Current Status of PAL-XFEL Project

15 May 2013

Heung-Sik Kang
On behalf of PAL-XFEL Project Team

IPAC 2013  Shanghai, China
Korean 4-th generation Light Source: PAL-XFEL

- **Wavelength**
  - Soft x-ray: 10 nm ~ 1 nm
  - Hard X-ray: 1.0 ~ 0.1 nm
    - Extendable to 0.06 nm

- **Undulator Beamline**
  - 3 Hard X-ray / 2 Soft X-ray lines

- **Project Period**: 2011 ~ 2015
- **Total Budget**: 400 M$	ext{\$}$
- **Accelerator Length**: 1.1 km

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**Building**

<table>
<thead>
<tr>
<th>Building</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Hall</td>
<td></td>
</tr>
<tr>
<td>1. Assembly</td>
<td>10</td>
</tr>
<tr>
<td>2. Linac</td>
<td>710</td>
</tr>
<tr>
<td>3. BTL</td>
<td>60</td>
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<tr>
<td>Undulator Hall</td>
<td></td>
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<tr>
<td>250</td>
<td></td>
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<tr>
<td>XFEL Beamline</td>
<td></td>
</tr>
<tr>
<td>1. Front-end</td>
<td>20</td>
</tr>
<tr>
<td>2. Experiment hall</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total Length [m]</strong></td>
<td><strong>1110</strong></td>
</tr>
</tbody>
</table>
Status of PAL-XFEL project as of May 9

- **Building and Infrastructure**
  - Site preparation work was finished in early May 2013.
  - Building construction has started and will be completed by November 2014.

- **Accelerator system**
  - Sub-system development is finished or underway.
  - Ordering contract of major sub-system will be completed by September 2013.
  - New concept is being studied to be implemented into the Baseline: self-seeding and ISASE.
# Project Schedule

<table>
<thead>
<tr>
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<tbody>
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<td>Test facility (ITF, ATF)</td>
<td>![Progress Arrow]</td>
<td>![Progress Arrow]</td>
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<td>Site Preparation</td>
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<td>![Progress Arrow]</td>
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<td>Install</td>
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<td>Linac Commissioning</td>
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<tr>
<td>FEL Commissioning</td>
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<td>![Progress Arrow]</td>
<td>![Progress Arrow]</td>
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<tr>
<td>Demo Experiment</td>
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<td>![Progress Arrow]</td>
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</tbody>
</table>

*now*
Building Construction Ceremony on 9 May 2013
Building Construction Ceremony on 9 May 2013

Microbunching Instability Workshop at Pohang on May 8-10, 2013
Parameters of PAL XFEL

- **Machine Parameters**
  - 10 GeV S-band linac / 0.2 nC / 0.4 mm-mrad / 60 Hz
  - Bunch current: > 3 kA at undulator
  - Photo-cathode RF-gun
  - Variable gap out-vacuum undulator: 5 m long and 7.2 mm min. gap
  - Aim to provide photon flux over $1 \times 10^{12}$ photons/pulse @ 0.1 nm
    - = 30 GW with 60 fs (15 GW from Ming-Xie formula)
    - = 60 GW with 30 fs ✅ achieved by Self-seeding or ISASE

- **Features**
  - Three bunch compressor lattice
  - Dechirper system using corrugated structure at the soft x-ray FEL line
Two Undulator Lines for Phase 1

Undulator Line | HX1 | SX1
---|---|---
Wavelength [nm] | 0.06 ~ 0.6 | 1 ~ 4.5
Beam Energy [GeV] | 4 ~ 10 | 3.15 (2.55)
Wavelength Tuning | 0.1 ~ 0.06 (Undulator Gap) 0.6 ~ 0.1 (Beam Energy) | 3 ~ 1 (Undulator gap) 4.5 ~ 3 (Beam Energy)
Undulator Type | Planar | Planar + APPLE II
Undulator Period [cm] | 2.44 | 3.4
Undulator Gap [mm] | 7.2 | 8.3
Three-Bunch Compressor Lattice

- 3-BC lattice
  - Very flexible in control of bunch current and bunch length by changing the BC3 bend angle of each X-ray FEL Line.
    - * Photon beam length for 0.2 nC: 30 ~ 90 fs for hard X-ray
    - 60 ~ 180 fs for soft X-ray
  - Simultaneous and independent operation for Soft X-ray FEL beamline
  - A dogleg to soft XFEL line is simple and no need to care about instability because of low beam current (600 A)

- Switching to Soft X-ray FEL line
  - Slow kicker for pulse by pulse switching for single bunch operation
  - Fast kicker for Bunch-by-bunch switching for two bunch operation (50 ns separation)

First bunch → Hard X-ray, Second Bunch → Soft X-ray
3-D model of Linac

WEPFI045: PAL-XFEL Accelerating Structures
Undulator

- EU-XFEL undulator design
- 5-m long
- A space for 24 undulators
Undulator intersection

Position limit sensor
Phase shifter
Corrector
Beam loss monitor
Quadrupole
Mover
Cavity BPM
Pumping spool
Corrector
Limit sensor
Development of Sub-system

Klystron modulator
Undulator and phaseshifter
Undulator chamber
Injector Test Facility
Start-to-End Simulation for Hard X-ray Line

200 pC

Linac-1
2 x 2AC

Linac-2
10 x 4 AC

Linac-3A
2 x 4AC

Linac-3A
2 x 4AC

Linac-4
27 x 4 AC

BC1
BC2
BC3

19.4 MV/m
-19.4°

24.0 MV
-180°

19.1 MV/m
-17.0°

19.3 MV/m
-0.5°

21.0 MV/m
-0.5°

139 MeV

0.33 GeV

2.52 GeV

3.45 GeV

10 GeV

Current, energy spread, and emittance at the entrance of undulator

3.5 kA

55 fs

Begin of Undulator with 200 k particles and 100 slices
SASE: Time-dependent simulation

Slice-averaged power

- $P$ [W] vs $z$ [m]
- $P_{\text{set}}$ [W] vs $s$ [l(mm)]

- $P(\lambda)$ [a.u.] vs $\lambda$ [nm]
# Tolerance Study for Linac RF parameters

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>X</th>
<th>L2</th>
<th>L3, L4</th>
<th>Current Variation [%]</th>
<th>Arrival time variation [fs]</th>
<th>Energy jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>200 pC for SASE</strong></td>
<td>0.1 deg</td>
<td>0.1 deg</td>
<td>0.1 deg</td>
<td>0.5 deg</td>
<td>0.02 %</td>
<td>0.04 %</td>
<td>0.02%</td>
</tr>
<tr>
<td></td>
<td>0.05 deg</td>
<td>0.1 deg</td>
<td>0.05 deg</td>
<td>0.5 deg</td>
<td>0.02 %</td>
<td>0.04 %</td>
<td>0.02%</td>
</tr>
<tr>
<td></td>
<td>0.02 %</td>
<td>0.04 %</td>
<td>0.02%</td>
<td>0.1 %</td>
<td>13</td>
<td>10.7</td>
<td>1.7 E-5</td>
</tr>
<tr>
<td><strong>100 pC for Self-seeding</strong></td>
<td>0.02 deg</td>
<td>0.05 deg</td>
<td>0.02 deg</td>
<td>0.5 deg</td>
<td>0.02 %</td>
<td>0.04 %</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

**RF stability requirement**
- **phase**: 0.03 degree
- **amplitude**: 0.01 %
### Klystron Beam Voltage Stability Requirement

- Because of a very short RF pulse length (a few micro-second) of normal conducting Linac, the RF phase stability is determined by the pulse-to-pulse stability of klystron beam voltage.

- Klystron modulator should be stable enough to satisfy the requirement.

#### RF Phase Stability Requirement

<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>Wavelength, m</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>Klystron cavity distance, m</td>
<td>0.65</td>
<td>0.6</td>
</tr>
<tr>
<td>Klystron voltage, kV</td>
<td>400</td>
<td>420</td>
</tr>
<tr>
<td>RF phase stability requirement, degrees</td>
<td><strong>0.03</strong></td>
<td><strong>0.05</strong></td>
</tr>
<tr>
<td>Klystron beam voltage stability, ppm</td>
<td><strong>55.3</strong></td>
<td><strong>26.1</strong></td>
</tr>
</tbody>
</table>
50-ppm Stability Inverter PS-type Modulator

- Collaborated with two local companies
- Both companies achieved the stability of 30 ppm.
Prototype of Undulator

- EU-XFEL undulator design is benchmarked. MOU to use the EU-XFEL design is agreed on 2011 June btw. PAL and EU-XFEL.
  - Variable gap out-vacuum
  - Undulator period: 2.44 cm
  - Minimum gap: 7.2 mm
  - Length: 5 m

THPME026: Preliminary Results of the PAL- XFEL Prototype Undulator Magnetic Measurements

Field measurement data

Position (m)

Magnetic Field (T)
Prototype of Phase Shifter

EU-XFEL type phase shifter (230 mm long)

A 100 mm long PM based Phase shifter is developed for PAL-XFEL with smaller phase integral.

Major Parameters of PAL-XFEL PS

- Continuously tunable for 3.0-1.0 nm radiation at E=3.15 GeV, with 0.8 mm inter-undulator length
- Magnetic length: ~100 mm
- Min gap: 7.2 mm
- Max gap: > 100.0 mm
- Max Phase integral: ~6,300 T²mm³
- Phase control accuracy: ±10 degree
- Gap Control accuracy: ± 20 um
- Full Magnet size: 20,000 (T) X 30 (H) X 50 (W)
- Half Magnet size: 10,995 (T) X 30 (H) X 50 (W)
- Magnet material: Br > 1.26T, Hcj 1670 kA/m

THPME027: Design and Fabrication of Prototype Phase Shifter for PAL XFEL
U-Chamber Cross section & Fabrication Procedure

**Fabrication procedure**

1. Extrusion
   - controlled gas environment.
2. Correction
   - stretching in controlled gas env.
3. AFM polishing *(if needed)*
4. Precision machining
5. Chemical cleaning
6. Welding

**Cross section**

- e-beam chamber
  - Cross section 5.2 x 11 mm
  - Thickness: 0.5 mm
- Undulator
- Magnet cage
- Magnet
- Cooling channel
- Holes for earth field correction coil
# Prototype of Undulatorator chamber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator length, m</td>
<td>5.0</td>
</tr>
<tr>
<td>Undulator period, cm</td>
<td>2.44</td>
</tr>
<tr>
<td>Undulator gap, mm</td>
<td>7.2</td>
</tr>
<tr>
<td>Material</td>
<td>A6063-T5/T6</td>
</tr>
<tr>
<td>Aperture (V x H), mm</td>
<td>5.2 x 11</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>0.5±0.05</td>
</tr>
<tr>
<td>Flatness</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Clearance (pole to chamber), mm</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Surface measurement result**
- Surface roughness : < 150 nm
- Oxidation layer thickness : < 5 nm

Holes for Cu coil and LCW
WEPWA043: Construction of Injector Test Facility (ITF) for the PAL XFEL
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

WEPWA040: Options for Operating Conditions of the PAL-XFEL Injector
Emittance Measurements

Projected emittance measurement with single quad scan

Charge: $\geq 200$ pC  
Energy: 139 MeV  
Repetition rate: 10 Hz  

$\varepsilon_x,100\% \sim 0.71$, $\varepsilon_y,100\% \sim 0.78$, 

WEPWA041: First Beam Measurements at PAL-XFEL ITF
New Concept for increasing radiation power and narrow bandwidth
HARD X-RAY SELF-SEEDING

HXRSS @ PAL-XFEL

1st undulator

SASE FEL

$e^-$ chicane

Single crystal

2nd undulator

Seeded FEL

$e^-$ dump

$e^-$

8 keV: 34 m
13 keV: 46 m

8 keV: (400) 8.7E-06
13 keV: (642) 1.6E-06

8 keV: 130 m
13 keV: 170 m

Collaborated with J. Wu in SLAC
With full length of 225 (red solid) m as compared to 130 m (red dashed), i.e., about 100 m left for other purpose.

Collaborated with J. Wu in SLAC.
ISASE Scheme

- Self-seeding: narrow bandwidth, but too high intensity fluctuation (over 70%) very sensitive to beam energy jitter
- Improved SASE (iSASE) scheme: Pellegrini and J. Wu
  - introduces repeating delays of the electron beam respect to the radiation field
  - increase the cooperation length and generate a smaller bandwidth than SASE
  - less sensitive to beam energy jitter
  - a tapered undulator enables ultra-high peak power.

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>Slippage/ 5-m undulator</th>
<th>Total slippage (12 undulatos) in SASE mode</th>
<th>Total slippage in ISASE mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>0.03 um</td>
<td>0.36 um</td>
<td>1.56 um</td>
</tr>
</tbody>
</table>

- Chicane (R56 = 2.4 $\mu$m) is 0.6 m long
- Only 2 m (0.4 m x 5) is increased

Collaborated with J. Wu in SLAC
Dechirper System
Start-to-End Simulation for Soft X-ray FEL Beamline

Linac-1 2 x 2AC
139 MeV

Linac-2 10 x 4 AC
24.0 MV

Linac-3A 2 x 4AC
19.01 MV/m

Laser Heater: OFF

Linac-3A 2 x 4AC
19.0 MV/m

Linac-3A 2 x 4AC
-17.0°

Linac-3A 2 x 4AC
-19.4°

Linac-4 27 x 4 AC

BC1 BC2 BC3_H

θ = 1.8°, ΔL = 6.0 m

BC3_S

Linac-3S 1 x 4AC

Hard X-ray

Soft X-ray

Nbins = 60, 200 k ptls

10 x 4 AC

Linac-1

2 x 2AC

Linac-2

Linac-3A

2 x 4AC

Linac-4

27 x 4 AC

Linac-3S

1 x 4AC

19.01 MV/m

-17.0°

19.0 MV/m

-19.4°

0.33 GeV

2.52 GeV

0.33 GeV

2.52 GeV
Simulation of longitudinal wake

a) Smooth, resistive pipe

b) Corrugated pipe with radius of 3 mm, L=15 m
One-meter long proto-type dechirper

- Collaborative R&D with SLAC (K. Bane, Z. Huang, G. Stupakov) and LBNL (P. Emma, Marco)

- Beam test at Injector Test Facility in July 2013

Adjustable gap type using two parallel plates with corrugations

corrugation period : 0.5 mm
corrugation depth : 0.6 mm
corrugation gap : 0.3 mm
Width of plate : 50 mm
Gap of two plates : 1 ~ 30 mm.
Acknowledgements

Thanks to...

- Kwang-Je Kim
- Zhirong Huang, Karl L.F. Bane, G. Stupakov, J. Wu, Patrick Krejcik
- Paul Emma
- S. Reiche, Bolko Beutner
- J. Pfluger
- Matsumoto, T. Inagaki, Y. Otake
Beam Based Feedback: Longitudinal

BC1
330 MeV
RF Gun
Electron beam
dump
Hard X-ray
SASE FEL

BC2
2.52 GeV
Laser
Heater

BC3
3.45 GeV
Soft X-ray FEL

L1 L2 L3B L4 Vertical Dump
L0 Kicker Septum

BC3_SL3:S

Vz BPM
Coherent Edge Radiation Detector

L3A

Thank you for your attention