Recent Progress of the RF and Timing System of XFEL/SPring-8

M. Musha: Univ. of Electro-communications

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Outline

- X-ray Free Electron Laser (XFEL) project at SPring-8
- Design of the RF and timing system
  - Requirements
  - Design concept
  - Optical RF and timing distribution system
  - Precise low-level RF control system
- Water-cooled enclosure
  - Water-cooled 19-inch rack
  - Water-cooled optical cable duct
- Performance measurement
  - Optical system
  - Low-level RF system
- Summary
XFEL Project at SPring-8
X-ray Free Electron Laser (XFEL)

- To generate coherent and intense x-rays.
  - For life sciences and material sciences etc.
- SASE process
  - Self-Amplified Spontaneous Emission
  - No optical cavity
  - Long undulator beamline is needed
    - To give rise to the interaction between electrons and x-rays.
- Low-emittance and high-peak-current beam are required.

![Diagram of XFEL](image.png)
X-ray wavelength: < 0.1 nm
Beam energy: 8 GeV
Key technologies
- Low-emittance thermionic electron gun: 0.6 $\pi$ mm mrad
- High-gradient C-band accelerator: 35 MV/m
- Short-period in-vacuum undulator: $\lambda_u = 18$ mm
First FEL light will be delivered in 2011.
**XFEL Machine Layout**

- **8GeV linear accelerator**
  - 238 MHz, 476 MHz, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz)
- **Key parameters of SASE-FEL**
  - Normalized slice emittance: \(0.7 \pi \text{ mm mrad}\)
  - Peak current: 3 kA
- **Slice emittance**
  - Accelerate without emittance growth
- **Peak current**
  - Compress the longitudinal bunch structure
- **Bunch compression**
  - Velocity bunching in the low energy region
  - Three bunch compressors (magnetic chicane)
  - Bunch length: 1 ns \(\rightarrow\) 30 fs (FWHM)
  - Peak current: 1 A \(\rightarrow\) 3 kA
Bunch Compressor

- In a magnetic chicane, low-energy electrons travels longer way than high-energy electrons.
- Accelerator gives an energy chirp to the beam.
  - Energy of head electrons is made lower than that of tail electrons.
  - Strength of the energy chirp is very sensitive to the compression ratio.
  - Precise RF phase and amplitude control system is demanded.
Design of the RF and Timing System
Requirements for the Timing System

- Should be as stable as possible!
  - This system provides the timing standard of the whole system.
- Timing stability of the acceleration field
  - Phase stability: 0.1 degree (rms) of 5712 MHz
  - Equivalent to 50 fs (rms)
- Amplitude stability of the acceleration field
  - 0.01% (rms)
- Many RF signals are needed
  - 5712MHz, 2856MHz, 1428MHz, 476MHz, 238MHz and Trigger pulse
- Long transmission length
  - Accelerator: 400 m
  - From the gun to the experimental hall: 700 m
    - Some experiments (pump-probe etc.) demand a precise time reference.
Design Overview

- Optical RF and timing distribution system
  - Attenuation of an optical fiber is much smaller than a metal cable
  - Need to stabilize the fiber length (1 μm = 5 fs)
- Low-level RF control system
  - IQ (In-phase and Quadrature) modulation and demodulation
  - High-speed D/A and A/D converters for baseband signals
Design Concept

- Eliminate fluctuation sources as much as possible before applying active feedback loops.
  - Select stable components (ICs, cables, passive elements ...)
    - Small temperature coefficient
    - Low-noise electric device
  - Stabilize the temperature of each component.
  - Provide low-noise electric power.
  - Reduce vibration of cables
- If there still remain any fluctuations, we use active feedback loops.
Optical RF and Timing Distribution System

- **Wavelength Division Multiplexing (WDM) technique**
  - To combine all signals to one fiber.
- **Phase-stabilized optical fiber (\(\sim 1\) ps/km/K)**
- **Water-cooled 19-inch rack and water-cooled optical fiber duct**
  - To reduce the thermal drift of the RF phase and amplitude
- **Length-stabilized fiber link**
  - Additionally prepared for the phase reference.
  - Michelson interferometer monitors the fiber length.
  - Fiber stretcher controls the fiber length.
  - Time drift of the WDM fiber is controlled at the receiver side.

![Diagram of the Optical RF and Timing Distribution System](attachment:image.png)
**Low-level RF Control System**

- **IQ modulator** produces the acceleration RF signal with appropriate phase and amplitude.
  
  \[ V(t) = I(t) \cos(\omega t) + Q(t) \sin(\omega t) \]

- **IQ demodulator** detects the phase and amplitude of the acceleration RF.

- Baseband waveforms are processed by VME high-speed D/A and A/D converter boards.
  - Sampling rate: **238 MSPS**
  - Resolution: **14 bits (D/A) and 12 bits (A/D)**

- All modules are enclosed in a water-cooled 19-inch rack.
  - To reduce the thermal drift.

- DC power is distributed from a **low-noise power supply**
  - Clean and stable power
  - Small heat load for the 19-inch rack
Water-cooled Enclosure
for the temperature stabilization

One of the features of our design
Water-cooled 19-inch Rack

- Heat exchanger cools the circulating air.
- Temperature stability of the cooling water is 0.4 K (p-p).
  Typically 0.2 K (p-p)
- Side-blowing type
  - Not to shake cables around the front panel.
  - Cable vibration is critical in the femto-second region!
  - VME boards are horizontally mounted.
- Front blowing-type
  - Other circuits (magnet power supply etc.)
Temperature Stability of the Rack

- We tested the temperature stability of the water-cooled rack.
- We intentionally decreased the water temperature by 0.4 K and outside temperature by 4 K at the middle of the measurement.
- Inside temperature drift was 0.42 K.
  - Appropriately follows the water temperature.
  - Almost no effect from outside.
Water-cooled Optical Fiber Duct

- Optical fiber temperature is stabilized by cooling water.
- Stability measurement
  - Water temperature fluctuation: 0.24 K (p-p)
  - Outside temperature fluctuation: 3.4 K (p-p)
- Inside temperature is regulated within 0.12 K (p-p)
  - < 200 fs (p-p) for 1km phase-stabilized optical fiber (PSOF)
Photograph of the Klystron Gallery

- A part of the RF and timing system has been installed.
Performance Measurement of the RF and Timing System
SSB Phase Noise

- We measured the SSB (Single Side Band) phase noise of the optical RF and timing distribution system.
  - Master oscillator itself
  - After transmission with the optical distribution system.
- No deterioration in < 1 MHz
- A little degradation above 1 MHz, but small enough (∼7 fs)
- Time jitter is estimated to be 30 fs (rms)
Stability of the Optical System

- Optical system was enclosed in a thermostatic chamber.
- Measurement period: **24 hours**
- Temperature stability: **0.7 K (p-p)**
- Phase stability: **0.71 degree (p-p)**
- Amplitude stability: **0.86% (p-p)**
- Drifts of detectors: 0.2 degree (p-p) and 0.06% (p-p)
Stability of the Low-level RF System

- VME-D/A → IQ modulator → Solid-state Amp. → IQ demodulator → VME-A/D
- Temperature stability: 0.3 K (p-p)
- Phase stability: 0.30 degree (p-p)
- Amplitude stability: 0.56% (p-p)
  - Resolution limit of 12-bit A/D converter.
  - Only random fluctuation can be seen. (No slow drift)

**Phase Stability Chart**

- 5712 MHz Phase
- 2 hours
- 0.30 deg

**Amplitude Stability Chart**

- 5712 MHz Amplitude
- 0.56%
Error Correction of IQ modulator

- IQ modulator and demodulator have some errors.
  - Phase: \( \sim 5 \text{ degrees (p-p)} \)
  - Amplitude: \( \sim 10\% \text{ (p-p)} \)
  - These errors disturb the fine tuning of the accelerator.
  - Cause an interference between the feedback controls of RF phase and amplitude.

- The error itself does not drift
  - Can be corrected by software.

- After correction
  - Phase error: 0.3 degree (p-p)
  - Amplitude error: 1% (p-p)

- Details are presented by T. Ohshima (WEP023).
Summary (1/2)

- **XFEL/SPring-8**
  - Generates coherent and intense x-rays with 0.1 nm wavelength region.

- **Requirements for the acceleration RF field**
  - Phase stability: 0.1 deg. (rms) of 5712 MHz (~ 50 fs)
  - Amplitude stability: 0.01% (rms)

- **Precise RF and Timing system**
  - Optical RF and timing distribution system
    - WDM technique and Length-stabilized fiber link
  - Low-level RF control system
    - IQ modulator and demodulator
Summary (2/2)

- Temperature regulation
  - Water-cooled 19-inch rack
  - Water-cooled optical fiber duct
  - Both enclosures can reduce the temperature fluctuation within 0.4 K (p-p).

- Phase stability
  - Optical system: 0.71 degree (p-p) of 5712 MHz
  - Low-level RF system: 0.30 degree (p-p) of 5712 MHz
  - Sufficient for XFEL/SPring-8

- Amplitude stability
  - Optical system: 0.86% (p-p)
  - Low-level RF system: 0.56% (p-p)
  - This drift is suppressed by a klystron that is operated at saturation point.
Acknowledgements

- We thank
  - Mitsubishi Electric TOKKI System
  - Kinden
  - And many other companies
  for their grate efforts to develop the precise RF and timing system.

- Thank you for your attention!
SCSS Test Accelerator

- Extreme ultraviolet (EUV) FEL facility
  - Wavelength: 50 – 60 nm for saturated output
  - Beam energy: 250 MeV
- Saturated EUV laser light has been stably generated since 2006.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>8 GeV</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>0.3 nC</td>
</tr>
<tr>
<td>Normalized Slice Emittance</td>
<td>0.7 $\pi$ mm mrad</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>60 pps maximum</td>
</tr>
<tr>
<td>Peak Current</td>
<td>3 kA</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>30 fs (FWHM)</td>
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<tr>
<td>Beam Radius</td>
<td>40 mm (RMS)</td>
</tr>
<tr>
<td>Undulator Period</td>
<td>18 mm</td>
</tr>
<tr>
<td>Undulator K-value</td>
<td>2.2 maximum</td>
</tr>
<tr>
<td>Undulator Gap</td>
<td>3 mm minimum</td>
</tr>
<tr>
<td>Number of Periods</td>
<td>$275 \times 18 = 4950$</td>
</tr>
</tbody>
</table>
Velocity Bunching

- For a low-energy beam (~1 MeV)
- Head electrons are decelerated and tail electrons are accelerated by an accelerating cavity.
- Tail electrons approach head electrons.
Peak Current and FEL Gain

FEL parameter  Peak current

\[ \rho = \left[ \frac{I_e \gamma \lambda^2}{16\pi I_A \sigma_x \sigma_y} \left( \frac{K [JJ]}{1 + K^2} \right)^2 \right]^{1/3} \]

FEL gain length

\[ L_{G1D} = \frac{\lambda_u}{4\pi \sqrt{3\rho}} \]

FEL power growth

\[ P_{FEL} \propto \exp(\alpha \cdot L_G) \]
E/O and O/E Converters

- **E/O Converter**
  - Light source: DFB-LD (Distributed FeedBack Laser Diode)
  - LiNbO₃ Mach-Zehnder modulator

- **O/E Converter**
  - Fast photo-diode
Fiber Length Stabilization

- Frequency-stabilized laser
  - Length standard
  - Frequency is locked to \(C_2H_2\) absorption line.
- Transmitted light is returned by a Faraday rotator mirror.
- Polarization beam splitter discriminates the transmitted light and the returned light.
- Returned light is fed into an interferometer to monitor the fiber length.
  - 55MHz Acousto-optic modulator (AOM) enables a heterodyne detection of the optical phase.
  - Digital phase frequency discriminator (DPFD) for the phase detection.
- Piezo-electric fiber stretcher controls the fiber length.
Fiber Length Stabilization Experiment

- We tested the fiber length stabilization system by using an optical fiber along the SPring-8 storage ring.
- Length fluctuation below 30 Hz was suppressed to 1 μm level.
PID Feedback Loop

- RF phase and amplitude detected by the IQ demodulator are fed back to the IQ modulator.
- PID (Proportional-Integral-Differential) algorithm
- Phase stability: 0.02 degree rms for 238 MHz
- Amplitude stability: 0.03% rms for 238 MHz
Stability of the Optical System

5712 MHz Phase

24 hours

5712 MHz Amplitude

0.71 deg

0.86%

2009/3/29 6:00 2009/3/29 12:00 2009/3/29 18:00 2009/3/30 0:00 2009/3/30 6:00

Inside Temperature

Ambient Temperature

28 27 26

28 23 18

°C