PAL-XFEL S-band Linac

Heung-Sik Kang
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
**PAL-XFEL Parameters**

**Main parameters**

- **e⁻ Energy**: 11 GeV
- **e⁻ Bunch charge**: 20-200 pC
- **Peak current**: > 3 kA
- **Slice emittance**: < 0.4 mm mrad
- **Repetition rate**: 60 Hz
- **FEL pulse duration**: 5 fs – 50 fs
- **SX line switching**: DC magnet
  
  (to be changed to Kicker by 2020)

**RF system**

- 50 S-band RF stations
  - 50 klystrons (80 MW, 4 us, 60 Hz, Thoshiba)
  - 50 klystron modulators
  - 42 energy doublers
  - 50 LLRF systems
  - 174 S-band accelerating structures
- 1 X-band RF

**Operation RF phase**

- **Gun**: -33.7
- **L1**: -10.5
- **X-linearizer**: -180.0
- **L2**: -19.6
- **L3**: -3.0
- **L4**: -2.0
A highly stable FEL performance is achieved through a reliable & stable operation of the S-band electron linac

- Based on a matured S-band technology established in Industry
- Temporal stability: ~18 fs (rms) between XFEL pulses and optical pulses from a synchronized laser system
- Relative electron beam energy jitter: < 1.5 x 10^-4
  → on crest acceleration: < 5 x 10^-5
- Electron beam arrival time jitter: < 15 fs
- Projected emittance
  - Injector: 0.42 / 0.43 mm-mrad @250 pC
  - Linac end: 0.60 / 0.55 mm-mrad @220 pC
- RF stability (rms)
  - L1 (w/o SLED): 0.01 degrees / 0.01%
  - L2, L3, & L4 (w/ SLED): 0.015 degrees / 0.02%
Linac System

- **Klystron modulator voltage stability**: < 30 ppm

L1 (w/o SLED) | L2, L3, and L4 (w/ SLED)

- Height of beam center: 80 cm
- Cooling temperature of accelerating structure: 30 +/- 0.01 °C
- Quasi symmetric feed (single arm coupling) to reduce the dipole kick
  - coupler cavity with round geometry: 120 structures by Mitsubishi
  - coupler cavity with racetrack geometry: 54 structures by Vitzro-Tech
Basic Unit Module of XFEL Linac

- Energy Doubler
- S-band Traveling Wave Accelerator Structures
- S-band Klystron Tube
- S-band Waveguide Network
- Dummy Load
- Linac Tunnel
- Klystron Gallery
- 2 m Thick concrete shielding

- 74 MW
- ~250 MW (SLED output)
Linac Tunnel
S-band Structure (Quasi-symmetric coupler with racetrack shape)

- Quasi symmetric feed (single arm coupling) to reduce the dipole kick
  - The same direction of coupler cavity makes the waveguide network simple
  - Racetrack type coupler cavity to reduce the quadrupole kick
- Max. accelerating gradient: 27 MV/m

**Table: S-band Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>S-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency(GHz)</td>
<td>2856 ±0.5</td>
</tr>
<tr>
<td>Mode</td>
<td>2p/3</td>
</tr>
<tr>
<td>Q</td>
<td>13,000</td>
</tr>
<tr>
<td>Shunt Impedance(Mohms)</td>
<td>53</td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>0.57(4.9dB)</td>
</tr>
<tr>
<td>Filling Time(us)</td>
<td>0.83</td>
</tr>
<tr>
<td>Water Temperature(°C)</td>
<td>30±0.01</td>
</tr>
<tr>
<td>Type</td>
<td>Quasi-Symmetric</td>
</tr>
<tr>
<td>Total Length(mm)</td>
<td>3138</td>
</tr>
</tbody>
</table>
S-band Energy Doubler

- Two-hole coupling structure to withstand 380 MW peak RF power
- Energy gain: \(~1.6\)
- Remote control of the tuning frequency by a stepping motor
- Collaborated with a Korean company: Vitzro-Tech
20-ppm Stability Inverter PS-type Modulator

- Collaborated with two Korean companies: Posco-ICT(Vitzro-Tech) & Dawon-Sys

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Output Power</td>
<td>125</td>
<td>kW</td>
</tr>
<tr>
<td>Max. Output Voltage</td>
<td>50</td>
<td>kV</td>
</tr>
<tr>
<td>Pulse width</td>
<td>7.5</td>
<td>μs</td>
</tr>
<tr>
<td>Avg. Output Current</td>
<td>8.5</td>
<td>A</td>
</tr>
<tr>
<td>AC Input Voltage</td>
<td>480</td>
<td>VRMS</td>
</tr>
<tr>
<td>Efficiency</td>
<td>90</td>
<td>%</td>
</tr>
<tr>
<td>Cooling water</td>
<td>40</td>
<td>L/Min</td>
</tr>
</tbody>
</table>

### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<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>RF pulse width(flattop)</td>
<td>μs</td>
<td>4</td>
</tr>
<tr>
<td>Load impedance</td>
<td>Ω</td>
<td>800</td>
</tr>
<tr>
<td>Pulse transformer turn ratio</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>PFN impedance</td>
<td>Ω</td>
<td>2.7</td>
</tr>
<tr>
<td>PFN voltage</td>
<td>kV</td>
<td>46</td>
</tr>
</tbody>
</table>

### rms Stability: 17.1 ppm
Peak-to-peak Stability: 120.0 ppm
RF gun

With 4 ports, we can make almost uniform electric field distribution.

This model is easy to fabricate.

Four ports is helpful to maintain the vacuum level.
RF timing distribution system

- based on low phase noise oscillator and coaxial cable (476 MHz) with passive stabilization
- Balanced optical & microwave phase detector (BOM-PD) for synchronization between RF and optical laser

Temperature stabilized duct for reference RF

Integrated jitter (1 Hz~1MHz) : ~0.6 fs

DRO : Dielectric resonator oscillator developed by RUPPtronik in Germany
 Beam-based Feedback

◆ Orbit feedback
  ▪ range: Linac to undulator
  ▪ use all correctors and BPMs except dispersive BPMS
  ▪ runs at 1 Hz
  ▪ The rms of the orbit variation along the undulator line
    x-plane: < 4.2 µm, y-plane : < 2.5 µm

◆ Energy feedback
  ▪ dispersive BPM
  ▪ runs at 1 Hz

◆ Bunch length feedback
  ▪ CRM (coherent radiation monitor)
    at bunch compressors
Thank you for your attention
Back-up slide
2018 User service operation statistics

- 2018 operation statistics
  - Planned beam time: 2057 h
  - Fault time: 101 h
  - Beam availability: 95%

Fault Statistics

- Control: 30%
- Modulator: 22%
- Beamline: 9%
- Laser: 2%
- LLRF: 7%
- Mag. PS: 7%
- Others: 22%
Machine Performances

- Photon energy: 2.0 ~ 14.5 keV
- FEL pulse energy: 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%
FEL intensity stability (9.7 keV FEL)

**Short-term (3 min.)**
- Intensity jitter: 3.1%

**Long-term (10 hour)**
- Jitter: 4.3% in rms
**Injector Emittance**

**Projected emittance**
- Beam energy: 135 MeV
- Beam charge: 250 pC

\[
\begin{align*}
E &= 0.135 \text{ GeV} \\
Q &= 0.252 \pm 0.00 \text{ pC} \\
\gamma_A &= 0.42 \pm 0.01 \text{ mrad} \\
\xi_x &= 1.10 \pm 0.01 \\
\end{align*}
\]

\[
\begin{align*}
x: & \quad 0.42 \text{ mm-mrad} \\
\end{align*}
\]

\[
\begin{align*}
E &= 0.135 \text{ GeV} \\
Q &= 0.251 \text{ nC} \\
\gamma_x &= 0.43 \pm 0.01 \text{ mrad} \\
\xi_x &= 1.03 \pm 0.01 \\
\end{align*}
\]

\[
\begin{align*}
y: & \quad 0.43 \text{ mm-mrad} \\
\end{align*}
\]

**Slice emittance**

Slice Emittance Scan on HL1:SCM11
29-Sep-2018 11:14:23 Asymmetric

**Cut-gaussian laser beam profile**
- **50 S-band RF stations**
  - 50 Klystrons (80 MW, 4 us, 60 Hz, Thoshiba)
  - 50 klystron modulators
  - 42 Energy doublers
  - 50 LLRF Systems
  - 174 S-band accelerating structures
- **1 X-band RF station**
- **27 Undulators (5-m variable gap, 20 for HX and 7 for SX)**
## 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>
</tr>
</thead>
<tbody>
<tr>
<td>Injector linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard X-ray main linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.33</td>
</tr>
<tr>
<td>L2</td>
<td>10</td>
<td>40</td>
<td>10</td>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td>L3A</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>L3B</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>3.45</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>27</td>
<td>108</td>
<td>27</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Soft X-ray linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflector (S-band)</td>
<td>L1, L3</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>3~3.5</td>
</tr>
<tr>
<td>Linearizer (X-band)</td>
<td>L1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total No.</td>
<td>51</td>
<td>180</td>
<td>42</td>
<td></td>
<td></td>
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</tbody>
</table>
## Main System Supplier for PAL-XFEL

<table>
<thead>
<tr>
<th>Item</th>
<th>No. of components</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band Accelerating Column</td>
<td>175</td>
<td>120: Mitsubishi 55: Vitzrotech</td>
</tr>
<tr>
<td>S-band Energy Doubler</td>
<td>42</td>
<td>Vitzrotech</td>
</tr>
<tr>
<td>200-MW Modulator</td>
<td>50</td>
<td>Vitzrotech Dawon-Sys</td>
</tr>
<tr>
<td>80 MW S-band Klystron</td>
<td>50</td>
<td>Toshiba</td>
</tr>
<tr>
<td>S-band LLRF / SSA</td>
<td>50</td>
<td>Mobiis</td>
</tr>
<tr>
<td>Magnet</td>
<td>251</td>
<td>KR Tech T. H. Elema</td>
</tr>
<tr>
<td>Undulator</td>
<td>37</td>
<td>SFA Seong-Ho High tech.</td>
</tr>
<tr>
<td></td>
<td>(20 for HX, 7 for SX)</td>
<td></td>
</tr>
<tr>
<td>BPM electronics</td>
<td>Stripline, cavity BPM</td>
<td>SLAC</td>
</tr>
</tbody>
</table>
X-band SSA

Specifications

• 20-way combiner + Dual direct. coupler I.L $< 0.8$dB
• Pout of Unit SSPA $> 49.0$dBm (80W)
• 20ea * Unit SSPA $> 62.0$dBm (1.6KW)
• Final Coaxial Cable I.L $< 0.5$dB
• Final Flange Adapter I.L $< 0.2$dB
• Final Pout $60.5$dBm (1.1KW)
High Power Test of Accelerating Structures

RF Conditioning time (60Hz, 27MV/m)

<table>
<thead>
<tr>
<th>Maker</th>
<th>Conditioning Time (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>94.69</td>
</tr>
<tr>
<td>MHI</td>
<td>31.36</td>
</tr>
<tr>
<td>VITZRO</td>
<td>29.81</td>
</tr>
</tbody>
</table>

Dark Current vs. Rep. Rate
SLED frequency tuning system

SLED

SLED frequency tuning system layout
5. Corporate Status

Current Business Scope

- Accelerator
  - Nuclear Fusion Biz
  - Photon Accelerator
  - Heavy Ion Accelerator
- Cryogenic
  - Cryo-plant
  - Cryomodule
  - Cooling system
- Plasma Application
  - KSTAR Power Supply
  - Radioactive Treatment
  - Plasma Torch
- Aerospace
  - Rocket Engine
  - Test Facility
  - H.P. Oxidizer Piping
- Vacuum System
  - Vacuum System
  - Vacuum Gate valve
- Electric Power
  - High Power Breaker
  - Semiconductor
  - VI
  - Insulation
5. Facility & Certification

Manufacturing Facility

- Brazing Furnace
- E-beam Welder (150kV)
- Cleanroom for Storage
- Machining (5 axis)
- Clean Room (10000 class)
- Clean Room (10 class)
- Chemical Treatment (18MΩ)
3. Main Business Participation (Project Experience)

PAL 4th Generation XFEL - Accelerating Column & Waveguide Components

- Vitzrotech had participated in 4th Generation PAL XFEL
- Designed, Analyzed, Fabricated, Supplied, Installed Accelerator Columns
  [From Engineering to Installation]
- Fabricated, Supplied, Installed whole quantities of Waveguide components and SLED Cavity
- Fabricated, Supplied, Installed Beam Line Systems
### 3. Main Business Participation (Project Experience)

**PAL 4th Generation XFEL – SLED Cavity**

#### Mechanical Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Divider Length [mm]</td>
<td>380</td>
</tr>
<tr>
<td>Vacuum Leak Rate [Pa.m²/sec]</td>
<td>(\leq 1.3 \times 10^{-11})</td>
</tr>
</tbody>
</table>

#### Electrical Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Q</td>
<td>(\geq 95,000)</td>
</tr>
<tr>
<td>Coupling Coefficient</td>
<td>5.0±0.1</td>
</tr>
<tr>
<td>Cavity mode</td>
<td>TE 0,1,5</td>
</tr>
<tr>
<td>Operating Freq. [MHz]</td>
<td>2.856</td>
</tr>
<tr>
<td>Operating Temp. [°C]</td>
<td>30±0.1</td>
</tr>
<tr>
<td>Maximum Peak RF Power [MW]</td>
<td>320</td>
</tr>
<tr>
<td>Maximum average RF power [kW]</td>
<td>(\leq 23)</td>
</tr>
</tbody>
</table>

**RF Inspection by Network Analyzer**
3. Main Business Participation (Project Experience)

**SLAC LCLS-II Project - X-Band Cavity RF BPM**

- Vitzrotech manufactured and supplied X-Band RF BPM (Beam Position Monitor) for SLAC LCLS-II with core technologies such as precision machining, precision joining (Brazing), precision assembly and Tuning.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole Cavity</td>
<td></td>
</tr>
<tr>
<td>Nominal Frequency TM(_{110})</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Tolerance TM(_{110})</td>
<td>+/- 10 MHz</td>
</tr>
<tr>
<td>QL or Qtotal</td>
<td>2000–3000</td>
</tr>
<tr>
<td>Cavity Coupling [(\beta)]</td>
<td>1.9–2.1</td>
</tr>
<tr>
<td>Q(_0)</td>
<td>5800–9300</td>
</tr>
<tr>
<td>Q(_{ext})</td>
<td>2762–4894</td>
</tr>
<tr>
<td>X/Y Cross Talk</td>
<td>&lt; -20 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Cavity</td>
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</tr>
<tr>
<td>Nominal Frequency TM(_{110})</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Tolerance TM(_{110})</td>
<td>+/- 10 MHz</td>
</tr>
<tr>
<td>QL</td>
<td>2000–3000</td>
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<tr>
<td>Cavity Coupling [(\beta)]</td>
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<td>Q(_{ext})</td>
<td>2762–4894</td>
</tr>
</tbody>
</table>

**Core Technology**

1. RF Analysis, Design (CST)
2. Precision Machining (Mirror surface)
3. Surface Treatment for Ultra High Vacuum Component
4. Ultra Precision Assembly & Brazing
   - (Feedthrough + Cavity Body)
5. RF Test & Tuning