Beam Diagnostic System of XFEL/SPring-8

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Outline

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  – SCSS Test Accelerator
  – XFEL Machine Layout and Parameters

• Beam Diagnostic System
  – Requirements and Solutions
  – RF Cavity BPM
  – Transverse Beam Profile Monitor
  – Current Transformer
  – Temporal Bunch Structure Measurement

• 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 π mm mrad
  - High-gradient C-band accelerator: 35 MV/m
  - Short-period in-vacuum undulator: $\lambda_u = 18$ mm, $K < 2.2$
- First FEL light will be delivered in 2011.
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.
XFEL Building

• Construction was completed in March 2009.
• **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: \(1 \text{ ns} \rightarrow 30 \text{ fs} \) (FWHM)
  – Peak current: \(1 \text{ A} \rightarrow 3 \text{ kA}\)

• Coherent X-rays are generated by in-vacuum undulators
## 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>$0.7 \pi$ 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 µm (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>
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 \( \mu \text{m} \) precision
  - Position resolution < 0.5 \( \mu \text{m} \)
  -> RF cavity BPM

- **High-resolution transverse beam profile monitor**
  - Beam radius: 40 \( \mu \text{m} \) (RMS)
  - For emittance and Twiss parameter measurement etc.
  - Spatial resolution < 10 \( \mu \text{m} \)
  -> 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: \(0.2 \, \mu\text{m}\)
  - Measured with three adjacent BPMs.
  - Compare the 2\(^{nd}\) BPM data with the interpolation from 1\(^{st}\) and 3\(^{rd}\) BPMs.
Beam Profile Monitor
Precise Beam Profile Monitor

• Requirements
  – Spatial resolution: < 10 µm
    • Beam radius is 40 µm (RMS) in the undulator section.
  → Custom imaging system

• Screen type
  – Fluorescent screen for low energy part (< 100 MeV)
    • Ce: YAG etc.
  – Optical transition radiation (OTR) for high energy part
    • Stainless steel foil

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
Spatial Resolution

- Spatial resolution of the imaging system was measured by using a grid distortion pattern.
- **Spatial resolution**: $2.5 \mu m$ (HWHM)
  - x4 optics
  - Consistent with lens simulation

![Grid distortion pattern](image)
OTR Target

- 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 unified by a diffusion bonding technique.
- Surface roughness: several 10 nm
- Flatness: 3 µm
Beam 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).
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.

1mV/div, 10µs/div
Transverse RF Deflector
Temporal Structure Measurement

- Temporal beam structure is converted to spatial distribution by transverse RF voltage.
- Beam image is taken by an OTR monitor.
- Required temporal resolution: < 10 fs
  - 100 fs/mm on the screen (after 5–10m drift space)
  - Deflecting voltage: 40 MV at crest phase
- Installed downstream of 3rd Bunch compressor
**C-band RAIDEN Cavity**

- **Racetrack-shaped iris-coupling deflecting 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 1.7m x 2 cavities are driven by 50 MW klystron.
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 vs. Measurement

- X-mode
- Y-mode

Frequency [MHz]

Simulation HEM11

X-mode

5712 MHz

Y-mode
Summary

• RF cavity BPM
  – Position resolution: 0.2 µm

• Beam Profile Monitor
  – Spatial resolution of the imaging system: 2.5 µm
  – Variable magnification: x1 – x4
  – Thin OTR target and Ce:YAG fluorescent screen

• Current transformer
  – Differential output
  – Rise time: 0.2 ns

• Transverse RF deflector
  – For Temporal Bunch Structure Measurement
  – C-band RAIDEN cavity (racetrack-shape iris)
  – Will be installed downstream of the third bunch compressor.

• Beam monitors are ready for XFEL
  – Design work has been almost completed.
  – Performance was confirmed to be sufficient by beam tests.
Supplements
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.
BPM Electronics

- 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 µm**
  – More than 20 ADC counts / µm
  – 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.
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 \text{ pixels} \\
= 13.4 \text{ \(\mu\text{m}@\text{OTR foil}$$

$\sigma_x = 9.8 \text{ pixels} \\
= 15.8 \text{ \(\mu\text{m}@\text{Ce:YAG}$$

Horizontal Pixel Number
## 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>$\varphi_a$</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>µs</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>MΩ/m</td>
</tr>
</tbody>
</table>
Machining of the Cell

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

• Other part
  – Machined by a precise lathe with a diamond bit
  – Roughness $< 1 \, \mu\text{m} \, \text{pk-pk}$