Improvements of Transverse and Longitudinal Beam Diagnostics in SACLA

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Outline

• Introduction
  – X-ray free-electron laser facility, SACLA
  – Current problems
• L-band transverse RF deflector cavity in the injector section
  – Brief introduction and typical results
• Improvements of transverse profile monitor
  – Mitigation of coherent OTR
  – Beam test results
• Summary
**XFEL facility “SACLA”**

- **E-Gun**
- **Chopper**
- **500 kV thermionic gun**
  - $\beta \gamma e \sim 1 \text{ mm mrad}$
- **Acc. cavities**
  - (238 MHz, 476 MHz, L-band, C-band)
- **C-band high-gradient accelerators**
  - $> 35 \text{ MV/m}$

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**BL2:**
- 6.85 GeV, 5.5 keV

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**BL3:**
- 7.8 GeV, 12.7 keV

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**0.8 GeV max.**

**~0.1 keV Soft XFEL**

**8 GeV max.**

**~10 keV XFEL**

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**In-vacuum undulators**

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**In-vacuum undulators**

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**$\lambda_u$: 18 mm**
Current problems

• Bunch compression condition is hard to be reproduced after the replacement of the gun cathode.
  – We had only one transverse deflector cavity (TCAV) to monitor a longitudinal bunch profile after BC3.
    • C-band TCAV after BC3 is essential to the tuning of BC2 and BC3.
    • A new TCAV was needed for tuning of velocity bunching and BC1.
  – We installed a L-band TCAV (1428 MHz) to the velocity bunching section.

• Transverse profile monitors did not work properly due to coherent OTR (optical transition radiation).
  – Transvers profile monitors are necessary for the emittance measurement and the envelop matching in the undulator section.
  – A short-bunch beam ($< \sim 100$ fs) generates intense coherent OTR.
  – We tried several mitigation schemes of COTR.
L-band transverse deflector

- Polarization control is needed.
  - Longitudinal magnetic field in a solenoid lens rotates the stretched image.
- Two input ports intersecting with a right angle can generate arbitrary polarization.
Polarization was adjusted to obtain vertical or horizontal sweep on the screen.

Position-to-time coefficient: 0.07 mm/ps

Temporal resolution: ~ 10 ps

Large chromatic aberration exists due to a large energy chirp.

These images are still useful to reproduce the longitudinal profile in the velocity bunching section.
• E-T phase-space profile was appropriately obtained at the dispersive section of BC1.
Coherent OTR problem

- OTR (optical transition radiation) profile monitors after BC3 did not work due to coherent OTR (COTR) problem.
- Short-bunch (<100fs) beam produced intense COTR.

OTR Target: stainless-steel mirror

Intense COTR
COTR mitigation schemes

- OTR targets were replaced with YAG:Ce.
  - COTR is still generated by YAG:Ce.
- Some COTR mitigation schemes have been tested.
  - Use the $1/\gamma$ directionality of OTR

Mask scheme

Perforated mirror scheme

H. Maesaka et al., IBIC’12, MOIC02.
S. Matsubara et al., IBIC’12, MOIC04.
Y. Otake et al., PRAB 16, 042802 (2013).
PSI scheme

- Some profile monitors based on PSI scheme were installed in 2017.

R. Ischebeck et al., PRAB 18, 082802 (2015).
Imaging system for PSI scheme

- Rotation stages for the lens and camera are necessary to correct aberration.
Fast gate scheme

• Fluorescence lifetime of YAG:Ce is about 50 ns.
• COTR is prompt radiation.
• COTR can be temporally discriminated from YAG scintillation.
• We installed a fast gate camera to one of the profile monitors.
Profile monitor images

Mask scheme

Perforated mirror scheme

Hot spots due to imperfections

PSI scheme

Fast gate scheme
**Timing shift of normal cameras**

- Timing jitter of the camera system is about 100 ns.
- We can get beam profiles without COTR by adjusting the camera trigger timing just after COTR.
- Geometrical COTR mitigation scheme is still needed.
  - General imaging device may be damaged by intense COTR.
- Since the image intensity changes shot-to-shot due to the timing jitter, software normalization is necessary.

![PSI scheme](image)

![Timing Adjustment](image)

![COTR disappeared](image)
Known problems

• Mask scheme
  – Intense stray COTR light is observed around the beam image.
  – Bothersome mask adjustments are needed.

• Perforated mirror scheme
  – Shadow of the mirror hole can appear if the image is out of focus.
  – Stray COTR light still exists.

• PSI scheme
  – Stray COTR light still exists.

• Fast gate scheme
  – Expensive.
  – Image intensifier has poor resolution.
    • a few 10 µm

• Timing shift of the normal camera
  – Software normalization is needed.
### Comparison of COTR mitigation schemes

#### Geometrical COTR mitigation schemes

<table>
<thead>
<tr>
<th></th>
<th>COTR separation</th>
<th>Tuning</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>COTR mask</td>
<td>Acceptable</td>
<td>Difficult</td>
<td>Reasonable</td>
</tr>
<tr>
<td>Perforated mirror</td>
<td>Good</td>
<td>Easy</td>
<td>Reasonable</td>
</tr>
<tr>
<td>PSI scheme</td>
<td>Very good</td>
<td>Moderate</td>
<td>Expensive a little</td>
</tr>
</tbody>
</table>

#### Temporal COTR mitigation schemes

<table>
<thead>
<tr>
<th></th>
<th>COTR separation</th>
<th>Resolution</th>
<th>Tuning</th>
<th>Jitter</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast gate camera</td>
<td>Very good</td>
<td>Bad</td>
<td>Easy</td>
<td>Good</td>
<td>Expensive</td>
</tr>
<tr>
<td>Timing shift of a normal camera*</td>
<td>Good</td>
<td>Good</td>
<td>Easy</td>
<td>Moderate</td>
<td>Free</td>
</tr>
</tbody>
</table>

*: Geometrical COTR mitigation scheme must be used together to protect the camera from the intense COTR.

*We employed the timing shift of normal camera combined with geometrical schemes (perforated mirror and PSI scheme) for most of our profile monitors.*
Summary

• Transverse and longitudinal profile monitors are important for the XFEL facility SACLA.

• L-band TCAV
  – We designed a L-band TCAV and installed it to the velocity bunching section.
  – Temporal profile and energy v.s. time phase-space distribution were successfully obtained.

• Transverse profile monitors suffered COTR problems.
  – We tried several geometrical COTR reduction methods.
  – Mask, perforated mirrors and PSI scheme
  – Timing shift of the camera trigger worked well.

• Now, the COTR problem was almost solved by the combination of the geometrical COTR reduction and the timing shift of the camera trigger.