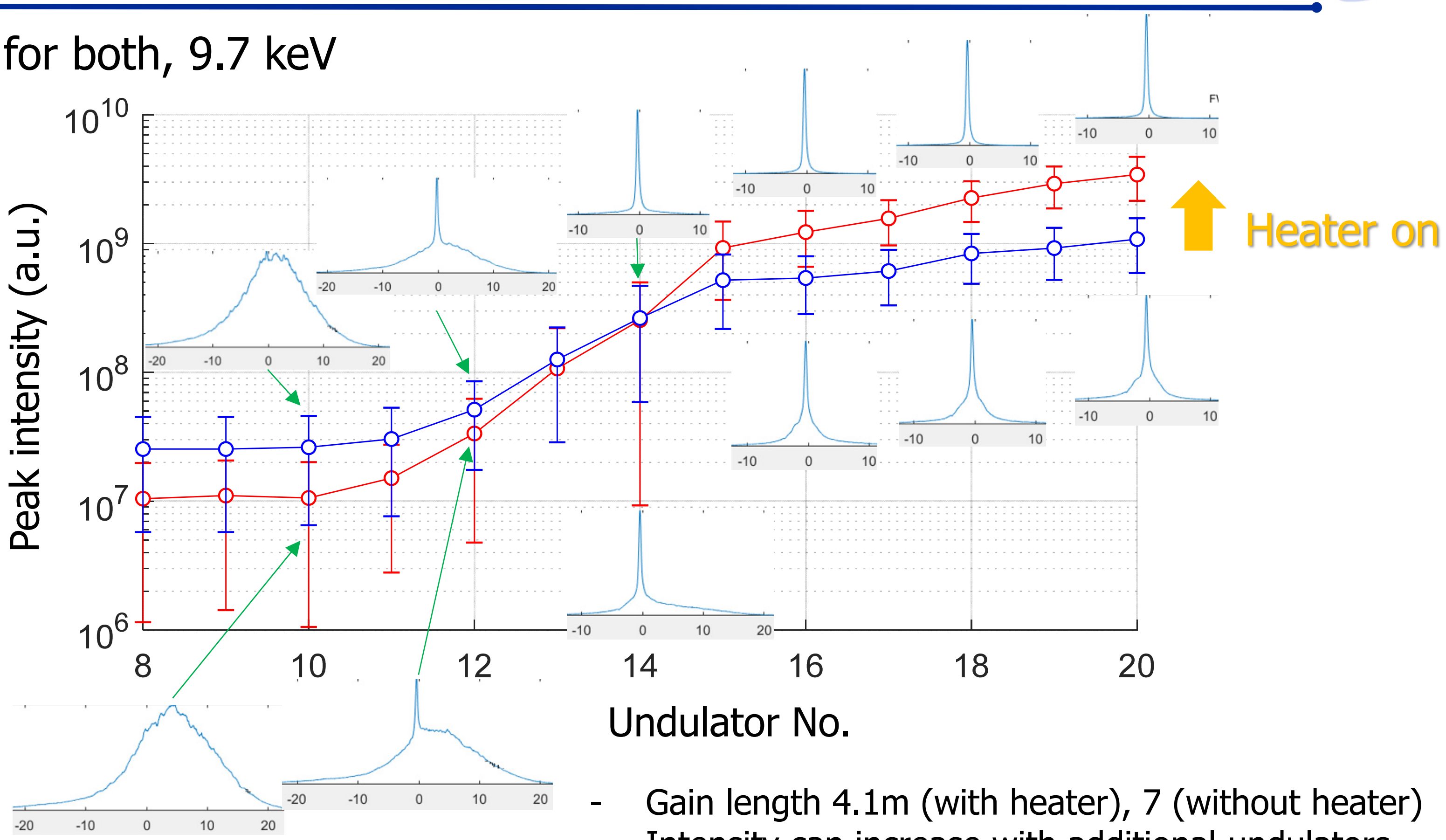
1 eV bandwidth histogram





Improved Seeding with laser heater, Gain curve

~400 μJ for both, 9.7 keV



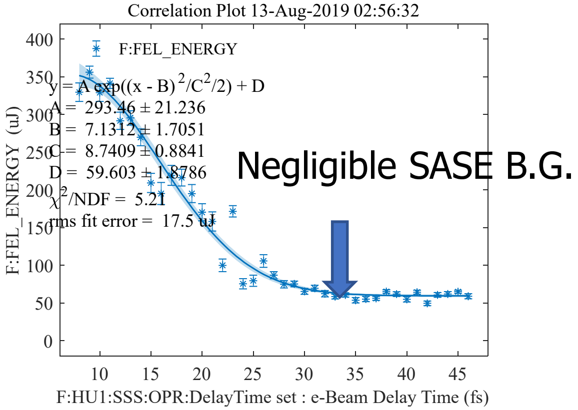
- Gain length 4.1m (with heater), 7 (without heater)
- Intensity can increase with additional undulators.

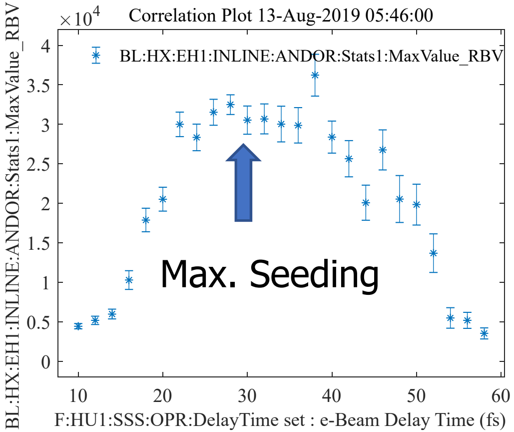
Self-Seeding Optimization, ~ 1 hour

- Setup singleshot spec.
- Spectral overlap of two undulator regime
- Finding seeding lines
- Set a delay time
- Tapering & phaseshifter opt.

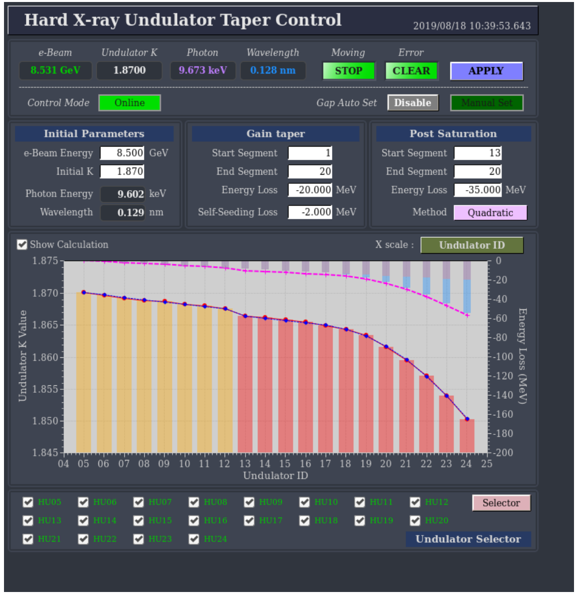
No RF phase tuning
From opt. SASE config.

Delay time





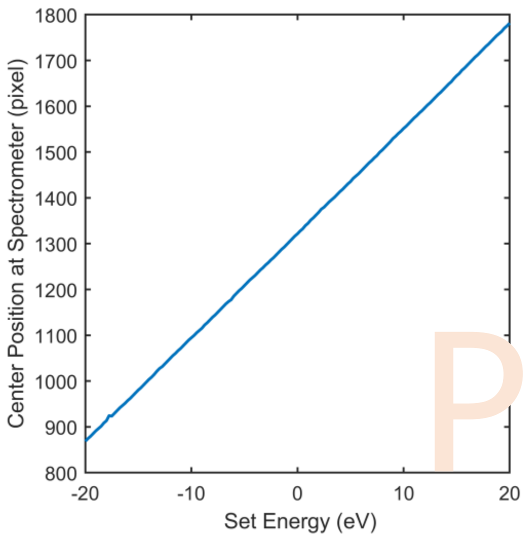
Tapering

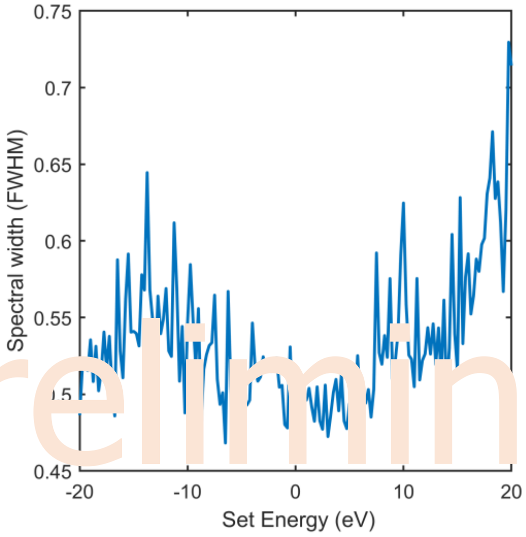


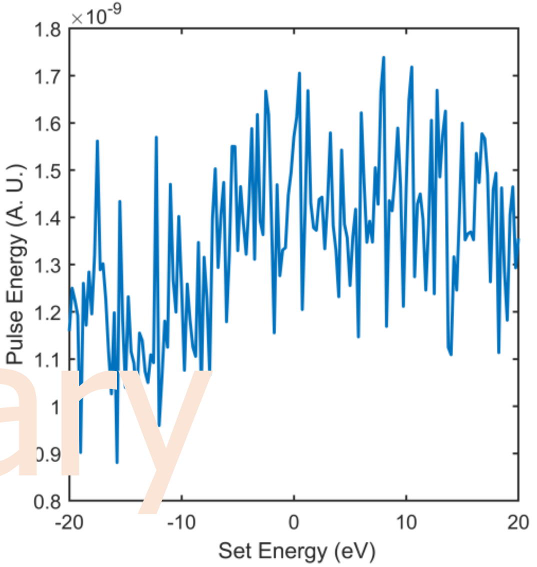
- 15 fs FWHM at 4 kA peak current
- Zeroth trailing regime for large T_0

For user experiment

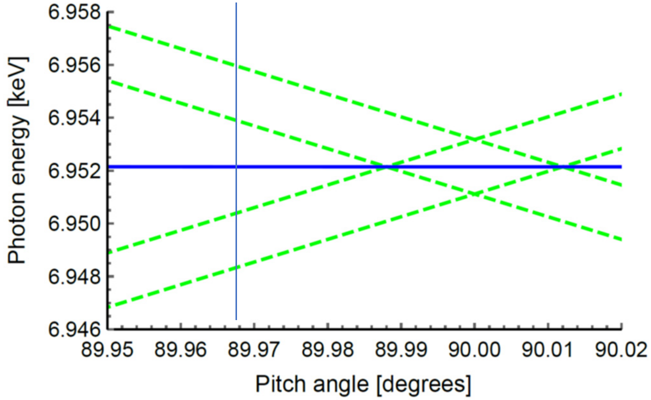
- Fast switch between SASE and seeding mode, <1 hour
- Energy scanning capability test
  - Step scan : 9700±20 eV with ~0.2 eV step size
  - Measured by Si(333) single shot spectrometer







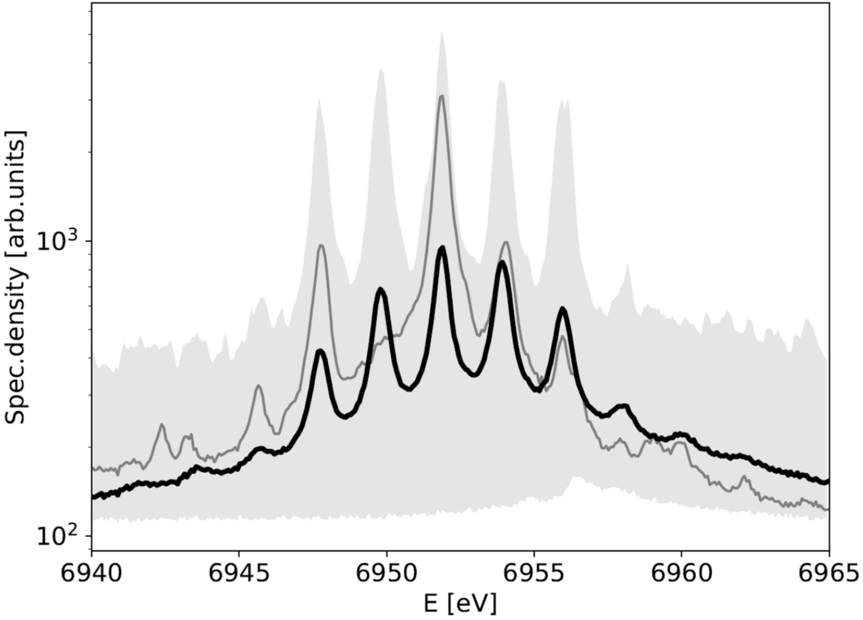
Attosecond pulse trains using self-seeding



GENERATING TRAINS OF ATTOSECOND PULSES WITH A FREE-ELECTRON LASER

Svitozar Serkez et al. THP051

Non-linear intermodulation yields satellites – "beat waves"



Summary

Current Status

- PAL-XFEL HXSS is successfully installed and has been commissioned with electron energy jitter of ≈10^{-4} rms
- Two seeding modes are commissioned [Low charge (40 pC, ~7 fs), nominal change (180pC, ~29.5 fs)].
- Lowest (3.5 keV) and highest (14.4 keV) self-seeding was demonstrated.
- Laser heater improve the intensity stability, spectral purity and brightness (x9 compared to SASE) of seeded FEL
- User- service is ready (DCM is not necessary with minimal side bands)

Future & Improvement plans

- Finding applications and test experiments
- Test at low photon energy with laser heater (and higher heater power)