Sub-20-femtosecond timing jitter of PAL-XFEL

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on behalf of PAL-XFEL team

Pohang Accelerator Laboratory
PAL-XFEL: Third Hard-Xray Femtosecond Laser

**Photocathode**
- RF-gun

**Acceleration column**
- RF-gun
- Undulator
- Beam abort dump
- Tune-up dump
- Main dump

**Main parameters**
- **e⁻ Energy**: 10 GeV
- **e⁻ Bunch charge**: 20-200 pC
- **Slice emittance**: 0.5 mm mrad
- **Repetition rate**: 60 Hz
- **Pulse duration**: 5 fs – 100 fs
- **Peak current**: 3 kA
- **SX line switching**: DC (Phase-1) Kicker (Phase-2)

<table>
<thead>
<tr>
<th>Undulator Line</th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength [nm]</strong></td>
<td>0.1 ~ 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 or gap)</td>
<td>4.5 ~ 3 (energy) 3 ~ 1 (gap)</td>
</tr>
<tr>
<td><strong>Undulator Type</strong></td>
<td>Planar, out-vac.</td>
<td>Planar + EPU</td>
</tr>
<tr>
<td><strong>Undulator Period / Gap [mm]</strong></td>
<td>26 / 8.3</td>
<td>35 / 8.3</td>
</tr>
</tbody>
</table>
Injector Laser

Experimental Lasers
for soft X-ray

Experimental Lasers
for hard X-ray

RF components
in Linac

And diagnostics
(bunch arrival time monitor)

Time and energy relationship
(phase space)

4.0% RMS for 1 hour

Time resolution
(timing jitter between FEL and optical laser)
Content

- Timing distribution based on low phase noise oscillation coaxial cable with passive stabilization
- Timing jitter performance of gun and linac in terms of arrival jitter
- e-bunch arrival jitter and FEL jitter (bunch arrival time) (optical crosscorrelator)
PAL-XFEL timing distribution (2.856GHz RF)

Integrated jitter (1 KHz~ 1 MHz) : ~0.8 fs
-160 dBc/Hz at 100KHz offset
-170 dBc/Hz at 1 MHz offset

Integrated jitter (1 Hz~1MHz) : ~0.6 fs
Temperature stabilization of RF Cables

Duct cross-section

With cover open

LCW flow diagram

Temperature stability of Duct: 0.01°C/day
Injector laser room

Clean Room Temperature stability 0.1 ℃
Humidity stability 1%
Phase Drift monitoring using drift-free optical link

~ 0.5 ps/day

10 fs rms jitter

Libera Sync3

~ 750 m
Time scale of timing error in reference timing distribution

100 Seconds: 10.2 fs RMS

10 minutes: 14.8 fs RMS

1 hour: 24.8 fs RMS

1 day: 275 fs RMS

Jitter (fs RMS) vs. Time (Seconds) graph
Photocathode gun - e⁻ bunch arrival jitter

Home-built sensitive phase detector
Between RF and optical laser
(2.856 GHz) (79.33 MHz Ti:S)
Provides **10 fs level jitter**

Gun RF amplitude stability for one day

RF system adds ~10⁻⁴ amplitude jitter
~10 fs timing jitter

B-A = λ/2
Beam arrival time jitter at gun

Monopole S-band cavity (phase cavity)

GUN, ~11 fs rms

1 hour
Beam arrival time jitter at gun and undulator end

GUN, ~11 fs rms

Undulator end, ~19 fs rms
E-beam energy jitter

100 fs drift /10^{-3} energy change at BC2
FEL timing jitter

FEL/optical laser cross-correlation

\[ \Delta t_{\text{OXC}} \text{ [fs]} \]

\[ \text{Pulse #} \]

\[ \Delta t_{\text{BAM1}} \text{ [fs]} \]

\[ \text{Pulse #} \]

\[ \text{# of events} \]

\[ \Delta t \]

18.3 fs RMS

\[ \text{# of events} \]

\[ \Delta t \]

20 fs RMS

e\text{- bunch arrival time at undulator end}
Stability of electron beam and FEL generation

In general, e⁻ beam arrival time doesn’t tell FEL pulse length fluctuation and position (optical laser temporal profile will be stable)

~20 fs RMS
~8 fs RMS

In our case, e beam and FEL process seems to be stable in 10 fs scale (3 BC scheme, careful Undualtor BBA, Matching helps)
Summary

- Currently, PAL-XFEL and optical laser for exp. shows sub 20 fs jitter performance at the measurement time scale of time-resolved experiment (~10 minutes).
  - Temperature stabilized, vibration resistive coaxial cable based RF timing distribution with the combination of low phase RF oscillators provide ~ 1 fs RMS (1 second time scale), ~ 15 fs RMS (10 minutes time scale), ~500 fs drift (1 day)

- ~10 fs RMS arrival time jitter at the gun become twice at the undulator end and which is correlated with energy jitter: 100 fs drift /10^{-3} energy change at BC2

Beam based Feedback loop and/or
Optical timing test (Libera Sync 3, 2.2 km, 3 days)

- Reference amplitude
- Libera Sync amplitude
- Reference Phase
- Libera Sync Phase
- A - B

Phase drift <10fs
Phase drift estimation due to RF Cables

- 476 Mhz low loss cables
  : Huber+Suhner, SUCOFEEDE_ 1_5/8_LA,
  Loss : <1.5 dB/100m
  Drift : ≈ 130 fs/mK
  → For 1 km and with 0.1°C stability, 13 ps drift is expected
     (The huge drift will be compensated by LLRF and beam based feedback)
     Should be compensated

- 2856 Mhz low drift cables
  : RFS, LCF38-50J 3/8”
  Loss : 20.5 dB/100m at 3 GHz
  Drift : ≈ 7 fs/mK
  → For 50 m (max. distance for 2.856 GHz distribution and with 0.1°C stability, 35 fs drift is expected. (15fs for L0, 20 fs for L1&L2)
     considered as minimal
Approximately 14 fs residual phase jitter from 1 Hz to 100 KHz

Out-of-loop measurement

Phase Noise at 2.856 GHz (dBc/Hz)

Offset Frequency (Hz)