XFEL Performance achieved at PAL-XFEL

H.S. Lee
On Behalf of PAL-XFEL

Pohang Accelerator Laboratory

Location of PAL-XFEL


PAL-XFEL
0.1 nm hard X-ray FEL using a 10 GeV normal conducting linac
Apr. 2011: PAL-XFEL project started
Jun. 2012: Ground-breaking
Dec. 2014: Building completed
Jan. 2016: Installation completed
Apr. 2016: Commissioning started
Jun. 2017: User-service started
PAL-XFEL
Profile Monitor HU1E:SCM36 16-Mar-2017 20:40:0
0.1 nm
y (mm)
x (mm)
◆ 14 Jun. 2016 First SASE lasing at 0.5 nm
◆ 28 Oct. 2016 Lasing at 0.15 nm
◆ 27 Nov. 2016 Saturation of 0.15 nm
◆ 16 Mar. 2017 Saturation of 0.1 nm

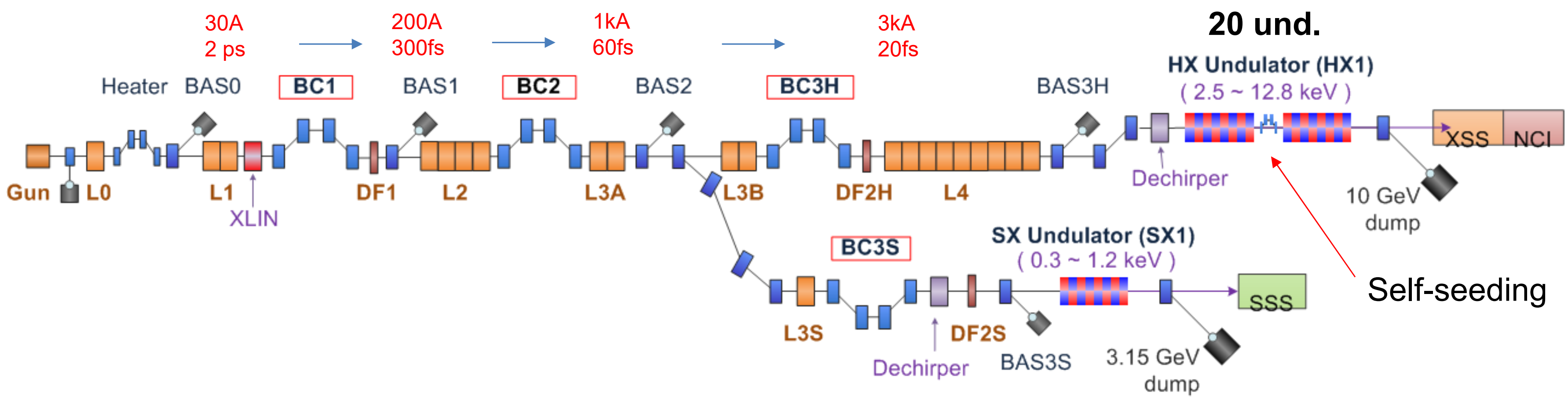
Outline

- Status of PAL-XFEL
  - Parameters
  - Commissioning results
- Performance of PAL-XFEL
  - FEL optimization
  - FEL stability
  - 20 fs timing jitter
- Self-seeding
- Summary

Brief Timeline

• April 2011	PAL-XFEL project started
• Sep. 2012	Construction started
• Jan. 2015	Building completed
• Dec. 2015	Installation completed
• April 12, 2016	Commissioning started
• June 14, 2016	First SASE lasing at 0.5 nm
• Oct. 28, 2016	Lasing at 0.15 nm
• Nov. 27, 2016	Saturation of 0.15 nm (project completed)
• March 16, 2017	Saturation of 0.1 nm (design goal achieved)
• June 7, 2017	First User Service
• May 30, 2018	Self-Seeding Test
• Nov. 2018	Permission granted to operate up to 11 GeV
• Mar. 2019	60 Hz operation started

PAL-XFEL Parameters



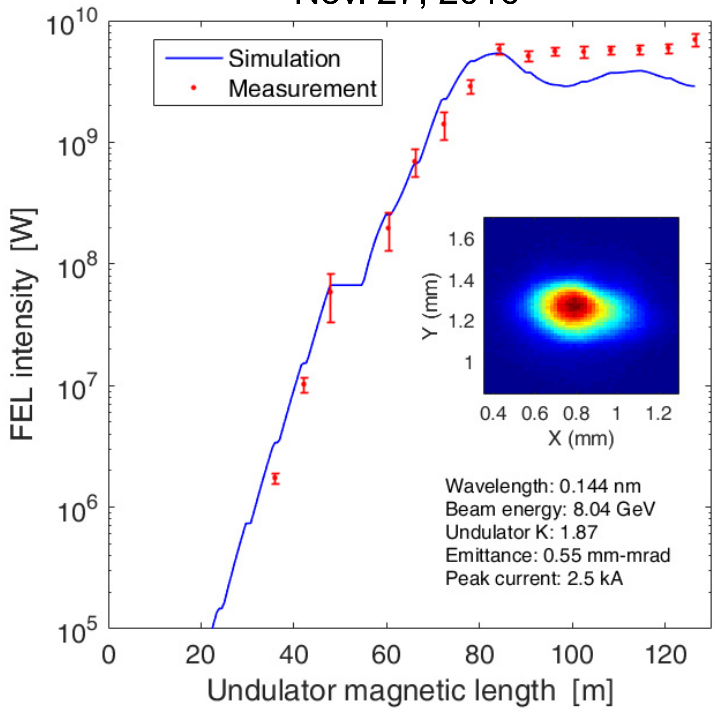
Main parameters

e^- Energy	11 GeV
e^- Bunch charge	20-200 pC
Slice emittance	< 0.4 mm mrad
Repetition rate	60 Hz
Pulse duration	5 fs – 50 fs
Peak current	3 kA
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, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

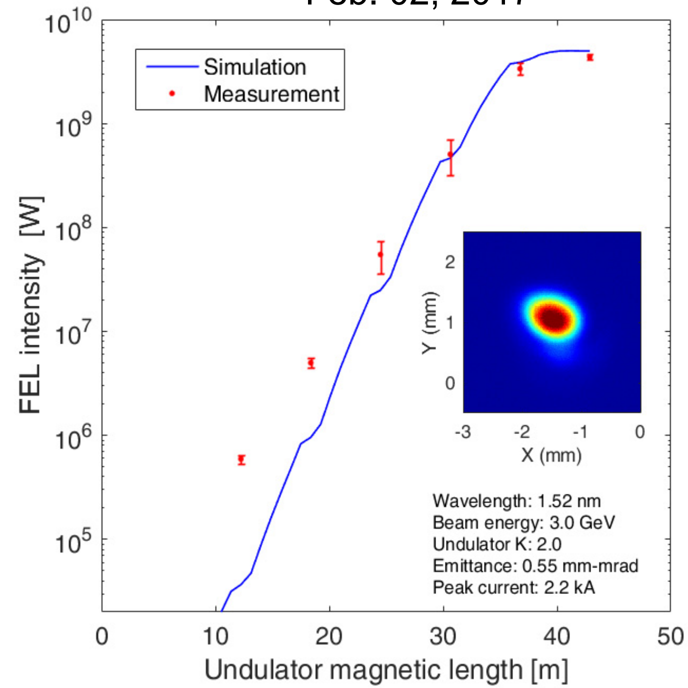
Saturation Curve

Nov. 27, 2016



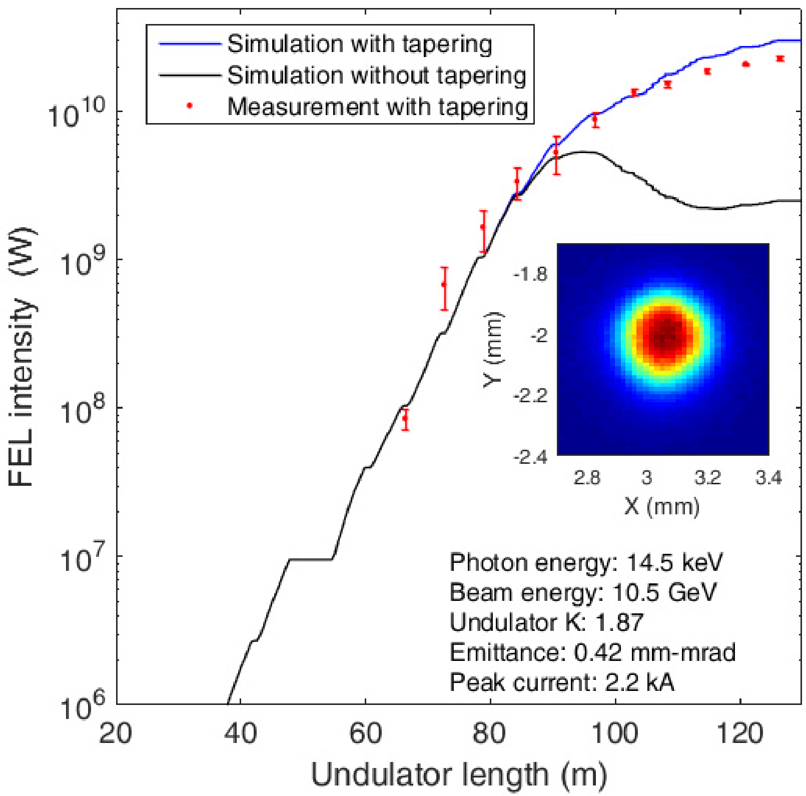
Hard X-ray

Feb. 02, 2017

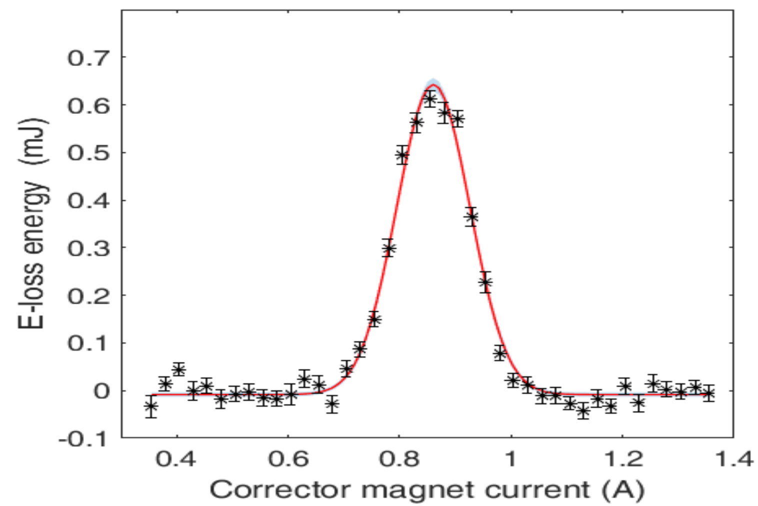


Soft X-ray

Saturation of 14.5 keV FEL (Nov. 07, 2017)



- E-beam: 10.5 GeV
- FEL beam energy: 0.65 mJ
  = 2.8 E+11 photons/pulse



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FEL Optimization Procedure

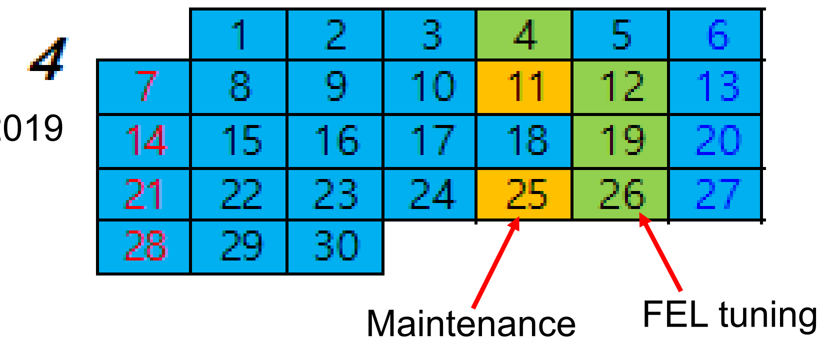
1. **e-Beam based alignment** in undulator section (2 hours)
2. **Undulator offset tuning** (15 min. for 20 undulators)
   : to find the undulator field mid-plane
3. **Undulator gap tuning** (25 min. for 20 undulators)
   : to find the gap distance for the same undulator K

Un-compressed e-beam

4. **Lattice matching**
5. **Phase-shifter gap tuning** (15 min. for 20 undulators)
   : phase matching between two undulators
6. Undulator tapering

compressed e-beam

April of 2019

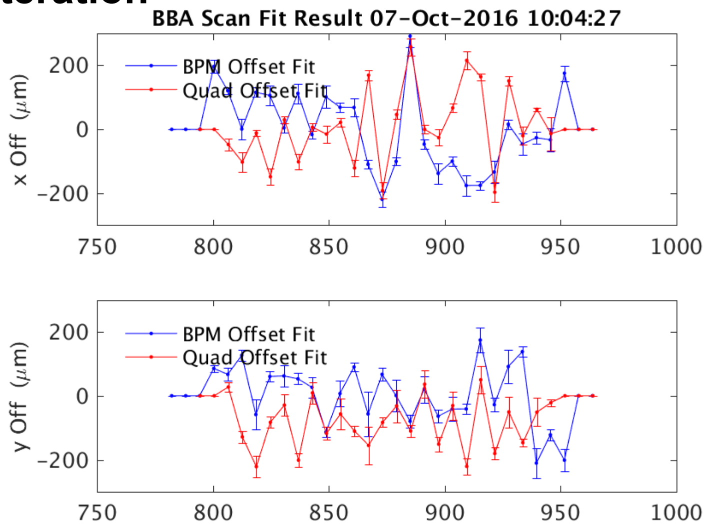


We do this procedure every week

Undulator BBA

- Same BBA algorithm as LCLS
- e-BBA is to find BPM and Quad offsets on straight line
  1) Beam positions are measured at four different beam energy: 4.0, 5.0, 6.6 and 10 GeV
  2) Calculate the BPM and Quad offsets for dispersion free, and apply them to the BPM's BBA offset and quad mover offset, respectively.
  - Repeat 1) & 2) until the calculated BPM offsets are smaller than 5 um
- **It takes about 10 minutes for one iteration**. At least 7 or 8 iterations are required.

1-st iteration



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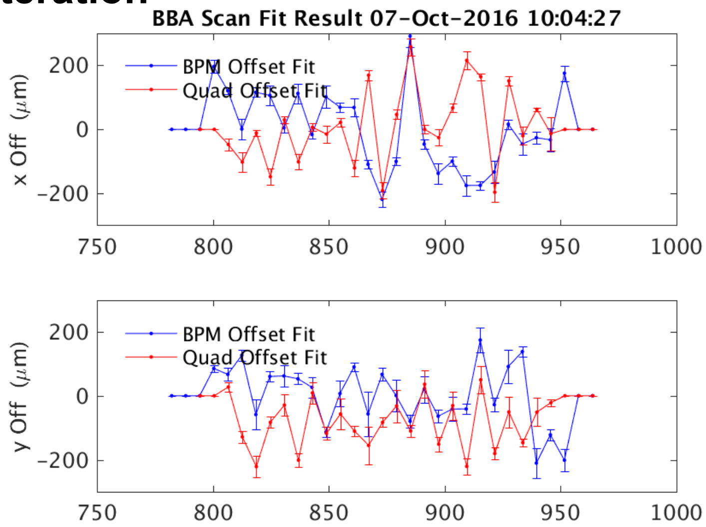
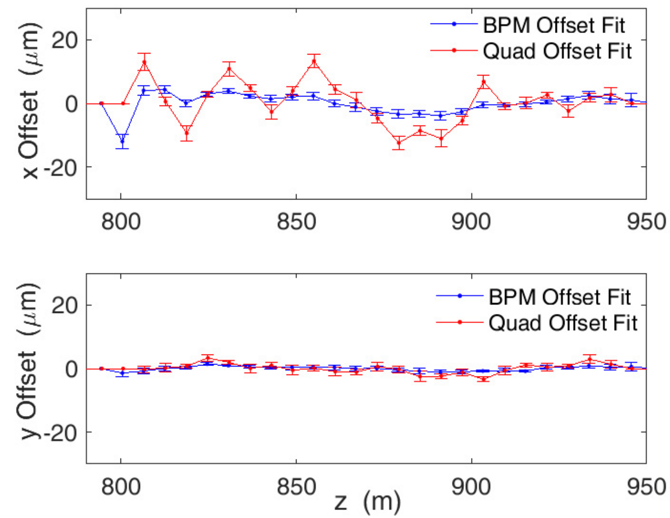
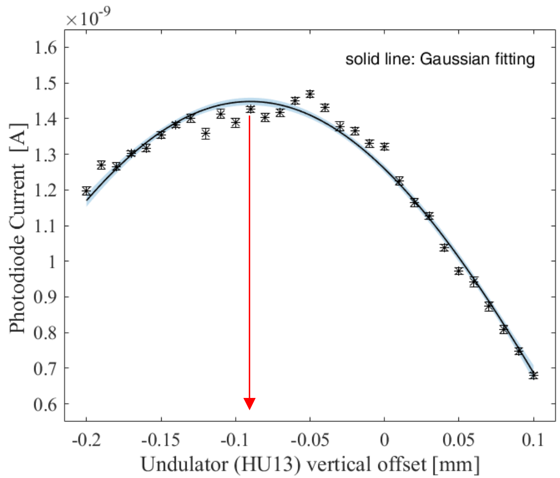


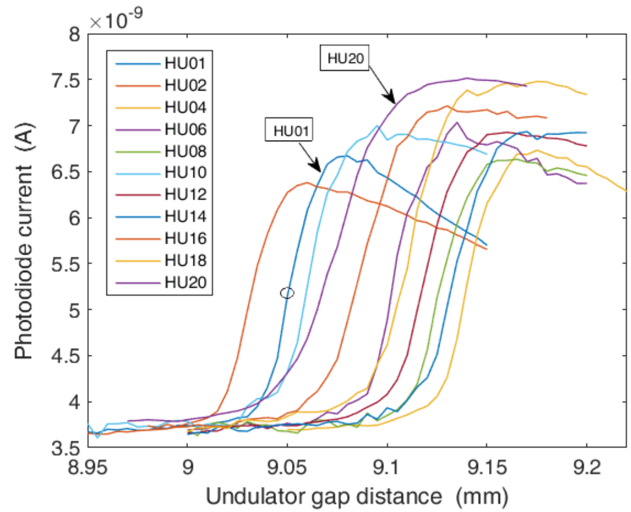
8-th iteration



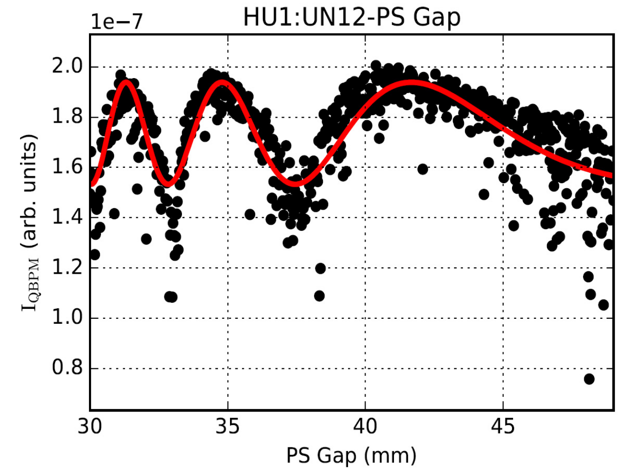
Undulator Offset Tuning
(for undulator field mid-plane)



Undulator Gap Tuning
(gap distance for the same undulator K)



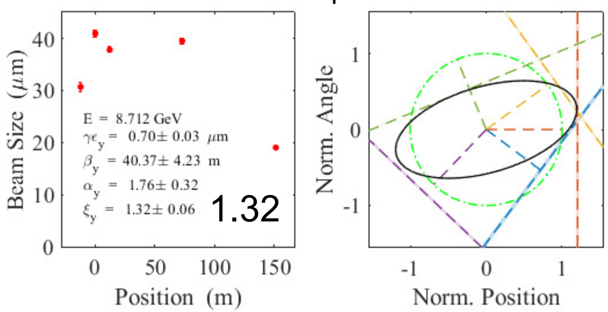
Phase-shifter Gap Tuning
(phase matching between two undulators)



Undulator Lattice Matching

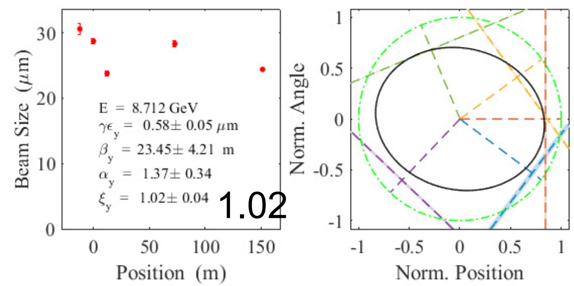
before

Ver. plane



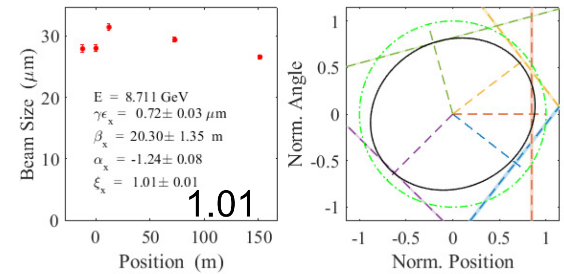
after

Ver. plane

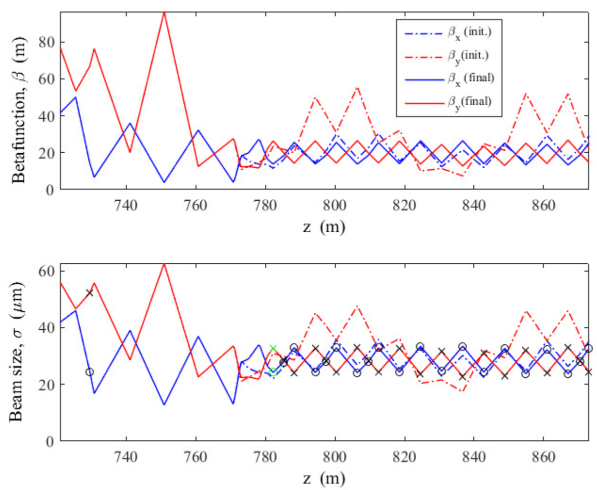


y-Emittance: 0.58

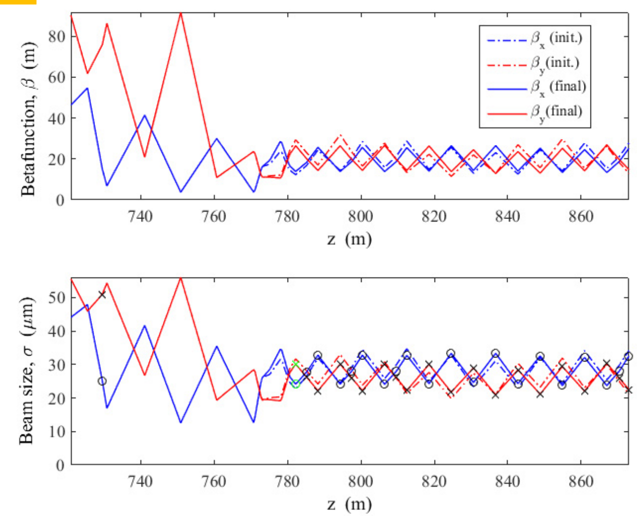
Hor. plane



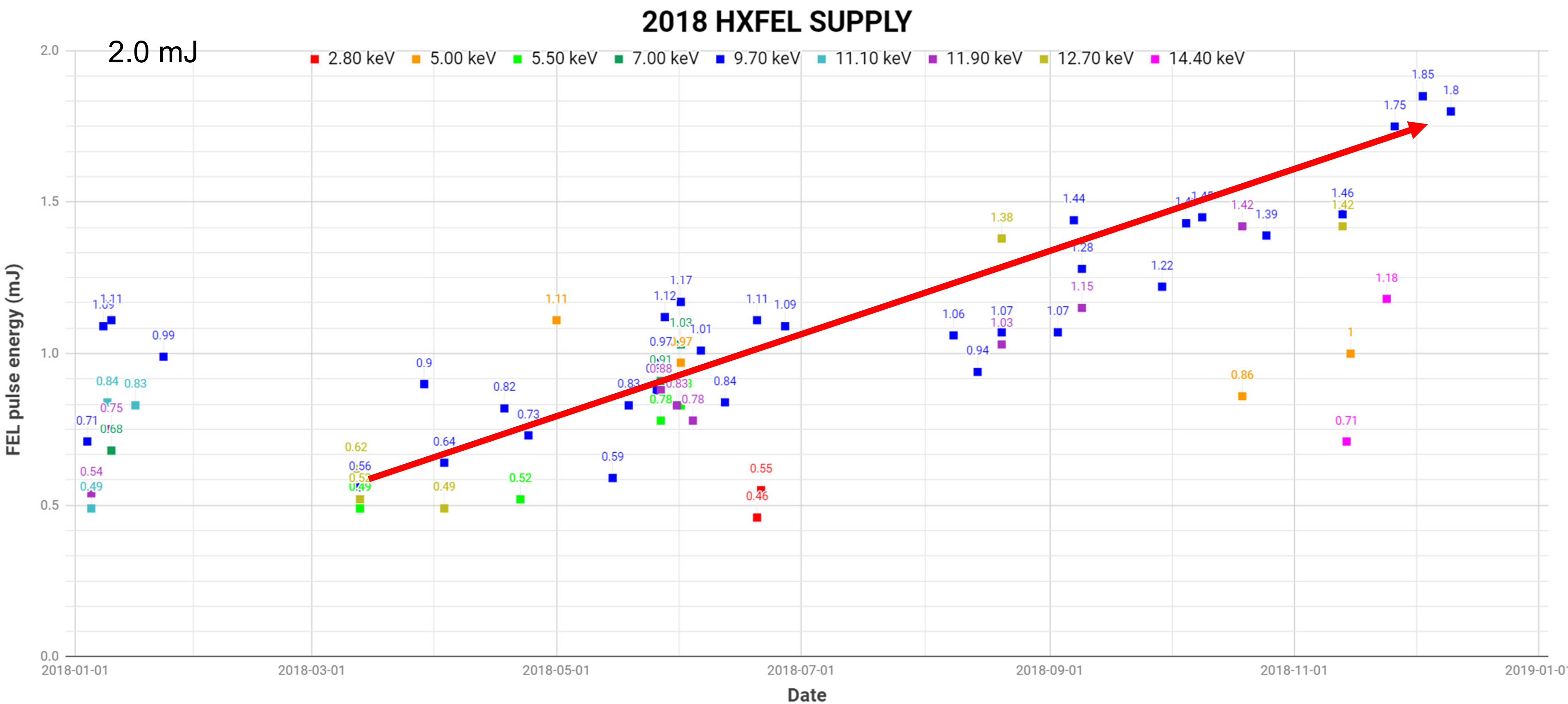
x-Emittance: 0.72



(matching)



FEL Energy delivered to Users (2018)



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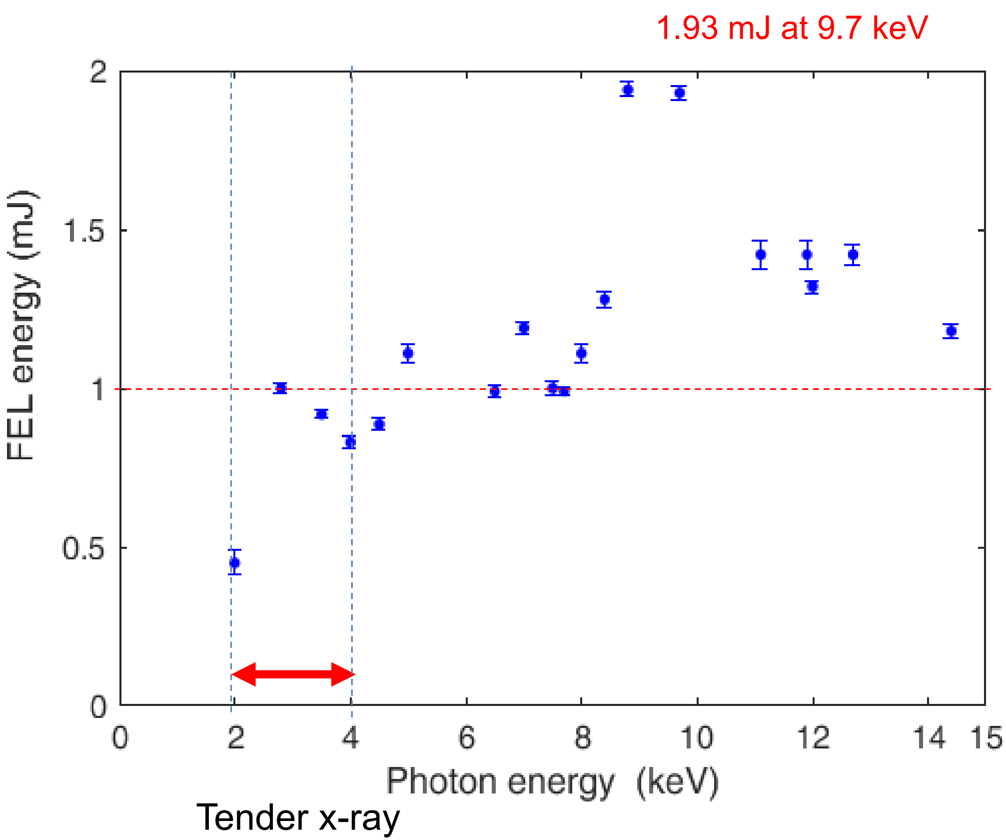
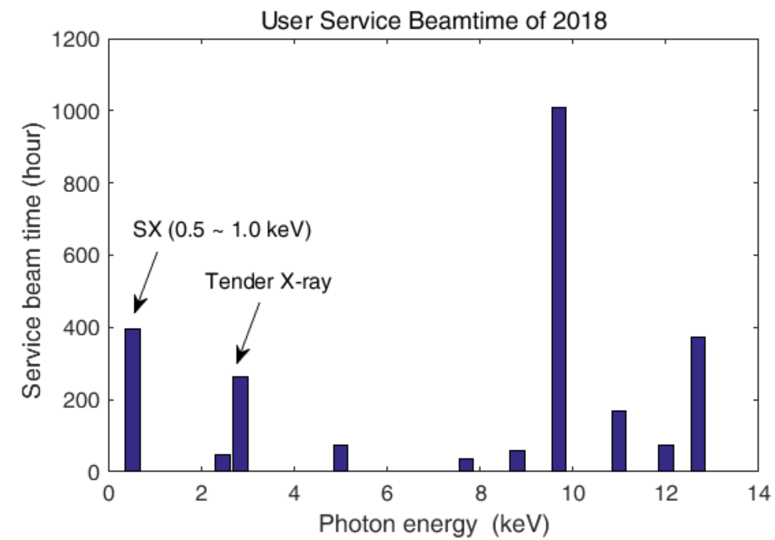
Machine Performances

◆ Photon energy	2.0 ~ 14.5 keV
- Saturated FEL up to 14.5 KeV	
◆ FEL pulse power	2.0 mJ at 9.7 KeV
◆ FEL beam pulse duration	10 ~ 35 fs (fwhm)
◆ FEL power stability	< 5% RMS
◆ FEL position stability	< 10% of beam size
◆ FEL central wavelength jitter	0.024 %
◆ E-beam energy jitter	< 0.015 %
◆ E-beam arrival time jitter	< 15 fs
◆ FEL beam availability	~ 95%

Hard X-ray FEL Intensity

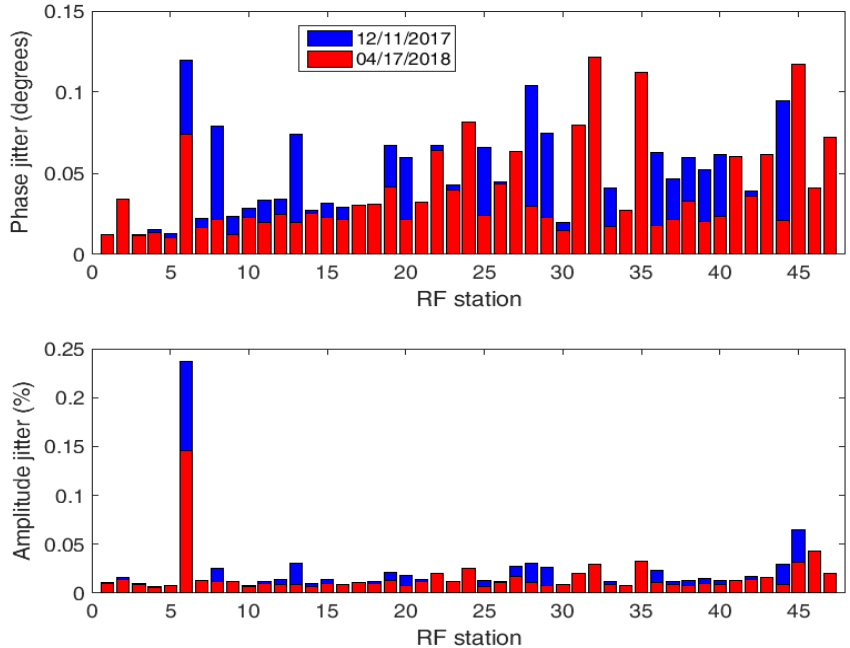


- Access to the tender X-ray range (2.0 ~ 4 keV) presently is only available at PAL-XFEL
- This regime allows access to the Ru L edge and the M edges of the 4d transition metals.



Electron Beam Energy Jitter

RF system jitter performance

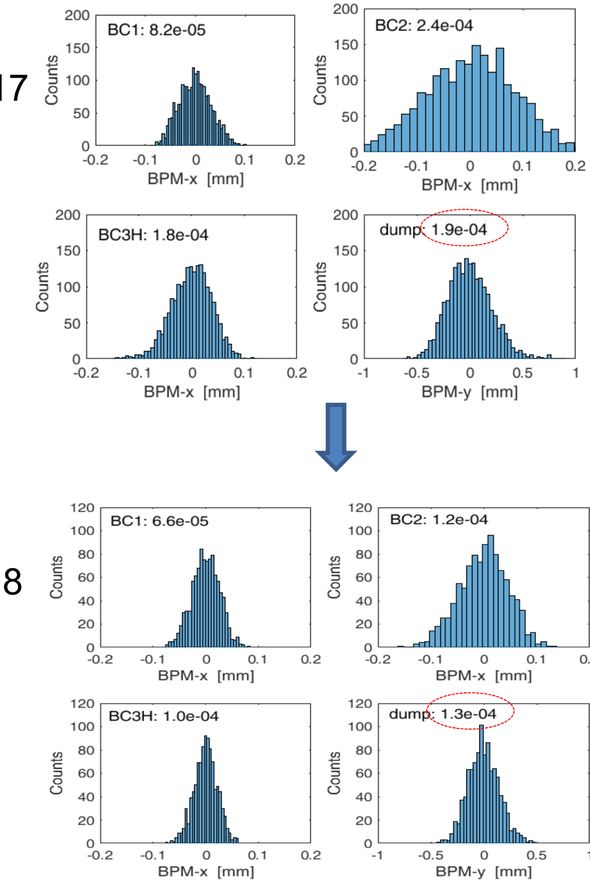


1) Stability of klystron magnet power supply was improved from 1,000 ppm to 100 ppm level.
2) Thyratron runtime issue was resolved

Energy jitter at four dispersive points

12/11/2017
(11 Dec.)

4/17/2018
(17 Apr.)



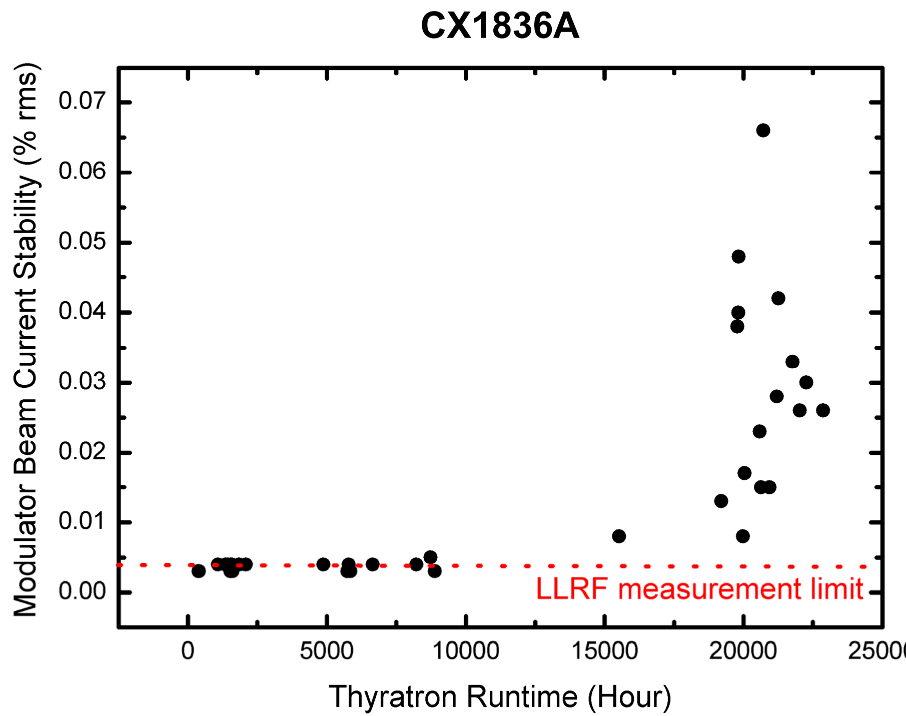
1.9E-4

1.3E-4

Modulator performance vs. Thyratron runtime

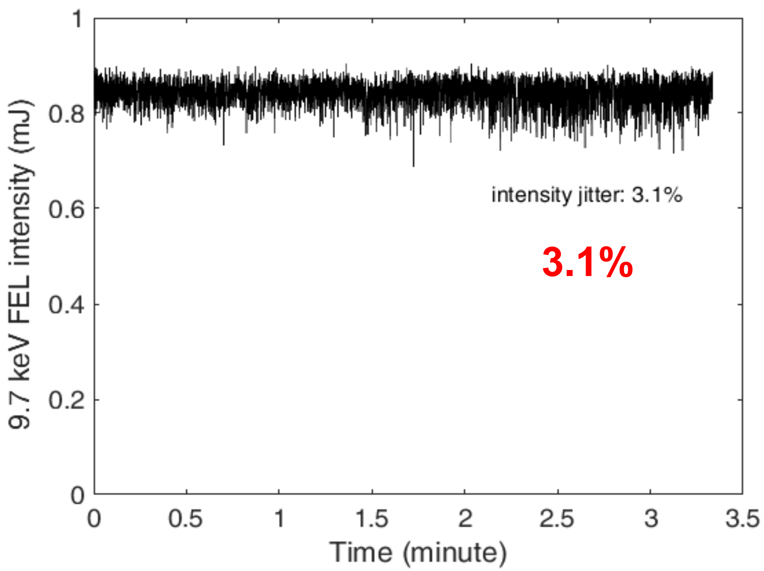
CX1836A, CX1836AP, CX1836AX
Air Cooled, Deuterium Filled
Two-Gap Metal/Ceramic Thyratrons

1.	Peak Forward Anode Voltage	+ 50 kV
2.	Peak Inverse Anode Voltage	- 50 kV
3.	Peak Anode Current	10 kA
4.	Average Anode Current	10 A
5.	Rate of Rise of Anode Current	10 kA/us
6.	Maximum Operating Frequency	10 kHz
7.	Anode Delay Time	200 ~ 350 ns
8.	Anode Delay-time Drift	15 ~ 25 ns
9.	Time Jitter	3 ~ 10 ns
10.	Minimum Recovery Time	20 us

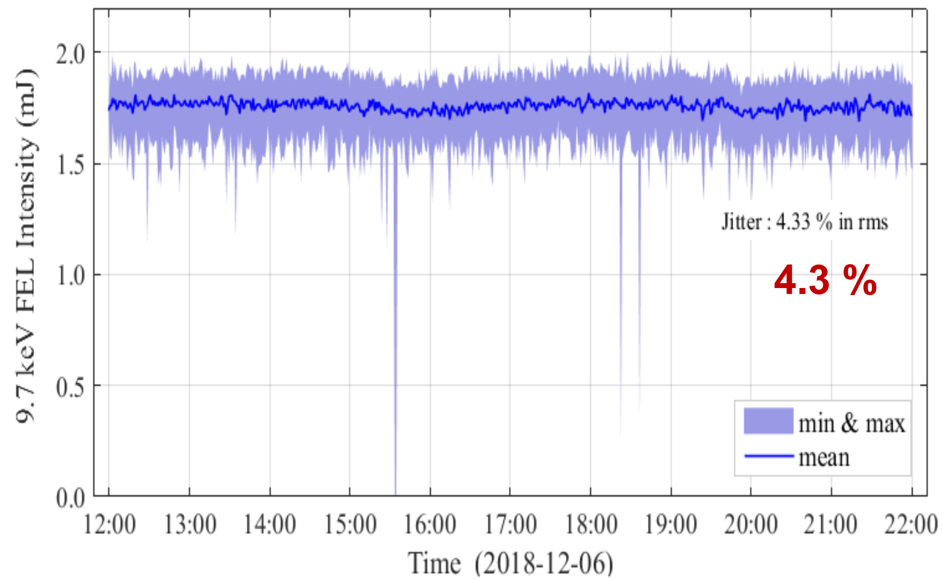


FEL intensity stability (9.7 keV FEL)

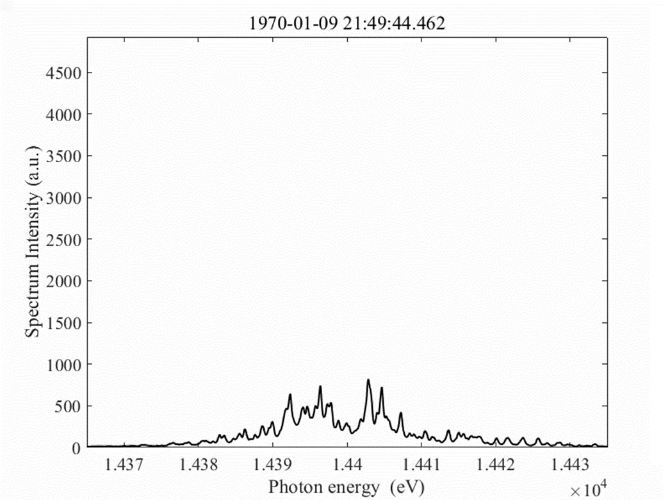
Short-term (3 min.)

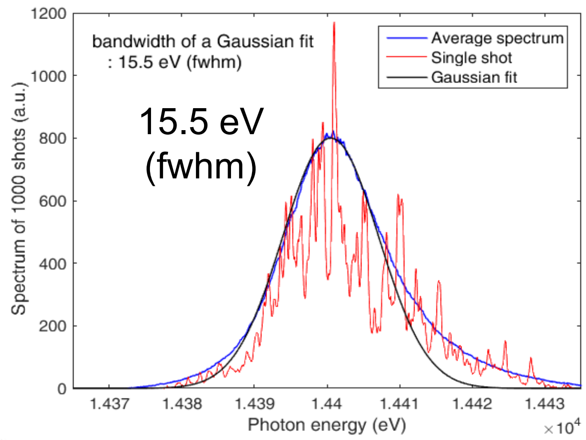


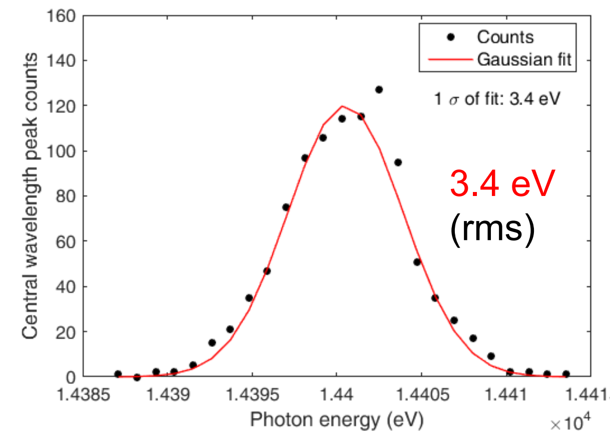
Long-term (10 hour)

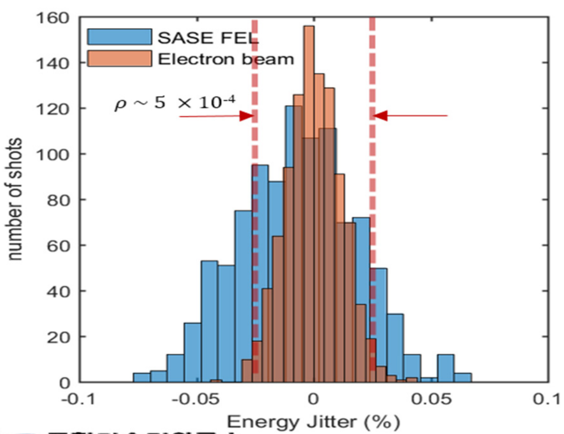


Central Wavelength Jitter (14.4 keV FEL)









- Central wavelength jitter (3.4 eV) is **5 times smaller** than **SASE bandwidth** (15.5 eV in FWHM)
- Relative central wavelength jitter: **2.4 E-4**

PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

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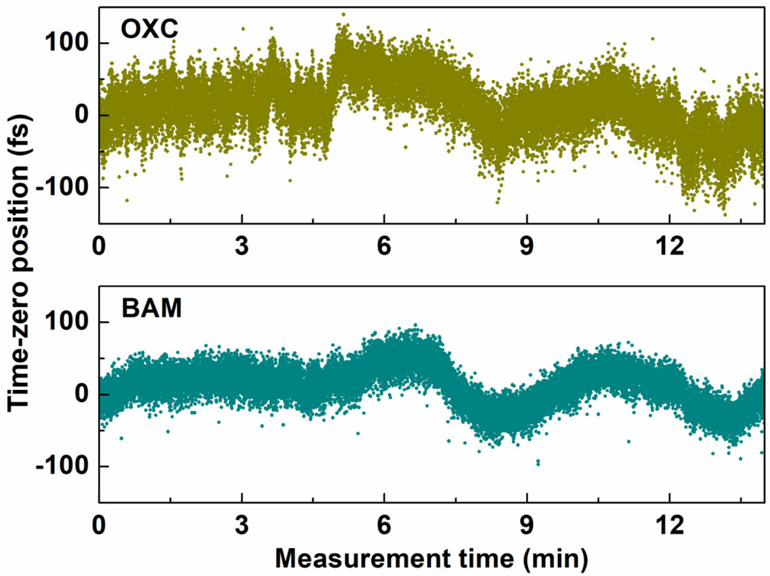
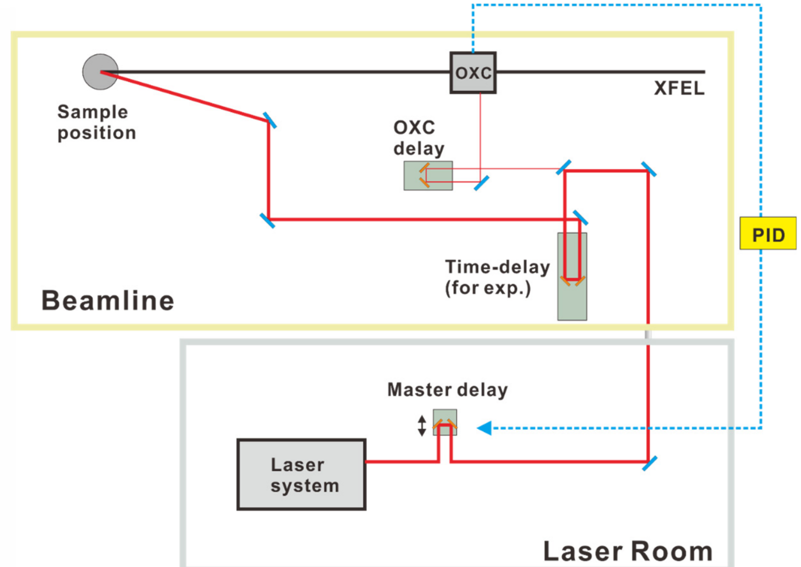
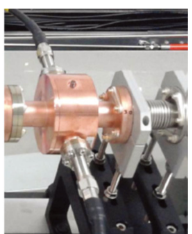
Timing jitter between XFEL and optical laser (Long-term)

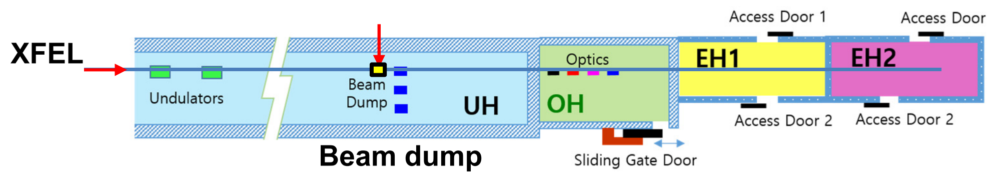
Stability for 14 minutes







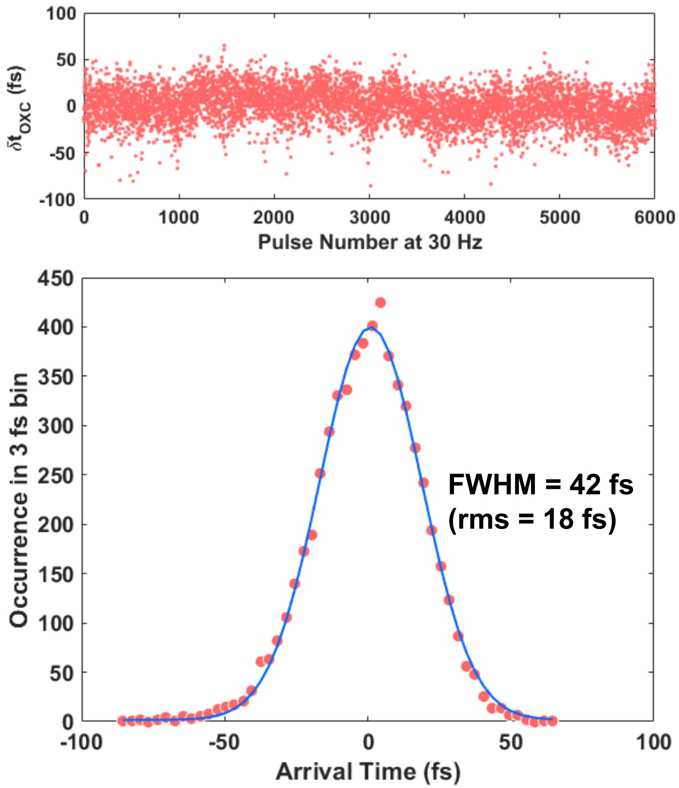
BAM



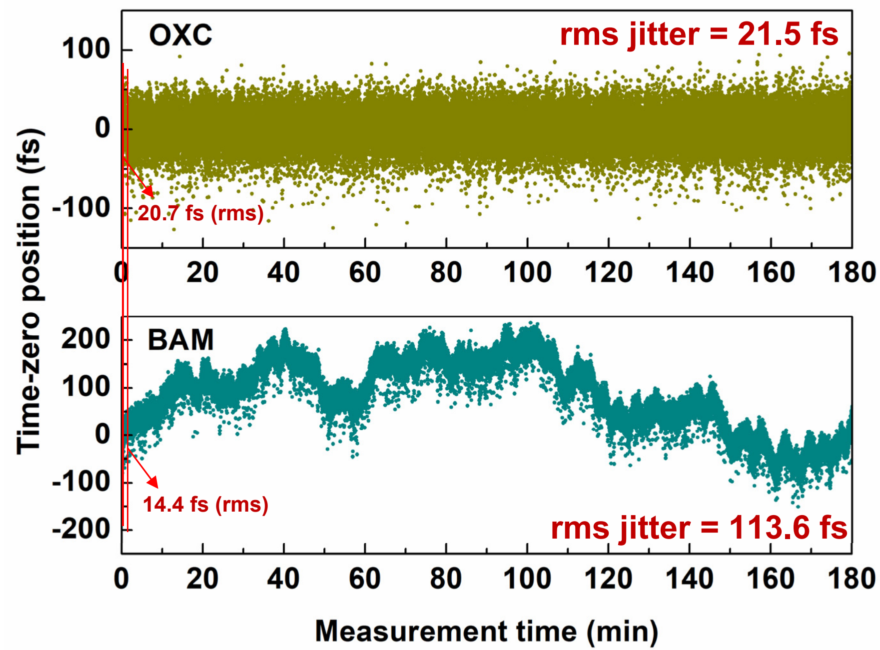
BAM: Beam arrival monitor (Phase cavity)

After Slow Drift Correction

Statistics for 6000 XFEL shots (30 Hz)

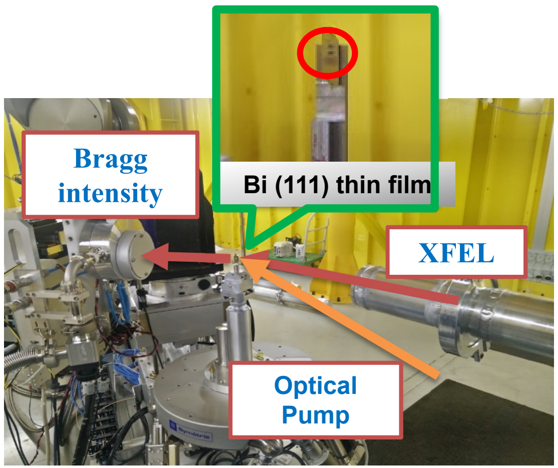


Stability for 3 hours

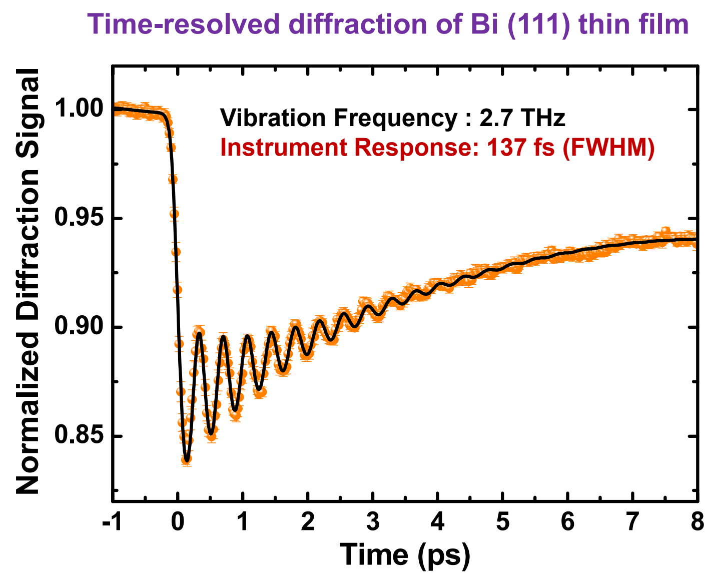


Timing jitter between pump laser and probe XFEL @ sample

Bi(111) thin film (50 nm) on GaSb(111)/Si(111)
X-ray: 6 keV
X-ray size: ~ 60 x 60 um^2
Laser: 800 nm, 100 fs
Detector: MPCCD 0.5M



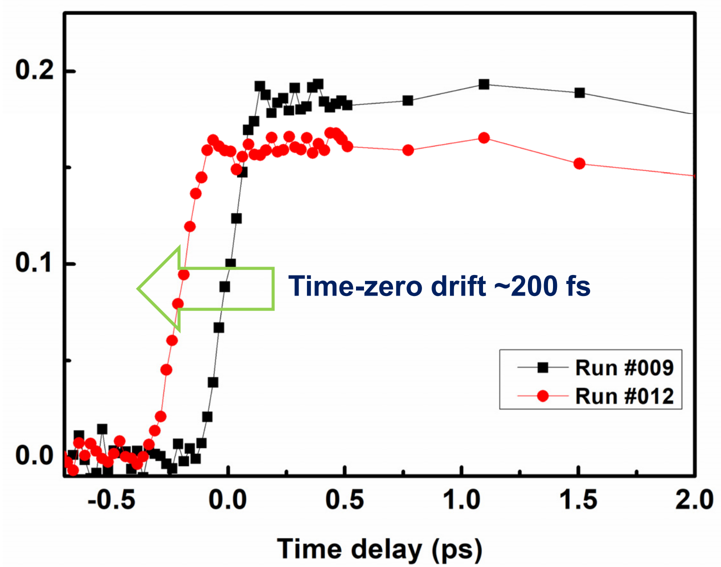
No timing jitter correction
- averaged by 50 trials of the time delay scan and normalized by GaSb(111) Bragg peak intensity
- **Only slow time-drift correction**



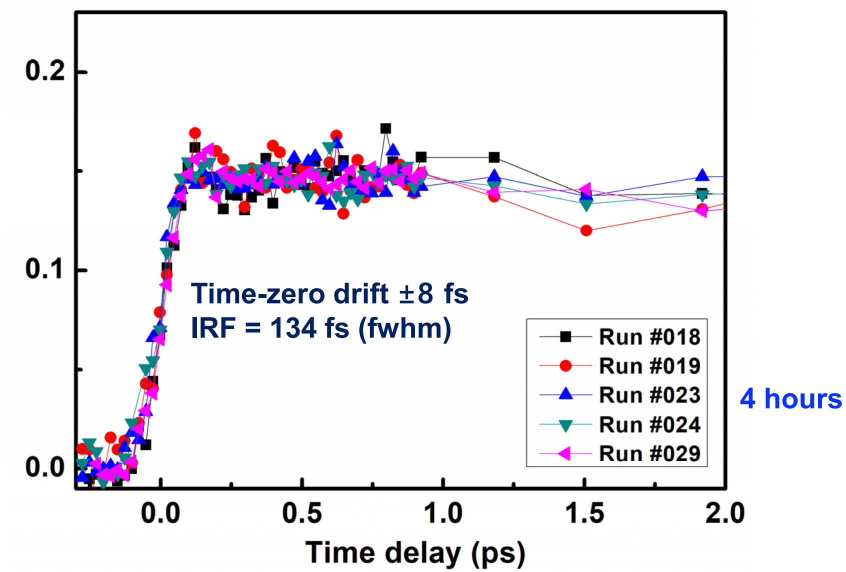
Result in User experiment (2019-1st-XSS-011, Prof. J. Kim, Inha Univ.)

Time-evolution of 1st rSV (Singular value) from Time-resolved BiI_3 solution scattering experiment

no drift correction



Slow drift corrected



* It took 20 min per single run.

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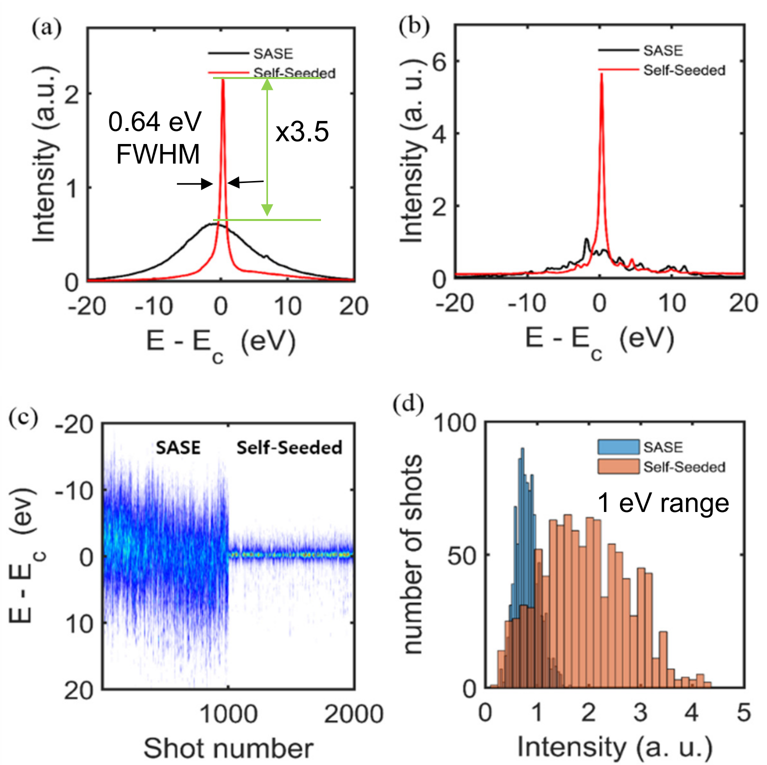
PAL-XFEL HXSS project history

- **Collaboration with APS/USA and TISNCM/Russia**
  - Design of Diamond crystal monochromator by APS (Yuri Shvyd'ko, Deming Shu, and Kwang-Je Kim)
  - 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

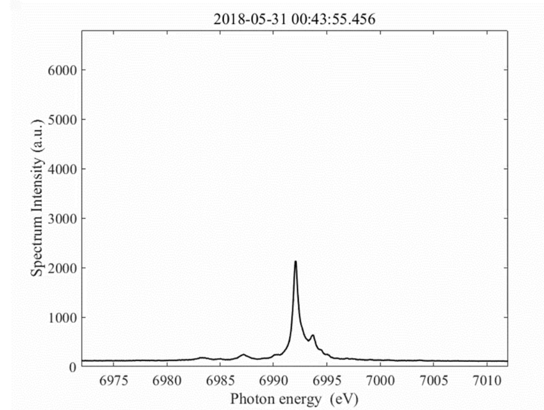
- **Commissioning of PAL-XEL HXSS**
  - May 2018: Low bunch charge 40 pC for 8.4 keV, crystal offset calibration with undulator radiation
  - Oct. 2018: Nominal bunch charge 180 pC for 7,8. keV, crystal offset calibration with crossing points of self-seeding (Collaboration with ANL, LCLS, EuXFEL)
  - Nov. 2018: Seeding for 3.5 keV with 30 um crystal and 14.4 keV (Collaboration with LCLS, ANL)

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

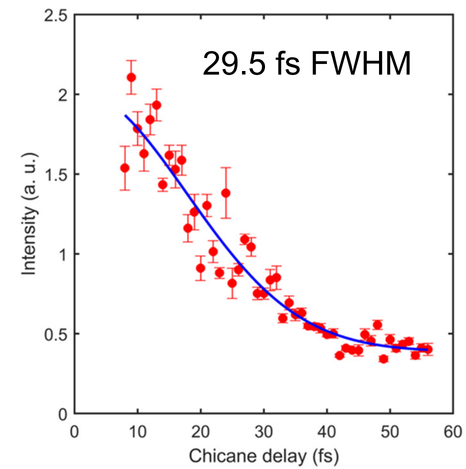
7keV at 60 fs delay



Si(111) single shot spectrometer used



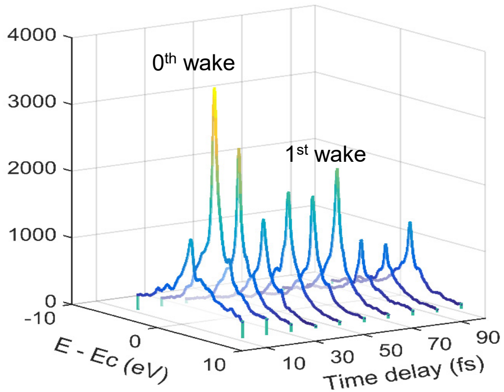
SASE pulse length measurement

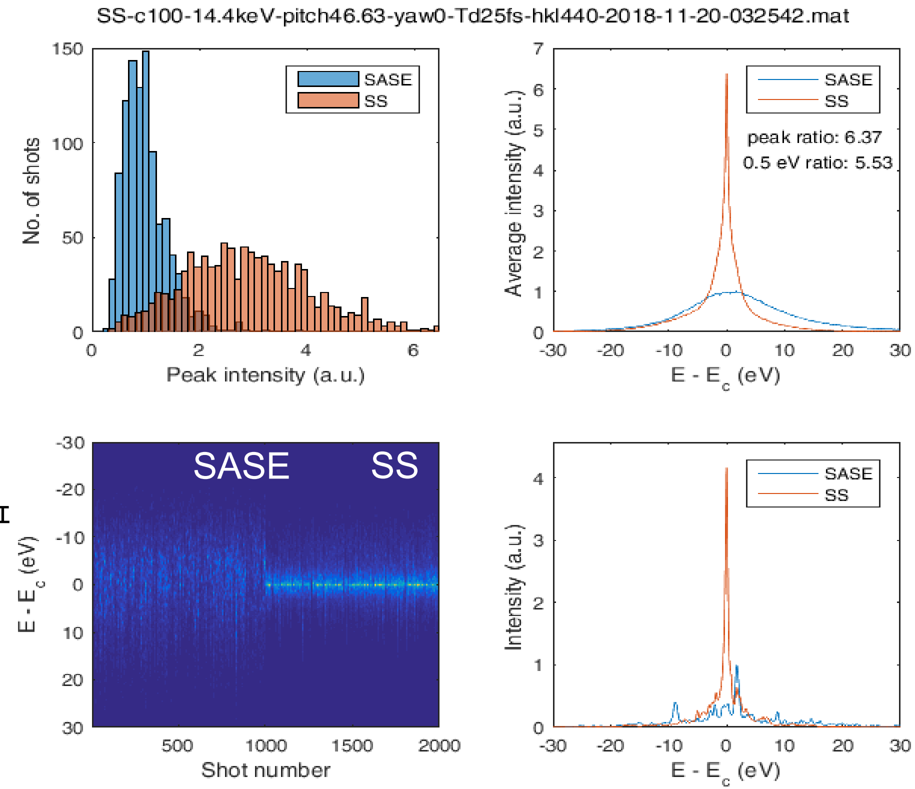


- Beam parameter
  - Charge: ~180 pC
  - Peak current: ~2.5 kA
  - Emittance: ~0.4 mm-mrad
- Seeding
  - Pitch angle: 89.5 deg [400]
  - FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
  - BW (FWHM): 0.64 eV (seeded), 12 eV (SASE)
    (limited by Si (111) spectrometer resolution of ~0.6 eV)

Self-Seeding at 14.4 keV

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





- Time-delay: 25 fs (0th wake of FBD)
- Peak intensity ratio of SS and SASE: 6.37
- A fraction of 1-eV BW over entire spectrum0.047ㄷㅍ
  - SASE: 0.047
  - SS : 0.226
- FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
- BW reduction: ~ 35 times
  - SASE: 16.9 eV, SS: 0.49 eV

Summary

- **A mJ-level intensity** is available for photon energies of 2.5 to 14.5 keV
- **A distinguishing performance (world's best)** was achieved by FEL optimization through BBA, undulator parameter optimization, and lattice matching
- **The unprecedented temporal stability** was realized with the timing jitter of ~18 fs (rms) between X-ray pulses and optical pulses from a synchronized laser system
- A **14.4 keV self-seeding** was successfully demonstrated for the first time

Poster Contribution from PAL-XFEL

TUPRB065 **Widely Tunable Hard X-ray Self-seeding at PAL-XFEL**

TUPRB066 **New Hard X-Ray Undulator Line in PAL-XFEL**

TUPRB067 **Hard X-Ray Attosecond Pulse Generation Using Slotted Foil in PAL-XFEL**

TUPRB068 **Measurement of the Spectro-Temporal Profile of X-Ray Pulse in Free Electron Lasers as Slicing the Electron Beam Using a Lined Slotted Foil.**

TUPRB069 **Study of FEL Operation without X-band Linearizer in HX Line at PAL-XFEL**

TUPMP032 **Design of the Analog to Digital Converter Scheme for High - Precision Electromagnet Power supply**

THPRB117 **Stability and Reliability Issues of PAL-XFEL Modulator**

THPGW089 **Mechanical Design of a Diamond Crystal Hard X-Ray Self-Seeding Monochromator for PAL-XFEL (Deming Shu, ANL, Argonne, Illinois)**

Poster Contribution from PAL-XFEL

TUPRB065 **Widely Tunable Hard X-ray Self-seeding at PAL-XFEL**

TUPRB066 **New Hard X-Ray Undulator Line in PAL-XFEL**

TUPRB067 **Hard X-Ray Attosecond Pulse Generation Using Slotted Foil in PAL-XFEL**

TUPRB068 **Measurement of the Spectro-Temporal Profile of X-Ray Pulse in Free Electron Lasers as Slicing the Electron Beam Using a Lined Slotted Foil.**

TUPRB069 **Study of FEL Operation without X-band Linearizer in HX Line at PAL-XFEL**

TUPMP032 **Design of the Analog to Digital Converter Scheme for High - Precision Electromagnet Power supply**

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Thank you for your attention