Beam operation at the PAL-XFEL Injector Test Facility

Pohang Accelerator Laboratory
Contents

• PAL-XFEL Project

• Injector Test Facility

• Electron Beam Property Measurement

• Beam Test of Accelerator Components
PAL-XFEL Overview
## PAL-XFEL Parameters

### Undulator Line

<table>
<thead>
<tr>
<th>Undulator Line</th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>0.06 ~ 0.6 nm</td>
<td>1 ~ 4.5 nm</td>
</tr>
<tr>
<td><strong>Electron Beam Energy</strong></td>
<td>4 ~ 10 GeV</td>
<td>3.15 GeV</td>
</tr>
<tr>
<td><strong>Wavelength Tuning</strong></td>
<td>0.1 ~ 0.06 nm (Undulator Gap)</td>
<td>3 ~ 1 nm (Undulator gap)</td>
</tr>
<tr>
<td></td>
<td>0.6 ~ 0.1 nm (Beam Energy)</td>
<td>4.5 ~ 3 nm (Beam Energy)</td>
</tr>
<tr>
<td><strong>Undulator Type</strong></td>
<td>Planar</td>
<td>Planar + APPLE II</td>
</tr>
<tr>
<td><strong>Undulator Period</strong></td>
<td>26 mm</td>
<td>37 mm</td>
</tr>
<tr>
<td><strong>Undulator Gap</strong></td>
<td>8.3 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td><strong>Repetition Rate</strong></td>
<td>60 Hz</td>
<td></td>
</tr>
</tbody>
</table>

**Hard X-ray Undulator Hall**  
(~225 m including Dump Section)

**Soft X-ray Undulator Hall**  
(~110 m including Dump Section)

---

*FEL2014, Basel, 25-29 August 2014*
PAL-XFEL Commissioning

• The building is under construction, to be ready by December 2014
• Component installation from late autumn 2014 for a year
  – All accelerator components to be installed
• Beam commissioning from winter 2015
  – 10 Hz repetition rate
• First FEL expected in late spring 2016
  – 0.3 nm at hard X-ray beamline with 6 GeV
Test Facilities/Lab for PAL-XFEL (2012~)

- ITF (Injector Test Facility): Injector components and diagnostics commissioning
- ATF (Accelerator Test Facility): High power RF components R&D and test
- IDL (Insertion Device test Lab): Field measurement, control test
- PTF (Photon Test Facility): Photon Beamline components test, pump-probe test

Arial view of PAL site in July 2014
Goal: Development and test of injector components
Diagnostics test using electron beams

- S-band photocathode gun for beam generation
- Ti:sapphire laser system
- Two S-band 3 m traveling-wave structures. Max beam energy ~ 140 MeV

- Test of high power RF system (klystron, modulator, RF window, SiC load) and low level RF, solid state amplifier
- Test of various accelerator components
- Operation normally at 10 Hz, tested up to 60 Hz

- Building construction started in 2011
- First electron beam in December 2012
- Operational until summer 2015
ITF Layout

beam dump

dipole magnet

diagnostics

quadrupole magnet

accelerating structures

solenoid magnets

modulators

klystrons

waveguide

attenuators phase shifters

electron gun
Installation

Tunnel

Gallery

Laser room

Baseline gun
RF Amplitude & Phase Control of Gun

6 dB power divider

from klystron
to gun

1st acc. structure

attenuator

phase shifter
ITF Beam Diagnostic Components

RF Gun
Accelerating Column
Deflector
Dipole Magnet
Dechirper
Screen
Stripline BPM
Laser
Quadrupole
Gun1

- Developed at PAL (with POSTECH) since 2005
- Design based on BNL S-band gun
- 1.61 cell & side coupling with 2 RF coupling and 2 pumping holes
- Drive laser normal incident to cathode
- Solenoid immediate downstream of the gun
- Designed for 120 Hz operation at 120 MV/m
- Beam commissioning ongoing at ITF
- RF operation is stable up to 30 Hz & 120 MV/m. 60 Hz test was done shortly in summer 2014

J. H. Hong et al, FEL2013, p. 279
Cold Test and Installation of Gun1

Cold test result

Gun installed in ITF

Gun after brazing
60 Hz Gun Operation

Waveguide Vacuums

Klystron Beam Voltage

Gun Vacuums

41.5 kV, 40 Hz (rf 1.5 us)

41.5 kV, 60 Hz (rf 1.5 us)

41.5 kV, 60 Hz (rf 1.75 us)

41.5 kV, 40 Hz (rf 1.75 us)
## Laser System

![Image of laser system](image-url)

### Ti:sapphire Laser Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillator rep. rate</td>
<td>79.333 MHz</td>
</tr>
<tr>
<td>Amplifier rep. rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Center wavelength</td>
<td>770 nm</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>~150 ps</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>20 mJ</td>
</tr>
<tr>
<td>Energy jitter (RMS)</td>
<td>~0.24 %</td>
</tr>
</tbody>
</table>

---

C. H. Kim, C. K. Min
Photocathode Drive Laser Geneartion

- Repetition rate of seed laser (Coherent Mira) set to 79.333 MHz, synchronized to the master oscillator.
- Regenerative amplifier (Coherent Legend Elite) used to generate pre-amplified output with about 150 ps and 120 Hz repetition rate.
- Post-power amplifier boosts output power up to 2.5 W (rms noise; 0.24 %)
UV & IR Laser Transportation

**UV Laser Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength</td>
<td>257 nm</td>
</tr>
<tr>
<td>Pulse energy (variable)</td>
<td>Up to 1 mJ</td>
</tr>
<tr>
<td>Pulse duration (variable)</td>
<td>3~5 ps</td>
</tr>
<tr>
<td>Energy jitter (RMS)</td>
<td>~1 %</td>
</tr>
<tr>
<td>Beam size at cathode (variable)</td>
<td>&lt;1 mm</td>
</tr>
</tbody>
</table>

**IR Laser for Laser Cleaning**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength</td>
<td>770 nm</td>
</tr>
<tr>
<td>Pulse energy (variable)</td>
<td>&lt; 400 uJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>~ 150 ps</td>
</tr>
<tr>
<td>Energy jitter (RMS)</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>Beam size at gun (variable)</td>
<td>&lt; 1 mm</td>
</tr>
</tbody>
</table>
Drive Laser Pulse Length Measurement

Different frequency generation (DFG)

Pulse duration by DFG cross-correlation measurement

A drive laser pulse to the cathode is not affected by this measurement

C. H. Kim, C. K. Min

Drive Laser Shape Monitoring

Optics table

Hard aperture
Image transport to cathode

Quad
Iris

Motorized mount
Energy meter
Shutter
Camera

Cathode

C. H. Kim, C. K. Min

Beam profile in virtual cathode camera, φ1 mm iris

Coutesy of C.Min

Accelerating Structures

Delivered from Mitsubishi Heavy Industries

Installed in ITF tunnel

RF coupler
Bunch Generation at Cathode

Beam Charge VS Phase

Quantum Efficiency

J. Hong et al, FEL2014, THP011
Best Results from ITF – July 2013

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>135 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>200 pC</td>
</tr>
<tr>
<td>Gun phase</td>
<td>35 degs</td>
</tr>
<tr>
<td>Acc’s phase</td>
<td>on-crest (both)</td>
</tr>
</tbody>
</table>

![Laser beam profile](image)

\[
\varepsilon_{\text{rms}} (\mu \text{m})
\]

- 100%
- 95%
- 90%
- 80%

Laser beam profile

Emittance with Various Laser Size & Length at 200 pC

Measured in summer 2013

Minimum emittance with 3 ps laser pulse length
Both measurements show discrepancy to simulation
Emittance with longer laser pulse is lower according to simulation
Emittance (95%) at 200 pC
RF deflector for vertical streaking
Horizontal emittance of bunch slices measured

Measurement condition not optimized
Projected & slice emittance measurement planned in September 2014

J. H. Lee et al, FEL2014, THP013
Possible Sources of Large Emittance Value – I

Higher order mode and field alignment of gun solenoid

Gun solenoid
Higher order mode of solenoid field

- Corrector coils to be repaired in September 2014, for higher order mode compensation
Gun solenoid micro-mover is manufactured for beam-based alignment, to be installed at ITF in winter 2014.
Possible Sources of Large Emittance Value – II

Non-ideal longitudinal & transverse profile of drive laser pulse
Possible Sources of Large Emittance Value – III

- Alignment of beam to RF and solenoid fields
  -> New alignment done recently
- Non-symmetric RF coupler field of accelerating structures (?)
  -> Study underway

MHI J-type coupler with circular coupler cell

RF power in
e-beam


32
Other Tests Done

• Laser cleaning of cathode

• Beam test of accelerator components
  – Stripline BPM
  – Beam arrival time monitor (cavity type)
  – Dechirper
  – ...

Laser Cleaning

150 ps long IR (760 nm) laser used for cleaning

QE maps

Photocathode is the central area of the copper gun cavity back plane
QE recovered from 4.0\times10^{-5} to 1.3\times10^{-4} and stayed for a few months

C. K. Min, 6th Hard X-ray Collaboration Meeting, DESY, 2014
Beam Test of Stripline BPM

Calibrated Libera Single Pass E
- KX = KY = 6.666 mm
- Attenuator setting = 18 dB
- Measured resolution = 1.4552 μm

Libera Brilliance Single Pass and BPM controller produced by SLAC were tested at ITF ~ 3 μm with 200 pC (PAL-XFEL linac requirement < 5 μm)
Beam Arrival Time Monitor

2.856 GHz signal analyzed with the LLRF module

Time resolution ~ 10 fs

46 fs rms jitter for 20 min

76 fs rms jitter for 8 hours
Corrugated-Wall Dechirper

Corrugated structure

FIG. 7 (color online). Screen 6 images (top-row: measured, bottom-row: simulated, $Q = 150$ pC), with $g = 6$ mm, rf deflector switched off and L0a phase adjusted 10 degrees off crest, showing no dipole kick when gap is centered on the beam (left), but a strong tail kick with gap off axis by 1 mm (right). The bunch head is at left in each image.

P. Emma et al., PRL 112, 034801 (2014)
Plans

- Vacuum line upgrade with low mu materials in winter 2014
- Laser shaping improvement for spatial & temporal
- Gun solenoid higher order mode cancelation in September 2014
- Finer beam-based alignment including gun solenoid micro-mover in winter 2014
- Test of new gun with coaxial coupler in winter 2014
- Laser heater test in winter 2014
Laser Heater

- Components are ready for installation
- Full beam test to be done at ITF for efficient injector commissioning at PAL-XFEL
Gun2

- 1.5 cell S-band gun with coaxial coupler
- Lower emittance and better thermal behavior expected

To be installed in the ITF tunnel in winter 2014
• PAL-FEL ITF is running for injector commissioning prior to main linac commissioning in a year
• Beam property measurement ongoing, the present beam quality satisfies the required parameter for initial beam commissioning of PAL-XFEL
• R&D and test of diagnostics, high power RF, laser ongoing
• New gun and laser heater to be tested
• ITF to be operational till summer 2015
Thanks