
FLS 2010

March, 2010
Outline

• Introduction
  – X-ray FEL Project at SPring-8
  – SCSS Test Accelerator

• Transverse Distribution Diagnostics
  – Transverse Beam Profile Monitor
    • OTR and Fluorescence

• Longitudinal Distribution Diagnostics
  – Transverse RF deflecting cavity
  – RF zero phasing method
  – Streak camera
  – EO sampling

• Summary
Introduction
X-ray FEL Project at SPring-8

- X-ray wavelength: < 0.1 nm
- Self-amplified spontaneous emission (SASE) process
- 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, $K < 2.2$
- First XFEL light will be delivered in 2011.
SCSS Test Accelerator

- To check the feasibility of XFEL
- To develop each subsystem
- 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 2007.
**XFEL Machine Layout**

- **8GeV linear accelerator**
  - 238 MHz, 476 MHz, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz)
- **Bunch compression**
  - Velocity bunching in the low energy region
  - Three bunch compressors
  - Bunch length: 1 ns $\rightarrow$ 30 fs (FWHM)
  - Peak current: 1 A $\rightarrow$ 3 kA
- **Coherent X-rays are generated by in-vacuum undulators**
Transverse Distribution Diagnostics
Transverse Distribution Diagnostics

• Requirements
  – Spatial resolution < 10 μm
  – Beam radius: 40 μm (RMS) in the undulator section
  – For emittance and Twiss parameter measurement etc.

• High-resolution beam profile monitor
  – Optical transition radiation (OTR) monitor (> ~100 MeV)
    • Target: Stainless steel foil with polished surface
  – Phosphor screen monitor (< ~100 MeV)
    • Target: Ce:YAG (0.1mm-thick) or Desmarquest AF995
  – Custom-made imaging system
  – We didn’t observe COTR 😊

Imaging System

- Custom-made lens system
- Variable magnification: x1 – x4
  - Lens and CCD camera are mounted on a motorized stage
  - x1 optics: Beam finding
  - x4 optics: Precise measurement (2.5 μm resolution)
Beamspot Images

- Taken at the SCSS test accelerator
  - Beam energy: 250 MeV
  - Horizontally focused by Q-magnet.
- Image width is consistent with the natural divergence due to beam emittance
- Deterioration of Ce:YAG image is small (< 10 µm).
Projected Emittance Measurement

- Q-scan method at SCSS test accelerator
- Projected emittance
  \[ \sim 3 \pi \text{ mm mrad} \text{ (normalized)} \]
  - Consistent with simulation
  - Slice emittance of the lasing part is better than this value. \(< 1 \pi \text{ mm mrad}\)

<table>
<thead>
<tr>
<th>Beam Energy [MeV]</th>
<th>Norm. Emittance ((\epsilon_x, \epsilon_y)) [(\pi\text{mm.mrad})]</th>
<th>Calculation ((\epsilon_x, \epsilon_y)) [(\pi\text{mm.mrad})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>(3, 3)</td>
<td>(2.8, 2.6)</td>
</tr>
<tr>
<td>250</td>
<td>(4, 2)</td>
<td>(2.3, 2.3)</td>
</tr>
</tbody>
</table>

Focusing Magnet Strength \(1/f\) (m\(^{-1}\))

50 MeV
0.25 nC/bunch
Longitudinal Distribution Diagnostics
Requirements for Longitudinal Distribution Diagnostics

- Bunch length and peak current measurement
- Slice emittance measurement
  - Thermionic-cathode injector causes a difference between projected emittance and slice emittance.
- Energy v.s. Time distribution measurement
  - Strongly related to bunch compression
- Wide range of bunch length

\[ \text{Beam energy (MeV)} \]

\[ \begin{align*}
\text{BC1 in} & \quad \sim 20 \text{ps} \\
\text{BC1 out} & \quad \sim 3 \text{ps} \\
\text{BC2 out} & \quad \sim 300 \text{fs} \\
\text{BC3 out} & \quad \sim 30 \text{fs}
\end{align*} \]
Longitudinal Diagnostic Methods

• Transverse RF deflecting cavity
  – C-band RAIDEN cavity
  – 10 fs resolution

• RF zero phasing method
  – ~100 fs resolution

• Streak camera
  – OTR is observed
  – 200 fs resolution

• EO sampling
  – ~100 fs resolution
Transverse RF Deflecting Cavity
Temporal Profile Measurement

- The electron bunch is vertically pitched by transverse RF voltage and the temporal structure is converted to a spatial distribution.
- Beam image is taken by an OTR monitor.
- Required temporal resolution: < 10 fs
  - 100 fs/mm on the screen (after 5–10m drift space)
  - Peak deflecting voltage: 40 MV
- Installed downstream of 3rd Bunch compressor
C-band RAIDEN Cavity

- **Racetrack-shaped Iris-coupling DeflectioN structure**
  - To separate x- and y-mode
  

- **Resonant Frequency: 5712 MHz**
  - To obtain higher kick voltage
  - To fully utilize the C-band accelerator resource

- **Backward traveling wave of HEM11-5π/6 mode**

- **Deflecting voltage: 40 MV**
  - When **two 1.7m-cavities** are driven by a 50 MW klystron.
- Measure the horizontal slice emittance.
- Transverse RF cavity pitches the beam.
- Longitudinally sliced beamlet is extracted by a slit.
- Q-scan method is applied to the beamlet.
- We put a BPM before the slit in order to monitor which part of the beam is extracted.
  - The net kick angle is affected by RF phase jitter and beam arrival timing jitter.
Energy v.s. Time Measurement

- Leak dispersion from bunch compressor by using a Q-magnet at the dispersive part.
- Kick the beam with the transverse cavity.
- OTR monitor observes energy v.s. time distribution.
- A simulation showed that the bunch compression ratio is not affected by the Q-magnet.
RF Zero Phasing
RF Zero Phasing Method

- Accelerate the beam at the zero-crossing phase before the bunch compressor
  - Large energy chirp is given to the bunch
- In the dispersive part, the temporal structure can be seen as an energy distribution by an OTR monitor.
  - Temporal structure is horizontally yawed at the monitor.
  - Possibility to measure the vertical slice emittance

![Diagram of C-band Accelerator, Bunch compressor, OTR monitor, and energy distribution]

Energy spread proportional to bunch length
RF Zero Phasing Data

- Taken at the SCSS test accelerator
- Bunch length ~ 300 fs (FWHM)
  - Total bunch length ~ 1 ps including non-lasing tail
- Profiles are slightly different between positive slope condition and negative slope one.
  - Due to initial energy chirp, time dependence of beta function etc...
- Resolution is approximately 100 fs.
- Less than 100 fs resolution can be achieved in the XFEL case.
Streak Camera
Streak Camera Setup

- OTR light is detected by a streak camera, FESCA 200 (Hamamatsu Photonics Co.).
- Bandpass filter is used to reduce the propagation delay dependence on the wavelength.
- More simple than transverse RF cavity.
Streak Camera Results

Individual shots
Not enough intensity
Time jitter comes from the trigger circuit of the streak camera

Accumulated after jitter correction by using the peak of each shot

- ~ 300 fs (FWHM) bunch length
- Consistent with zero-phasing method
Streak Camera Results (cont’d)

- Accumulated after the jitter correction by the gravity center of each shot.
- In this case, bunch length is \(~ 1\) ps (FWHM)
  - Error on the jitter correction?
  - Due to the tail component?
- Need to reduce the error from jitter correction.
Possible Improvements

• Reduce the trigger jitter itself of the streak camera
• Provide time reference light synchronized to the beam
  – Jitter correction is done by using the reference light
  – Use 5.712 GHz optical comb generator
    • Wavelength: 1550 nm
    • Pulse width: 1 ps
    • Jitter < 100 fs
    • Converted to 775 nm with SHG (Second Harmonic Generator)
Energy v.s. Time by Streak Camera

- Streak camera can also observe energy v.s. time distribution in the same way as transverse cavity.
  - Time resolution is 200 fs, so this method can be employed at BC1 and BC2.
EO Sampling
EO Sampling

- Electro-optical (EO) crystal rotates the polarization of reference light depending on the electric field pattern of the beam.
EO Sampling Results

• ~100 fs resolution is expected
Summary

• Transverse Distribution Diagnostics
  – OTR and phosphor screen monitors with custom-made lens system
    • < 10 μm resolution
  – Use Q-scan method to obtain the emittance

• Longitudinal Distribution Diagnosis
  – To measure bunch length, slice emittance, energy v.s. time distribution, etc.
  – C-band transverse RF deflecting cavity (10 fs resolution)
  – RF zero phasing (~100 fs resolution)
  – Streak camera (~200 fs resolution)
  – EO sampling (~100 fs resolution)

• Slice emittance
  – Transverse RF cavity with slit and Q-scan. (Horizontal slice emittance)
  – RF zero phasing also has a possibility. (Vertical slice emittance)

• Energy v.s. time
  – Leak dispersion from a bunch compressor and use transverse RF cavity or streak camera
Supplements
### XFEL Machine Parameters

<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>$0.7 \pi \text{ mm mrad}$</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>
</tr>
<tr>
<td>Beam Radius</td>
<td>40 $\mu$m (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>
Target

• **OTR target (> ~100 MeV)**
  – Thin stainless steel foil
    • Thickness: 0.1 mm
    • To reduce radiation damage of other components.
  – 1mm-thick frame to support the foil
    • Ten 0.1 mm-thick foils are stacked and joined by a diffusion bonding technique.
  – Surface roughness: several 10 nm
  – Flatness: 3 μm

• **Phosphor screen (< ~100 MeV)**
  – Ce:YAG scintillator (0.1mm-thick)
  – Alumina fluorescent plate
    • Desmarquest Co. AF995
Spatial Resolution

• Spatial resolution of the imaging system was measured by using a grid distortion pattern.

• Spatial resolution: 2.5 μm (HWHM)
  – Optical magnification: x4
  – Consistent with ray-tracing simulation
Screen Actuator

- **3-state pneumatic actuator**
  - 2 screens and a beam hole
  - For the beam energy of 30 – 300 MeV
    - Because of the poor OTR yield
Projection of Beam Image

OTR Ce:YAG Projection

$\sigma_x = 8.3$ pixels
$= 13.4 \ \mu m @ OTR$ foil

$\sigma_x = 9.8$ pixels
$= 15.8 \ \mu m @ Ce:YAG$
Coherent OTR Search

Bunch compression ratio was changed by the RF phase of S-band accelerator.

SCSS test accelerator

50MeV Dump

C-TWA

Chicane

250MeV Dump

Photon Diagnostics

Observed point

Superposition of 5 shots

Very stable

Courtesy of K. Togawa
OTR Intensity v.s. Bunch Compression

- OTR intensity as a function of S-band RF phase.
- Compression factor (calculation) is also plotted.

We didn’t observe non-linear amplification of OTR.
Projected Emittance Measurement

- We use Q-scan method.
- Beam size is obtained from an OTR monitor.

\[
\sigma_x^2 = A(X + B)^2 + C
\]

\[
X \equiv \frac{L}{f}, \quad A \equiv \epsilon \beta_0, \quad B \equiv \frac{L \alpha_0}{\beta_0} - 1, \quad C \equiv \frac{\epsilon L^2}{\beta_0}
\]

\[
\therefore \epsilon = \frac{\sqrt{AC}}{L}, \quad \alpha_0 = (B + 1) \sqrt{\frac{A}{C}}, \quad \beta_0 = L \sqrt{\frac{A}{C}}, \quad \gamma_0 = \frac{1 + \alpha_0^2}{\beta_0}
\]
Estimation of Slice Emittance from SASE-FEL Energy Curve

- FEL energy curve was compared with simulation

Slice emittance of SCSS test accelerator:
~ 0.7 $\pi$ mm mrad

Gun emittance is conserved
COTR Measurement at Undulator Exit

- Due to micro-bunching in the undulator
Parameters of RAIDEN Cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Deflecting Voltage</td>
<td>$V_y$</td>
<td>40</td>
<td>MV</td>
</tr>
<tr>
<td>RF deflecting phase</td>
<td>$\phi_a$</td>
<td>0</td>
<td>degree</td>
</tr>
<tr>
<td>Fractional bunch length for X-ray oscillation</td>
<td>$\sigma_z$</td>
<td>200</td>
<td>fs</td>
</tr>
<tr>
<td>Beam energy at the deflector</td>
<td>$p_z c$</td>
<td>1.45</td>
<td>GeV</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>$f_a$</td>
<td>5712</td>
<td>MHz</td>
</tr>
<tr>
<td>Type of structure</td>
<td></td>
<td>CZ</td>
<td></td>
</tr>
<tr>
<td>Resonant mode</td>
<td></td>
<td>HEM11</td>
<td></td>
</tr>
<tr>
<td>Phase shift per cell</td>
<td>$\beta D$</td>
<td>$5\pi/6$</td>
<td>rad</td>
</tr>
<tr>
<td>Group velocity</td>
<td>$v_g/c$</td>
<td>-2.16</td>
<td>%</td>
</tr>
<tr>
<td>Filling time</td>
<td>$T_f$</td>
<td>0.27</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>$Q_a$</td>
<td>11500</td>
<td></td>
</tr>
<tr>
<td>Transverse shunt impedance</td>
<td>$z_y$</td>
<td>13.9</td>
<td>$\text{M}\Omega/m$</td>
</tr>
</tbody>
</table>
Machining of the Cell

• Race-track iris
  – Made by a precise milling machine
  – Electrochemically polished
  – Surface roughness: 1 \( \mu \text{m} \) pk-pk

• Other part
  – Machined by a precise lathe with a diamond bit
  – Roughness < 1 \( \mu \text{m} \) pk-pk
Low-level RF Measurements

- Measured with a 7-cell model.
- Pass band
  - Y-mode is clearly separated from x-mode.
- Shunt impedance
  - Bead perturbation measurement
  - Simulation: 13.9 MΩ/m
  - Measurement: 13.7 MΩ/m

Simulation

- HEM11
- X-mode
- Y-mode

![Graph showing simulation and measurement results](image)

- 5712 MHz
- $5\pi/6$
Coherent Radiation
Coherent Radiation

• Coherent Transition Radiation (CTR)
  – Detect RF wave from a phosphor screen.
  – Before BC1.
  – Tested at SCSS test accelerator.

• Coherent Synchrotron Radiation (CSR)
  – Non-destructive
  – Detect THz radiation by a pyro-electric detector.
  – The relationship between the radiation intensity and the bunch length is measured with a transverse cavity.
  – In preparation of an experimental setup at SCSS test accelerator
RF Wavemeter

- Several waveguide is connected in series
- Detect the rf signal in each waveguide
- Waveguide is used as a high-pass filter

<table>
<thead>
<tr>
<th>Cross-section [mm$^2$]</th>
<th>Critical frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40×20</td>
<td>3.75</td>
</tr>
<tr>
<td>20×10</td>
<td>7.5</td>
</tr>
<tr>
<td>10×5</td>
<td>15</td>
</tr>
<tr>
<td>5×2.5</td>
<td>30</td>
</tr>
<tr>
<td>2.5×1.3</td>
<td>60</td>
</tr>
</tbody>
</table>
CTR Results

CTR after 476MHz cavity.
Horizontal axis shows the RF phase of 476 MHz cavity.
Consistent with peak current simulation

![CTR Results Diagram]

**Setup**

- Screen
- Beam
- Spectrometer
- Mesh
CTR Intensity

\[ P(\lambda) = p(\lambda)N[1 + N \cdot f(\lambda)] \]

- \( p(\lambda) \): Radiation from single electron
- \( N \): Number of electrons
- \( f(\lambda) = \left| \int S(z) \exp \left(2\pi j \frac{z}{\lambda}\right) dz \right|^2 \)
- \( S(z) \): Electron distribution function

\( f(\lambda) \sim 0 \Rightarrow P(\lambda) \propto N \)
\( f(\lambda) \sim 1 \Rightarrow P(\lambda) \propto N^2 \)

Coherent radiation (large intensity)
Longitudinal profile can be estimated from this spectrum.
Requirements and Solutions for the Beam Diagnostic System

• High-resolution beam position monitor (BPM)
  – To maintain the overlap between an electron beam and X-rays in the undulator section with 4 μm precision
  – Position resolution < 0.5 μm
  → RF cavity BPM

• High-resolution transverse beam profile monitor
  – Beam radius: 40 μm (RMS)
  – For emittance and Twiss parameter measurement etc.
  – Spatial resolution < 10 μm
  → OTR monitor and fluorescent screen monitor with a custom imaging system

• Noise-free high-speed current transformer (CT)
  – Need to reduce noise coming from the power supply of a klystron.
  – Rise time < 1 ns
  → Differential CT

• Temporal bunch structure measurement system
  – Bunch Length: 30 fs (FWHM)
  – Temporal resolution < 10 fs
  → C-band transverse RF deflecting cavity
RF Cavity BPM
RF Cavity BPM

- Details will be reported by MOPD07 in the today’s poster session.
- Resonant Frequency: 4760 MHz
- Required position resolution: < 0.5 μm
RF-BPM Resolution

- Position resolution: **0.2 μm**
  - Measured with three adjacent BPMs.
  - Compare the 2\textsuperscript{nd} BPM data with the interpolation from 1\textsuperscript{st} and 3\textsuperscript{rd} BPMs.
Quantity of Beam Monitors

- RF cavity BPM (RF-BPM): 56
- Beam profile monitor (PRM): 43
- Current transformer (CT): 30
- Transverse RF deflector: 1
Detection Principle of RF-BPM

• TM110 dipole resonant mode of a pillbox cavity

\[ E_z = E_0 \ J_1 \left( \frac{\chi_{11} r}{a} \right) \cos \phi \ e^{j\omega t} \]

– E-field is linear around the axis

• Output voltage

\[ V = V_1 q x + jV_2 q x' + jV_3 q + V_n \]

• Need to discriminate in-phase component from quadrature.
• IQ demodulator
• Attenuator switch extends the dynamic range to 100 dB
  – From sub-μm to a few mm
• Baseband signals are recorded by a 12-bit VME waveform digitizer.
Position Sensitivity

• Measurement
  – Motorized stage of the BPM was moved
  – Beam was fixed

• Position sensitivity: $0.1 \, \mu m$
  – More than 20 ADC counts / $\mu m$
  – ADC noise $< 2$ counts (RMS)
Beam Arrival Timing Resolution

• Beam arrival timing can be measured by the phase of the reference cavity (TM010).
  – Useful to monitor the timing drift of the machine
  – Required temporal resolution: < 50 fs

• Arrival timing resolution: 25 fs
  – Measured by the reference cavities of two neighboring BPMs.
Current Transformer
Differential Current Transformer

- 2 positive ports and 2 negative ports
- Common-mode noise can be subtracted
CT Results

- Rise time: 0.2 ns
- Pulse height is proportional to the beam charge
Common-mode Noise Reduction

- Common-mode noise was reduced to 1/10.