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

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

**Undulator Line**

<table>
<thead>
<tr>
<th></th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy [keV]</td>
<td>2.0 ~ 14.5</td>
<td>0.25 ~ 1.25</td>
</tr>
<tr>
<td>Beam Energy [GeV]</td>
<td>4 ~ 11</td>
<td>3.0</td>
</tr>
<tr>
<td>Wavelength Tuning</td>
<td>energy</td>
<td>gap</td>
</tr>
<tr>
<td>Undulator Type</td>
<td>Planar, out-vac.</td>
<td>Planar</td>
</tr>
<tr>
<td>Undulator Period / Gap [mm]</td>
<td>26 / 8.3</td>
<td>35 / 9.0</td>
</tr>
</tbody>
</table>

**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)
Saturation Curve

Nov. 27, 2016

- Simulation
- Measurement

- Hard X-ray
  - Wavelength: 0.144 nm
  - Beam energy: 8.04 GeV
  - Undulator K: 1.87
  - Emittance: 0.55 mm-mrad
  - Peak current: 2.5 kA

Feb. 02, 2017

- Simulation
- Measurement

- Soft X-ray
  - Wavelength: 1.52 nm
  - Beam energy: 3.0 GeV
  - Undulator K: 2.0
  - Emittance: 0.55 mm-mrad
  - Peak current: 2.2 kA
Saturation of 14.5 keV FEL (Nov. 07, 2017)

- E-beam: 10.5 GeV
- FEL beam energy: 0.65 mJ
  \[= 2.8 \times 10^{11} \text{ photons/pulse}\]
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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
4. Lattice matching
5. Phase-shifter gap tuning (15 min. for 20 undulators)
   : phase matching between two undulators
6. Undulator tapering

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

![Graph showing BPM and Quad offsets](image-url)
Undulator BBA

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1-st iteration

![BBA Scan Fit Result 07-Oct-2016 10:04:27]

8-th iteration

![BPM Offset Fit & Quad Offset Fit](x_offset)

![BPM Offset Fit & Quad Offset Fit](y_offset)
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

\[ E = 8.712 \text{ GeV} \]
\[ \gamma_{\text{rel}} = 0.70 \pm 0.03 \text{ } \mu \text{m} \]
\[ \beta_y = 46.37 \pm 4.23 \text{ m} \]
\[ \alpha_y = 0.37 \pm 0.34 \text{ m} \]
\[ \zeta_y = 1.32 \pm 0.06 \text{ m} \]

1.32

Norm. Angle

Hor. plane

Ver. plane

\[ E = 8.712 \text{ GeV} \]
\[ \gamma_{\text{rel}} = 0.72 \pm 0.03 \text{ } \mu \text{m} \]
\[ \beta_y = 23.45 \pm 4.21 \text{ m} \]
\[ \alpha_y = 1.37 \pm 0.34 \text{ m} \]
\[ \zeta_y = 1.02 \pm 0.04 \text{ m} \]

1.02

Beam Size (\mu m)

y-Emittance: 0.58

x-Emittance: 0.72

after

Ver. plane

\[ E = 8.712 \text{ GeV} \]
\[ \gamma_{\text{rel}} = 0.72 \pm 0.03 \text{ } \mu \text{m} \]
\[ \beta_y = 20.30 \pm 1.35 \text{ m} \]
\[ \alpha_y = 1.24 \pm 0.08 \text{ m} \]
\[ \zeta_y = 1.01 \pm 0.03 \text{ m} \]

1.01

Norm. Angle

Hor. plane

Beam Size (\mu m)

(matching)
FEL Energy delivered to Users (2018)

2018 HXFEL SUPPLY

Date

FEL pulse energy (mJ)

2.0 mJ
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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.

1.93 mJ at 9.7 keV

![Graph showing FEL energy vs. photon energy](image)

**Tender x-ray**

![Bar chart showing service beamtime of 2018](image)

**User Service Beamtime of 2018**

- SX (0.5 ~ 1.0 keV)
- Tender X-ray
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.)
- BC1: 8.2e-05
- BC2: 2.4e-04
- BC3H: 1.8e-04
- Dump: 1.9e-04

4/17/2018 (17 Apr.)
- BC1: 6.8e-05
- BC2: 1.2e-04
- BC3H: 1.0e-04
- Dump: 1.3e-04
Modulator performance vs. Thyatron runtime

CX1836A, CX1836AP, CX1836AX
Air Cooled, DeuteriumFilled
Two-Gap Metal/Ceramic Thyatrons

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

CX1836A

<table>
<thead>
<tr>
<th>Thyratron Runtime (Hour)</th>
<th>Modulator Beam Current Stability (% rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>5000</td>
<td>LLRF measurement limit</td>
</tr>
<tr>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>15000</td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td></td>
</tr>
<tr>
<td>25000</td>
<td></td>
</tr>
</tbody>
</table>
FEL intensity stability (9.7 keV FEL)

**Short-term (3 min.)**

- **9.7 keV FEL intensity (mJ)**
- **Time (minute)**
- **intensity jitter: 3.1%**
- **3.1%**

**Long-term (10 hour)**

- **9.7 keV FEL Intensity (mJ)**
- **Time (2018-12-06)**
- **Jitter: 4.33% in rms**
- **4.3%**
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**
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Timing jitter between XFEL and optical laser (Long-term)

Stability for 14 minutes

BAM: Beam arrival monitor (Phase cavity)
After Slow Drift Correction

Statistics for 6000 XFEL shots (30 Hz)

FWHM = 42 fs (rms = 18 fs)

Stability for 3 hours

rms jitter = 21.5 fs

rms jitter = 113.6 fs
Timing jitter between pump laser and probe XFEL @ sample

- 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

Bi(111) thin film (50 nm) on GaSb(111)/Si(111)
X-ray: 6 keV
X-ray size: ~ 60 x 60 um²
Laser: 800 nm, 100 fs
Detector: MPCCD 0.5M

Vibration Frequency: 2.7 THz
Instrument Response: 137 fs (FWHM)

Time-resolved diffraction of Bi (111) thin film

Normalized Diffraction Signal

-1 0 1 2 3 4 5 6 7 8
Time (ps)

0.85 0.90 0.95 1.00
Normalized Diffraction Signal

Vibration Frequency: 2.7 THz
Instrument Response: 137 fs (FWHM)
Result in User experiment (2019-1\textsuperscript{st}-XSS-011, Prof. J. Kim, Inha Univ.)

Time-evolution of 1\textsuperscript{st} rSV (Singular value) from Time-resolved Bil\textsubscript{3} solution scattering experiment

* 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

7 keV at 60 fs delay

- 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 (0\(^{th}\) wake of FBD)
- Peak intensity ratio of SS and SASE: 6.37
- A fraction of 1-eV BW over entire spectrum:\( 0.047 \)
  - 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


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

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Thank you for your attention