Status of the PAL-XFEL Construction

0.1-nm Hard X-ray XFEL

- Project Period: 2011 ~ 2015
- Total Budget: 400 M$
- 10-GeV Electron Linac (Normal Conducting S-band, 60 Hz)
- Total Length: 1.1 km

Heung-Sik Kang, on behalf of PAL-XFEL Team
Pohang Accelerator Laboratory, Pohang, South Korea
Outline

• Introduction
• Status of Installation
• Sub-System Preparation
• Commissioning Schedule
# Hard X-ray FEL Facilities

<table>
<thead>
<tr>
<th></th>
<th>LCLS-1</th>
<th>SACLA</th>
<th>EU-FEL</th>
<th>PAL-XFEL</th>
<th>SwissFEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy, GeV</td>
<td>14</td>
<td>8</td>
<td>17.5</td>
<td>10</td>
<td>5.8</td>
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<tr>
<td>Photon energy, keV</td>
<td>12.4</td>
<td>15</td>
<td>25</td>
<td>12.4</td>
<td>12</td>
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<tr>
<td>Accelerator Type</td>
<td>NCRF (S-band)</td>
<td>NCRF (C-band)</td>
<td>SCRF (L-band)</td>
<td>NCRF (S-band)</td>
<td>NCRF (C-band)</td>
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<tr>
<td>Repetition rate</td>
<td>120</td>
<td>50</td>
<td>500,000</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Undulator</td>
<td>out-of-vacuum, fixed gap</td>
<td>In-vacuum, variable gap</td>
<td>out-of-vacuum, variable gap</td>
<td>out-of-vacuum, variable gap</td>
<td>In-vacuum, variable gap</td>
</tr>
<tr>
<td>First lasing</td>
<td>2009</td>
<td>2011</td>
<td>2016</td>
<td>2016</td>
<td>2017</td>
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<tr>
<td>Operation mode</td>
<td>SASE, Self-seeding</td>
<td>SASE, Self-seeding</td>
<td>SASE, Self-seeding</td>
<td>SASE, Self-seeding</td>
<td>SASE, Self-seeding</td>
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</table>
Undulator Lines

### Main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>e⁻ Energy</td>
<td>10 GeV</td>
</tr>
<tr>
<td>e⁻ Bunch charge</td>
<td>20–200 pC</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>0.4 mm mrad</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>5 fs – 100 fs</td>
</tr>
<tr>
<td>SX line switching</td>
<td>DC (Phase-1) Kicker (Phase-2)</td>
</tr>
<tr>
<td>e⁻ Energy Tuning</td>
<td>0.4 mm mrad</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>5 fs – 100 fs</td>
</tr>
<tr>
<td>SX line switching</td>
<td>DC (Phase-1) Kicker (Phase-2)</td>
</tr>
</tbody>
</table>

### Undulator Lines Table

<table>
<thead>
<tr>
<th>Undulator Line</th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [nm]</td>
<td>0.06 ~ 0.6</td>
<td>1 ~ 4.5</td>
</tr>
<tr>
<td>Beam Energy [GeV]</td>
<td>4 ~ 10</td>
<td>3.15</td>
</tr>
<tr>
<td>Wavelength Tuning [nm]</td>
<td>0.6 ~ 0.1 (energy) 0.1 ~ 0.06 (Gap)</td>
<td>4.5 ~ 3 (Beam energy) 3 ~ 1 (Undulator gap)</td>
</tr>
<tr>
<td>Undulator Type</td>
<td>Planar variable gap, out-vacuum</td>
<td>Planar + APPLE II variable gap, out-vacuum</td>
</tr>
<tr>
<td>Period / Gap [mm]</td>
<td>26 / 8.3</td>
<td>35 / 8.3</td>
</tr>
</tbody>
</table>
### Undulator Lines

**Hard X-ray Undulator Hall**
- Exp. Hall
- HX3, HX2, HX1
- $\lambda = 0.6 \text{ nm} \sim 0.06 \text{ nm}$

**Soft X-ray Undulator Hall**
- Exp. Hall
- SX2, SX1
- $\lambda = 4.5 \text{ nm} \sim 1.0 \text{ nm}$

<table>
<thead>
<tr>
<th>Undulator Line</th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength [nm]</strong></td>
<td>0.06 ~ 0.6</td>
<td>1 ~ 4.5</td>
</tr>
<tr>
<td><strong>Beam Energy [GeV]</strong></td>
<td>4 ~ 10</td>
<td>3.15</td>
</tr>
<tr>
<td><strong>Wavelength Tuning [nm]</strong></td>
<td>0.6 ~ 0.1 (energy) 0.1 ~ 0.06 (Gap)</td>
<td>4.5 ~ 3 (Beam energy) 3 ~ 1 (Undulator gap)</td>
</tr>
<tr>
<td><strong>Undulator Type</strong></td>
<td>Planar variable gap, out-vacuum</td>
<td>Planar + APPLE II variable gap, out-vacuum</td>
</tr>
<tr>
<td><strong>Undulator Period / Gap [mm]</strong></td>
<td>26 / 8.3</td>
<td>35 / 8.3</td>
</tr>
<tr>
<td><strong>Operation Mode</strong></td>
<td>SASE (2016) Self-Seeding (2017)</td>
<td>SASE</td>
</tr>
</tbody>
</table>
- 28 undulator space for HX1:
  - 18 undulators for Phase-1
- 15 undulator space for SX1:
  - 8 undulators for Phase-1
PAL-XFEL Layout

Injector

RF Gun
Laser heater
Spectrometer

L1
Deflector (Vert.)

L2:1
Spectrometer (15 deg)

L2:10

L2

Soft X-ray FEL
Experimental Hall

L3

3.0 GeV
Kicker / Septum Magnet

L3A

L3B

L3S
EMU/Dechirper

L4

3.45 GeV
Deflector (Vertical)

Spectrometer (10 deg)

L4:1
BC3

L4:9

Spectrometer (10 deg)

150 m
Hard X-ray FEL (1.0 ~ 0.06 nm)

L4:26

L4:27

EMU

0.5 deg

10 GeV

1.5 deg

Experimental Hall

SX1

SX2

Undulators

HX1

HX2

HX3
- 50 S-band RF stations
  - 50 Klystrons (80 MW, 4 us, 60 Hz)
  - 50 klystron modulators
  - 42 Energy doublers
  - 50 LLRF Systems
- 174 S-band accelerating structures (3 m)
- 1 X-band RF station
- 26 Undulators (5-m length, 8.3 mm gap)
Features of PAL-XFEL (1)

• Multiple beamline operation
  – Simultaneous operation of Soft & Hard X-ray Beamline
  – 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) \( \rightarrow \) 240 pulses per second

• A very long Undulator Hall (225 m)
  – enough to install 28 undulators \( (5 \text{ m} \times 28 = 140 \text{ m}) \)
  – Suitable for Self-seeding and undulator tapering for TW FEL
  – Able to achieve Photon flux of over \( 1 \times 10^{12} \) photons/pulse at 0.1 nm

• Ultra stable pulse RF system
  – Klystron beam voltage stability : < 30 ppm

• New concepts and Ideas
  – Dechirper for energy chirp control
  – Two diamond crystal holder for self-seeding monochromator
Features of PAL-XFEL (2)

• Multiple beamline operation
  – Simultaneous operation of Soft & Hard X-ray Beamline
  – 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second

• A very long Undulator Hall (225 m)
  – enough to install 28 undulators (5 m x 28 = 140 m)
  – Suitable for Self-seeding and undulator tapering for TW FEL
  – Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm

• Ultra stable pulse RF system
  – Klystron beam voltage stability : $< 30$ ppm

• New concepts and Ideas
  – Dechirper for energy chirp control
  – Two diamond crystal holder for self-seeding monochromator
Self-Seeding Simulation for PAL-XFEL

Self-seeding + undulator tapering

- ~ 500 GW for 8 keV
- ~ 250 GW for 13 keV

SASE (blue) SS (red) and 8 (Solid) 13 (Dashed) keV

8 keV Self-Seeing (blue) and SASE (black) FEL

\[ P_{\text{FEL}} = 5.1 \times 10^7 e^{-(r - 0.1476)^2/0.5^2} \]

FWHM bandwidth: 5.6 x 10^{-5}

BW: 5.6 x 10^{-5}
• **Flexibility for multiple beamline operation**
  – Simultaneous operation of Soft & Hard X-ray Beamline
  – 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second

• **A very long Undulator Hall (225 m)**
  – enough to install 28 undulators (5 m x 28 = 140 m)
  – Suitable for Self-seeding and undulator tapering for TW FEL
  – Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm

• **Ultra stable pulse RF system**
  – **Klystron beam voltage stability :** < 30 ppm

• **New concepts and Ideas**
  – Dechirper for energy chirp control
  – Two diamond crystal holder for self-seeding monochromator
Ultra Stable Pulse RF System

- Electron Beam Stability Requirements
  - Beam energy jitter: < 0.02 %
  - Beam arrival time: < 20 fs
  - Emittance growth: < 10%
  - Beam current change: < 10%

- Stability Requirements determined by Start-to-End simulation

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>X</th>
<th>L2</th>
<th>L3, L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Phase [degrees]</td>
<td>0.05</td>
<td>0.1</td>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>RF Amplitude [%]</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- Stability Requirements for RF System
  - S-band RF phase: 0.03 degree
  - S-band RF amplitude: 0.02%
  - X-band RF phase: 0.06 degree
Features of PAL-XFEL (4)

- **Flexibility for multiple beamline operation**
  - Simultaneous operation of Soft & Hard X-ray Beamline
  - 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second

- **A very long Undulator Hall (225 m)**
  - Enough to install 28 undulators (5 m x 28 = 140 m)
  - Suitable for Self-seeding and undulator tapering for TW FEL
  - Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm

- **Ultra stable pulse RF system**
  - Klystron beam voltage stability : < 30 ppm

- **New concepts and Ideas**
  - Dechirper for energy chirp control
  - Two diamond crystal holder for self-seeding monochromator
Correlated energy spread after final compression is larger than FEL parameter ($1 \times 10^{-3}$)
SASE Bandwidth vs. Energy Chirp

PAL-XFEL Soft X-ray FEL Line

Heung-Sik Kang
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Dechirper

0.5% 0.2%
1 nm 1 nm

RFG of Undulator with 200 k particles

Heung-Sik Kang
hskang@postech.ac.kr
Time-resolved chirp meas. & sims.

PAL-ITF

Time-resolved T-wake meas. & sims.

Measurement

Simulation

Wakefield Dechirper Chamber – Simulation & Measurement

PAL

POHANG ACCELERATOR LABORATORY

SLAC

BERKELEY LAB

corrugated chamber
STATUS OF INSTALLATION
<table>
<thead>
<tr>
<th></th>
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<td>Test Facility (ITF, ATF)</td>
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<td>Site Preparation</td>
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<td>Linac RF conditioning</td>
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<tr>
<td>Linac Commissioning</td>
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<tr>
<td>FEL Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**Undulator Install**

June 2015 - Dec. 2015
Monthly Installation Plan of the Linac

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
</table>

- **2014**
  - Nov: L1
  - Dec: L1

- **2015**
  - Jan: L2:1
  - Feb: Deflector (10 deg)
  - Mar: BC1
  - Apr: Deflector (10 deg)
  - May: BC3
  - Jun: Deflector (10 deg)
  - Jul: L3S
  - Aug: EMU/Dechirper
  - Sep: L3A
  - Oct: 3.0 GeV
  - Nov: BC2
  - Dec: BC3

- **2016**
  - Jan: L4:9
  - Feb: BC4
  - Mar: L5
  - Apr: Deflector (10 deg)
  - May: BC5
  - Jun: L6
  - Jul: Soft X-ray FEL
  - Aug: BC6
  - Sep: L7
  - Oct: Experimental Hall
  - Nov: L8
  - Dec: L9

- **2017**
  - Jan: L10
  - Feb: Deflector (10 deg)
  - Mar: BC11
  - Apr: Deflector (10 deg)
  - May: BC12
  - Jun: L3S
  - Jul: EMU/Dechirper
  - Aug: L3A
  - Sep: 3.0 GeV
  - Oct: BC2
  - Nov: BC3
  - Dec: BC4

- **2018**
  - Jan: L4:9
  - Feb: BC4
  - Mar: L5
  - Apr: Deflector (10 deg)
  - May: BC5
  - Jun: L6
  - Jul: Soft X-ray FEL
  - Aug: BC6
  - Sep: L7
  - Oct: Experimental Hall
  - Nov: L8
  - Dec: L9
Undulator Installation Plan

- e-beam dump
- HX undulator line
- Loading area
- experimental hall
- HX undulator and vacuum chamber will be installed from June 2015.
- It takes two weeks to install 1 set of undulator and chamber
Aug. 2015

- Beam dump and tune-up dump will be installed in Sep. 2015.
Undulator Installation Plan: Undulator Intersection Components

- IU devices will be installed in Sep. 2015.

- quadrupole Q6
- quad mover
- phase shifter
- air coil corrector
- cavity BPM
- beam loss monitor
- vacuum component
- Self seeding section will be installed in Oct. 2015.
  (except monochromator)
Aerial View of PAL (July 2012)
Aerial View of PAL (July 2013)
Aerial View of PAL (July 2014)
Aerial View of PAL (January 2015)
First Installation of S-band accelerating structures
(21 January 2015)
Modulators at Klystron Gallery
Modulators at Klystron Gallery
Hard X-ray Undulator hall
Hard X-ray Experimental Hall
1. LINAC RF
# Number of Major RF Components

<table>
<thead>
<tr>
<th>Classification</th>
<th>Section</th>
<th>K&amp;M</th>
<th>A/S</th>
<th>Energy Doubler</th>
<th>Energy (GeV)</th>
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</thead>
<tbody>
<tr>
<td><strong>Injector linac</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L1</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>10</td>
<td>40</td>
<td>10</td>
<td>2.52</td>
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<tr>
<td><strong>Hard X-ray main linac</strong></td>
<td>L3A</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>L3B</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>27</td>
<td>108</td>
<td>27</td>
<td>10</td>
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<tr>
<td><strong>Soft X-ray linac</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3~3.5</td>
</tr>
<tr>
<td><strong>Deflector (S-band)</strong></td>
<td>L1, L3</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Linearizer (X-band)</strong></td>
<td>L1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total No.</strong></td>
<td></td>
<td>51</td>
<td>180</td>
<td>42</td>
<td></td>
</tr>
</tbody>
</table>
Linac RF Stability

Since the intra-pulse feedback is not feasible in the RF of the normal conducting Linac, RF stability is solely determined by klystron Voltage stability.

\[
\frac{\Delta V}{V} = - \frac{mc^2}{eL} \frac{\lambda_0}{V_0} \left( \gamma^2 - 1 \right)^{3/2} \frac{\Delta \theta}{360}
\]

<table>
<thead>
<tr>
<th></th>
<th>S-band</th>
<th>X-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td>2.856</td>
<td>11.424</td>
</tr>
<tr>
<td>RF phase stability Goal  [degrees]</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Klystron beam voltage stability [ppm]</td>
<td>55</td>
<td>31</td>
</tr>
</tbody>
</table>
Ultra-Stable Modulator

rms Stability: 17.1 ppm
Peak-to-peak Stability: 120.0 ppm

Collaborated with two Korean companies
- POSCO-ICT
- Dawon-Sys

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF output power</td>
<td>MW</td>
<td>80</td>
</tr>
<tr>
<td>Max. peak power</td>
<td>MW</td>
<td>200</td>
</tr>
<tr>
<td>Beam voltage</td>
<td>kV</td>
<td>400</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>500</td>
</tr>
<tr>
<td>Beam pulse width</td>
<td>μs</td>
<td>8</td>
</tr>
<tr>
<td>Repetition rate max.</td>
<td>Hz</td>
<td>60</td>
</tr>
<tr>
<td>Pulse transformer turn ratio</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Pervance</td>
<td>μp</td>
<td>2</td>
</tr>
</tbody>
</table>
S-band Accelerating Structure

- Collaborated with a Korean company: Vitzro-Tech, Korea
- 120 modules made by MHI, Japan
- Accelerating gradient of 27 MV/m
- Qausi-symmetric coupler with racetrack shape

Collaborated with a Korean company:
- Vitzro-Tech, Korea

120 modules made by MHI, Japan
S-band Energy Doubler

- Two-hole coupling to withstand 380 MW peak RF power

* Collaborated with a Korean company: Vitzro-Tech, Korea
LLRF controller

- 10 Channels for pulse measurement
- 2 Channels for pulse generation
- IQ modulation & demodulation
- Arbitrary pulse-shaping function
- Klystron beam V & I measurement
- IPC based computation system
- Beam synchronous acquisition

Solid-State Amplifier

- Pulsed output power
- Power control : 600~900W

* Collaborated with a Korean company : MOBIIS, Korea
RF Stability Performance

- Using a Modulator, E37320 Klystron, SLED & LLRF for PAL-XFEL
- RMS Stability: Amplitude~0.02%, Phase~0.03° (for Klystron FWD)

※ averaged for 500ns within pulse
SUB-SYSTEM Preparation

2. UNDULATOR
# High Precision Undulator

## PAL-XFEL Undulator Error Budget for 0.1 nm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>σ</th>
<th>$P_i/P_0$ (%)</th>
<th>tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Angle, $\mu$rad</td>
<td>1.73</td>
<td>98</td>
<td>0.35</td>
</tr>
<tr>
<td>Cell Phase, degree</td>
<td>55.6</td>
<td>99.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Phase Shift, degree</td>
<td>55.6</td>
<td>99.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Break Length, mm</td>
<td>11.8</td>
<td>99.9</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta K/K$ (gap control, 1 $\mu$m)</td>
<td>0.00053</td>
<td>95</td>
<td>0.00017</td>
</tr>
<tr>
<td>Quad position, $\mu$m</td>
<td>3.63</td>
<td>95</td>
<td>1.2</td>
</tr>
<tr>
<td>Seg. Ver. Pos., $\mu$m</td>
<td>0.0183 mm$^2$</td>
<td>98</td>
<td>61</td>
</tr>
<tr>
<td>Jaw Pitch, $\mu$rad</td>
<td>60.8</td>
<td>99.5</td>
<td>6.1</td>
</tr>
</tbody>
</table>

## Undulator Stability Requirement

- Field accuracy: $< 2 \times 10^{-4}$
- Gap setting accuracy: $< 1$ um
Prototype Undulator

- EU-XFEL undulator design is benchmarked. A MOU to use the EU-XFEL design is agreed in June 2011 between PAL and EU-XFEL.
- PAL modified the design including the new magnetic design, EPICS IOC, and updated tolerances reflecting new parameters.
- A fully assembled HXU prototype was delivered in Dec 2012 and measured at the undulator measurement lab.

Undulator Measurement Room

Prototype Undulator under field measurement

stable temperature control of ±0.1°C
Field & Gap Reproducibility Errors

- **Field Errors**
  - The peak fields from 5 measurements are overlapped.
  - B errors are about $\pm 1.0$ G.
  - Orbit error from the measurements is less than 1 um.

- **Gap Reproducibility Errors**
  - The peak fields from 5 measurements are overlapped. Between each measurement, gap is opened to 100 mm and closed to measurement gap.
  - 1.5 Gauss difference translates to 1.0 $\mu$m gap error.
• Initial optical phase errors were very large because of girder deformations about 50 $\mu$m.
• The optical phase errors is corrected to about 3.0 degree (rms) at the tuning gap.
• In production phase, we expect 1 day for vertical orbit correction, 1 day for correction of dominant quad components, 3 days for the phase/horizontal orbit tuning.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Nominal value</th>
</tr>
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<tbody>
<tr>
<td>E</td>
<td>GeV</td>
<td>10.000</td>
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<tr>
<td>g</td>
<td>mm</td>
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<tr>
<td>(\lambda_u)</td>
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<td>(L_{\text{und}})</td>
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<td>(\lambda_r)</td>
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<tr>
<td>(B_{\text{eff}})</td>
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<tr>
<td>K</td>
<td>degree</td>
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<tr>
<td>Optical phase error</td>
<td>degree</td>
<td>less than 5.0</td>
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</tbody>
</table>
3. INJECTOR & INJECTOR TEST FACILITY
Injector Test Facility for PAL-XFEL

ITF Tunnel

ITF Modulator / Klystron
Two candidate designs for the PAL-XFEL gun

**PAL-XFEL baseline gun**: dual-coupler gun with additional two-holes to reduce quadrupole field

**Alternative gun design**: fully-symmetric coaxial coupler and cathode plug.

*PRST AB 14, 104203 (2011)*

Emittance growth due to multipole transverse magnetic modes in an rf gun
Gun Part of Injector

Pressure: \(< 5 \times 10^{-11}\) mbar (RF GUN)
Permeability: \(< 1.03\)
Laser Beam Profile
Longitudinal Evolution of Transverse Profiles
Emittance Measurement Result

- History of Projected Emittances (95%) at 200 pC

![Graph showing history of projected emittances](image-url)
Effect of synchronization between RF and Laser

Purifying of Laser
Oscillator RF signal (79.33 MHz) by adding Low pass filter

Control of Laser
oscillator sync. gain
SUB–SYSTEM Preparation

4. SELF-SEEDING MOCHROMATOR
Self-seeding of 1-μm e− pulse at 1.5 Å yields $10^{-4}$ BW with low charge mode.

courtesy of P. Emma
PAL-XFEL self-seeding collaboration project

- PAL-XFEL self-seeding team made a contract with ANL to develop a novel self-seeding monochromator for PAL-XFEL.
- Our self-seeding monochromator is based on the LCLS design.
- Two diamond crystals with \((400)\) and \((220)\) orientations will be installed into single chamber.
- The monochromator is designed to cover the photon energy from 5 keV to 10 keV.
- PAL and ANL focus on development of all diamond based crystal holder. The new holder might be resistive to thermal instability.
- The monochromator will be ready for installation in PAL-XFEL in Oct. 2016.
Self-Seeding Monochromator

PAL-XFEL hard x-ray self-seeding setup

- Screen monitor (empty slot)
- Self-seeding monochromator
- Vacuum chamber
- Chicane magnet

Monochromator chamber
- Ion pump
- Mounting assemblies inside the chamber
- Two crystals
- Electron bunch
- Photon

Designed by Bongi Oh (Chicane setup, PAL) and Dr. Deming Shu (Monochromator, ANL)
Diamond crystals; diffraction angle dependence

C(400), d=100 μm, Photon energy: 7~10 keV

\[ \theta = 83.3^\circ \]
\[ T_0 = 0.87 \text{ fs} \]
\[ \Delta E_0 = 0.24 \text{ eV} \]
\[ \Delta \theta_{30\%} = 87.08 \mu \text{rad} \]
\[ t_s = 22.7 \text{ fs}, x_0 = 0.8 \mu \text{m} \]

\[ \theta = 56.9^\circ \]
\[ T_0 = 0.74 \text{ fs} \]
\[ \Delta E_0 = 0.28 \text{ eV} \]
\[ \Delta \theta_{30\%} = 15.78 \mu \text{rad} \]
\[ t_s = 19.1 \text{ fs}, x_0 = 3.7 \mu \text{m} \]

\[ \theta = 50.6^\circ \]
\[ T_0 = 0.68 \text{ fs} \]
\[ \Delta E_0 = 0.31 \text{ eV} \]
\[ \Delta \theta_{30\%} = 12.52 \mu \text{rad} \]
\[ t_s = 17.6 \text{ fs}, x_0 = 4.4 \mu \text{m} \]

\[ \theta = 44.0^\circ \]
\[ T_0 = 0.61 \text{ fs} \]
\[ \Delta E_0 = 0.34 \text{ eV} \]
\[ \Delta \theta_{30\%} = 9.95 \mu \text{rad} \]
\[ t_s = 15.9 \text{ fs}, x_0 = 4.9 \mu \text{m} \]

\( T_0 \); characteristic time, \( \Delta E_0 \); energy bandwidth
\( \Delta \theta_{30\%} \); admissible strain, \( t_s \) = time delay, \( x_0 \) = spatial offset

C(220), d=30 μm, Photon energy: 5~7 keV

\[ \theta = 79.5^\circ \]
\[ T_0 = 0.86 \text{ fs} \]
\[ \Delta E_0 = 0.24 \text{ eV} \]
\[ \Delta \theta_{30\%} = 78.87 \mu \text{rad} \]
\[ t_s = 22.3 \text{ fs}, x_0 = 1.2 \mu \text{m} \]

\[ \theta = 63.3^\circ \]
\[ T_0 = 0.78 \text{ fs} \]
\[ \Delta E_0 = 0.27 \text{ eV} \]
\[ \Delta \theta_{30\%} = 29.24 \mu \text{rad} \]
\[ t_s = 20.2 \text{ fs}, x_0 = 3.0 \mu \text{m} \]

\[ \theta = 55.0^\circ \]
\[ T_0 = 0.71 \text{ fs} \]
\[ \Delta E_0 = 0.29 \text{ eV} \]
\[ \Delta \theta_{30\%} = 20.97 \mu \text{rad} \]
\[ t_s = 18.6 \text{ fs}, x_0 = 3.9 \mu \text{m} \]

\[ \theta = 44.6^\circ \]
\[ T_0 = 0.61 \text{ fs} \]
\[ \Delta E_0 = 0.34 \text{ eV} \]
\[ \Delta \theta_{30\%} = 14.48 \mu \text{rad} \]
\[ t_s = 15.9 \text{ fs}, x_0 = 4.8 \mu \text{m} \]

Courtesy of Yuri Shvyd'ko
Diamond Crystal holder design for LCLS

Diamond Crystal holder design for PAL-XFEL

Graphite

C(400) 100um

C(220) 30um

CVD Diamond 0.75 mm

Graphite
5. CONTROL SYSTEM

SUB-SYSTEM Preparation
Diagnostics and Control

- Event timing system delivered from SLAC was successfully tested at ITF in April 2014
- Stripline BPM control system
  - mTCA BPM control system successfully commissioned in June 2014: 3 - 4 μm at 200pC, 12 μm at 10pC
  - 140 Stripline BPM control system (mTCA based) contracted with SLAC in October 2014
    - 144 RTMs & 17 EVR fan-out module: SLAC
    - mTCA Crate, CPU, power module, AMC module: PAL
  - 155 stripline BPM pick-up was contracted with a Korean company
- Cavity BPM
  - 100 cavity BPMs contracted with a company in November 2014
  - Cavity BPM electronics is being tested at SLAC to be contracted in early 2015.
- Main control system (operator interface, control servers, and DB) is contracted with COSY-Lab.
CBPM: LCLS Beam Test (Nov. 2013)

- PAL CBPM
- Girder
- Existing CBPM
- CBPM Electronics

[Graphs showing BPM Resolution with axes labeled appropriately for horizontal and vertical resolutions.]
CBPM: LCLS Beam Test (Nov. 2013)
RF timing distribution system

Timing Room

- Rb 10 MHz
- OCXO 476 MHz
- DRO 2856 MHz

Event Timing System

476 MHz
30 dBm

X : X Band Cavity
B : Beam Arrival Monitor
D : Deflector

Gun Laser

DRO 2856

L3S D B C-BPM B EXP

/6 119 DRO 2856

DRO 2856

... X5

Gun L0 B L1 X B D L2 L3A,B D L4 B C-BPM B EXP
Temperature stabilized duct
Install and FEL Commissioning

- 1st FEL commissioning for 0.3 nm HX @10 Hz 2016. 01 ~ 2016. 06
- 2nd FEL commissioning for 0.1 nm HX @10 Hz 2016. 09 ~ 2016. 12

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<th>2015</th>
<th>2016</th>
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<th>0.3 nm FEL commission</th>
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<th>0.1 nm FEL commission</th>
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<td>2015 2016</td>
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</table>

- HX undulator hall should be accessible during the Linac RF conditioning
We hope
A successful FEL commissioning in 2016!!

Thank you for your attention