Updated Status of the PAL-XFEL Vacuum System

Donghyun Na
PAL VACUUM GROUP
POHANG ACCELERATOR LABORATORY

April. 2, 2014
Acknowledgement

The design and fabrication procedures are basically based on the previous work done by the vacuum group of LCLS, European XFEL, PSI and FERMI@ELETTRA.

We thank to them for the helpful discussions and the reference materials!
Contents

I. Introduction of PAL-XFEL

II. Linac Vacuum system

III. Undulator Vacuum system

IV. Summary
Schedules for Fabrication and Installation

2011


<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>

- **2011**: Concentrated on Al surface study
- **2012**: XFEL project start, ITF installation
- **2013**: Abrasive flow polishing test, Extrusion test (U-chamber)
- **2014**: 1st prototype (U-chamber), 2nd prototype (U-chamber: Ver. 2)
- **2015**: 3rd prototype (U-chamber: Ver. 3), RF conditioning start, Injector commissioning, Commissioning start, Purchase order (Gate valve, CCG...)
- **2016**: Purchase order (Small vacuum components), 1st prototype (BC, Collimator), Completion of installation, Installation start, 2nd prototype (U-chamber: Ver. 3)

Legend:
- ITF installation
- Abrasive flow polishing test
- Extrusion test (U-chamber)
- XFEL project start
Building Construction

July 20, 2013

August 2, 2013

Dec. 2013

March. 18, 2014
Vacuum system Requirement

**Injector Vacuum**

- Pressure @ RF gun $\sim 1 \times 10^{-10}$ mbar (cathode lifetime, dark current)
- Pressure @ Accelerating column $< 5 \times 10^{-7}$ mbar (RF break down)
- Symmetric beam pipe and RF shielded components are needed

RF photocathode gun (Cu cathode)
- **VTO** technology
  (STS chamber, 450°C, 24 h, $1 \times 10^{-9}$ mbar $O_2$)
- $P \sim 3 \times 10^{-11}$ mbar without RF power
- Less than $5 \times 10^{-10}$ mbar with RF power

- Outgassing rate: $2 \times 10^{-14}$ mbar l/s cm$^2$
Vacuum system Requirement

Linac Vacuum
- Pressure @ Klystron window $< 5 \times 10^{-8}$ mbar (RF break down)
- Pressure @ Accelerating column $< 5 \times 10^{-7}$ mbar
- RF shielding for joint and bellows are not needed (?)

Undulator Vacuum
- Surface roughness $< 200$ nm (100 nm)
- Surface oxide layer $< 5$ nm (10 nm)
- Pressure $< 1 \times 10^{-5}$ mbar (beam-gas interaction)
- RF shielding for joint and bellows are needed
Layout of Linac Vacuum

L1

L2, L3, L4

SIP(60 l/s)

CCG
pressure profile along a LINAC column for various pumps - PAL XFEL

(In case for some SIP failure)
Bunch compressor Vacuum system

Modeling of Bunch compressor2

- 4 Sputter ion pumps (60 l/s)
- Cold cathode gauge
- 4 Bellows
- Movable girder
- Beam Direction
1\textsuperscript{st} Prototype of Bunch compressor2

- **Dimension of Bunch compressor2**

![Diagram of Bunch compressor2](image)

- Changing the Bending Angle: $0^\circ \sim 3.7^\circ$

![Diagram of Bunch compressor2](image)

- Dimensions:
  - $7090.5$ (L1)
  - $1348.3$ (L3)
  - $1600$
  - $7090.5$
  - $5742.2$
  - $1348.3$
### Bunch compressor Vacuum system

#### Requirements of Bunch compressor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BC1</th>
<th>BC2</th>
<th>BC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 [m]</td>
<td>4.4845</td>
<td>7.1905</td>
<td>7.597</td>
</tr>
<tr>
<td>L2 [m]</td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>L3 [m]</td>
<td>1.146</td>
<td>1.3483</td>
<td>2.349</td>
</tr>
<tr>
<td>Dipole gap [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bimetal flange - Friction welding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam size (y) [mm]</td>
<td>0.121</td>
<td>0.068</td>
<td>0.053</td>
</tr>
<tr>
<td>Half aperture of Vacuum Chamber in x [mm]</td>
<td>50</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>0.33</td>
<td>2.52</td>
<td>3.45</td>
</tr>
<tr>
<td>Chamber material</td>
<td>Al</td>
<td>Cu</td>
<td>STS+Cu plating</td>
</tr>
<tr>
<td>Surface roughness (nm)</td>
<td></td>
<td>&lt; 250 (Collimator &lt; 200)</td>
<td></td>
</tr>
<tr>
<td>Leak tightness (mbar L/s)</td>
<td>&lt; 1 x 10^{-9}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (P_{ave}, mbar)</td>
<td>&lt; 5 X 10^{-7}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Bending Magnet Vacuum chamber (rectangular)**
1) Inner dimension: 100 x 25 mm, thickness 2 mm
2) roughness: < 250 nm
3) material: Al6063
4) relative permeability($\mu_r$): < 1.03

**Drift chamber (circular)**
1) O.D 42 mm, I.D 38 mm for Quadrupole chamber
2) O.D 100 mm, I.D 92 mm for Drift chamber
3) relative permeability($\mu_r$): < 1.03 for Q-chamber

**Diagnostic section**
1) Two sputter ion pump near diagnostic instrument to reduce pressure rise induced by collimator, slotted foil and screen
2) One cold cathode gauge to measure pressure
3) E-BPM, Collimator, Slotted foil, Screen will be placed

---

![Diagram of 1st Prototype of Bunch compressor2](image-url)
Collimator (Energy and Geometry)
### Collimator (Energy and Geometry)

#### Requirements of Collimator

<table>
<thead>
<tr>
<th>List</th>
<th>ECBC1</th>
<th>ECBC2</th>
<th>ECBC3</th>
<th>ECBC3SX</th>
<th>ECHXDogleg</th>
<th>GCL4E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collimator shape</strong></td>
<td>Parallel Jaw</td>
<td>Parallel Jaw</td>
<td>Parallel Jaw</td>
<td>Parallel Jaw</td>
<td>Parallel Jaw</td>
<td>Parallel Jaw</td>
</tr>
<tr>
<td><strong>Collimator material</strong></td>
<td>OFHC Cu</td>
<td>OFHC Cu</td>
<td>OFHC Cu</td>
<td>OFHC Cu</td>
<td>OFHC Cu</td>
<td>OFHC Cu</td>
</tr>
<tr>
<td><strong>Gap adjust</strong></td>
<td>Individual jaw movement</td>
<td>Individual jaw movement</td>
<td>Individual jaw movement</td>
<td>Individual jaw movement</td>
<td>Individual jaw movement</td>
<td>Individual jaw movement</td>
</tr>
<tr>
<td><strong>Beam offset tolerance</strong></td>
<td>1.257 cm</td>
<td>2.408 cm</td>
<td>1.049 cm</td>
<td>0.588 cm</td>
<td>0.053 cm</td>
<td>0.02 cm</td>
</tr>
<tr>
<td><strong>Jaw moving resolution</strong></td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>50 μm</td>
</tr>
<tr>
<td><strong>Jaw moving range</strong></td>
<td>-10 mm &lt; Δ &lt; 30 mm</td>
<td>-10 mm &lt; Δ &lt; 30 mm</td>
<td>10 mm &lt; Δ &lt; 30 mm</td>
<td>-10 mm &lt; Δ &lt; 30 mm</td>
<td>-10 mm &lt; Δ &lt; 30 mm</td>
<td>-5 mm &lt; Δ &lt; 10 mm</td>
</tr>
<tr>
<td><strong>Jaw length</strong></td>
<td>7.024 cm</td>
<td>18.024 cm</td>
<td>20.024 cm</td>
<td>20.024 cm</td>
<td>20.024 cm</td>
<td>20.024 cm</td>
</tr>
<tr>
<td><strong>Taper Angle</strong></td>
<td>1 deg</td>
<td>1 deg</td>
<td>1 deg</td>
<td>1 deg</td>
<td>1 deg</td>
<td>1 deg</td>
</tr>
<tr>
<td><strong>Surface roughness</strong></td>
<td>&lt; 200 nm</td>
<td>&lt; 200 nm</td>
<td>&lt; 200 nm</td>
<td>&lt; 200 nm</td>
<td>&lt; 200 nm</td>
<td>&lt; 200 nm</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td><strong>수량</strong></td>
<td>1 EA</td>
<td>1 EA</td>
<td>1 EA</td>
<td>1 EA</td>
<td>1 EA</td>
<td>25 EA</td>
</tr>
</tbody>
</table>
1st Prototype of Collimator Vacuum system

- Modeling of Collimator
1st Prototype of Collimator Vacuum system
Layout of Undulator Vacuum

- Undulator hall is long (190 m) enough for 30 sets of 5-m undulator
Layout of Undulator Vacuum

HX Undulator

(20 L/s)

Seeding section

(No space for gate valve between U-chambers)
### Change of Undulator and Vacuum Chamber

**PAL XFEL X-ray Undulator**

- **Variable Gap**: 8.3 mm (min)
- **Face of the Undulator Magnet**

**Vacuum Chamber**

- **Outer diameter**: 7.5 mm
- **Length**: 5,000 mm

---

<table>
<thead>
<tr>
<th></th>
<th>LCLS</th>
<th>PAL Ver. 2</th>
<th>PAL Ver. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Undulator Length [m]</strong></td>
<td>3.4</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Undulator Gap [mm]</strong></td>
<td>6.8</td>
<td>7.2</td>
<td>8.3</td>
</tr>
<tr>
<td><strong>Saturation length [m]</strong></td>
<td></td>
<td>115.7</td>
<td>128.8</td>
</tr>
<tr>
<td><strong>Quantity (required/fab.)</strong></td>
<td>33/40</td>
<td>33/40</td>
<td>33/40</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>A6063-T5</td>
<td>A6063-T5/T6</td>
<td>A6063-T5/T6</td>
</tr>
<tr>
<td><strong>Aperture (VxH) [mm]</strong></td>
<td>5 x 11</td>
<td>5.2 x 11 (racetrack)</td>
<td>6.7 x 13.4 (elliptical)</td>
</tr>
<tr>
<td><strong>Thickness [mm]</strong></td>
<td>0.5±0.05</td>
<td>0.5+0.05,-0.1</td>
<td>0.4±0.05</td>
</tr>
<tr>
<td><strong>Flatness</strong></td>
<td>&lt; 50</td>
<td>&lt; 100</td>
<td>&lt; 100</td>
</tr>
<tr>
<td><strong>Clearance (pole to ch.) [mm]</strong></td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Change of U-Chamber Cross section

Cross section (Ver. 2)
- e-beam chamber: Cross section 5.2 x 11 mm, Thickness: 0.5 mm
- Undulator
- Magnet cage
- Cooling channel
- Holes for correction coil

Cross section (Ver. 3)
- e-beam chamber: Cross section 6.7 x 13.4 mm, Thickness: 0.4 mm
- Undulator
- Magnet cage
- Cooling channel
- Holes for correction coil
U-Chamber Fabrication Procedure

Die / Tip Design & Build

Surface Analysis

A abrasive Flow Polishing

Precision Machining

6m extrusion chamber

0.5 mm ± 10 um
Extrusion in the controlled gas environment

Special extrusion procedure

➢ To prevent exposure to ambient air during extrusion process

Controlled gas \((\text{Ar} + \text{O}_2)\)

Vacuum chamber

Gas hole

Extrusion tip
Chemical polishing procedure

1. Hot DI storage tank → Aluminum (heating) → Drain
2. Chemical polishing storage tank → Chemical polishing → Circulation
3. DI water supply rinse → Rinsing → Drain
4. Citric acid storage tank → Cleaning, removing oxide layer → Circulation
5. DI water supply rinse → 1st rinsing → Drain
6. DI water supply rinse → 2nd rinsing, conductivity & PH check → Drain
7. LN2 supply dry → Dry → Packing
Precision machining results

➢ Chamber thickness

Precision machining results

0.5 mm ± 10 um

(Day 1)

0.5 mm ± 100 um

(Updated)

0.5 mm ± 10 um

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Precision machining results

- Chamber flatness

![Image of chamber flatness]

Graph showing precision machining results with less than 30 um flatness.
Roughness Result

Roughness measurement after abrasive flow machining

\[ R_a = \frac{1}{l} \int_0^l |f(x)| \, dx \]

- **Extrusion only**
  - Beam direction: 270 nm
  - Perpendicular direction: 200 nm

- **Extrusion & AFM SiC#600 40hrs**
  - Beam direction: 1.8 μm
  - Perpendicular direction: 1.1 μm

- **Extrusion & AFM Al₂O₃#320 40hrs**
  - Beam direction: 0.6 μm
  - Perpendicular direction: 0.6 μm

640x640 (um)
Oxide thickness - TEM images

May, 2013

Extrusion with polished tip and Controlled environment (Ar 90%+O₂ 10%)
+ Abrasive Flow Machining
+ Chemical cleaning

Extrusion with polished tip and Controlled environment (Ar 90%+O₂ 10%)
Oxide thickness - TEM images

March, 2014

Abrasive flow polishing

Oxide layer 4.42nm  
AFP 140 hr

Oxide layer 3.79nm  
AFP 140 hr + Citric acid

Test is ongoing

Chemical polishing

Oxide layer 4.17nm  
Chemical polishing

Oxide layer 3.40nm  
Chemical polishing + Citric acid

FIB Ga contamination
carbon  
Al
Undulator and Intersection Vacuum system

Undulator Inter-section (ver 3)

Length 1 m

Beam direction

Limit sensor  LVDT  phase shifter  beam loss monitor  mover  cavity BPM  quadrupole  pumping spool  corrector  limit sensor
Undulator and Intersection Vacuum system

- **Undulator Inter-section (ver 3)**

  - **Cross section of Undulator Intersection**
  - **Inter-section Vacuum chamber**
  - **RF shielded Al tube in Pumping spool**

  - Bellows (SST)
  - PS-chamber (Al)
  - QM-chamber (Al)
  - Inner Al pipe of RF shielded bellows
  - Al-Al joint (TIG welding)
  - Al-SST bi-metal joint (friction welding)
  - Pumping chamber (SST)
Undulator intersection (cross section)

- Undulator Inter-section (ver 3)

- Beam direction

- Al tube (I.D 9 mm) (for RF shield)
- RF contact
- friction welding
- Aluminum welding
- Al tube (I.D 9 mm) (for RF shield)
- bellows (SST 316L)
- RF contact
- QM chamber (Al, I.D 9 mm)
- undulator chamber (Al, 6.7 x 13.4 mm)
- Pumping slit (Al, 20 x 1 mm, 10 ea)
Undulator Inter-section (ver 3)

- Al tube (I.D 9 mm)
  (for RF shield)
- Phase shift chamber
  (Al, I.D 9 mm)
- BLM
  (O.D 19 mm)
- bellows
  (SST 316L)
- Al tube (I.D 9 mm)
  (for RF shield)
- PNW-15 flange
  (SST 316L)
Minimized Cross section change

Ver 2

Phase shifter chamber
Quadurpole chamber
BPM
Pumping spool

5.2 x 11 mm (race track)

Ver 3

Phase shifter chamber
BPM
Quadurpole chamber
Pumping spool

Minimized Cross section change
Reduced welding joint steps

Ver 2

5 Joint steps

Ver 3

2 Joint steps
3rd Proto-type Undulator intersection

Friction welding (SST316L / Al6063)
Pumping down test of U-chamber

- Measurement: Orifice method with ion gauge
- Test chamber: Half of the undulator chamber
- Pumping speed: 2.3 L/s
- Outgassing rate = $2.3 \times 10^{-11}$ mbar L/s cm$^2$ (@ 100 h)
Pumping down curve

20 h to reach 1E-6 torr

- P1 (GPATM), S = 0.01837 l/s, P1 = 1.27e-5 * t^(-0.8985), R=0.9981 (1 < t < 20 h)
- P2 (GPATM), S = 2.3 l/s, P2 = 7.5e-7 * t^(-0.9970), R=0.9983 (1 < t < 20 h)
- P3 (GPATM), S = 17 l/s, P3 = 3.6e-7 * t^(-1.0771), R=0.9987 (1 < t < 20 h)
Summary

- **Injector vacuum**
  - Combination of SIP and NEG is used for the gun vacuum (low 10\(^{-10}\) mbar)
  - ITF vacuum installation finished & commissioning is on-going
  - ITF gun vacuum will be optimized for the PAL-XFEL gun

- **Linac vacuum**
  - Much experience of S-band linac vacuum system with PLS-II linac

- **Bunch compressor, collimator**
  - Design of bunch compressor and collimator finished recently
  - Purchase order of the 1\(^{st}\) prototype BC in 2013.11
  - 1\(^{st}\) prototype collimator is fabricated (2014.03)

- **Undulator vacuum**
  - 3\(^{rd}\) prototype of U-chamber is now being fabricated
  - Satisfies RF requirements (roughness<200 nm, oxide layer<5 nm)
  - 3\(^{rd}\) version of the undulator intersection fabricated (2014.03)
  - Chemical polishing technique is developed for the U-chamber (for better quality control)
Thank you for your attention