Measurement of ultrashort electron and x-ray beams for x-ray free-electron lasers

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Outline

- Motivation and background;
- Overview of ultrashort diagnostics;
- Experimental study of longitudinal mapping with a high-resolution spectrometer at LCLS;
- An X-band transverse deflector for e-beam and x-ray pulse measurement;
- Discussions on optical streaking techniques.
motivation/background

- Growing interests in a few fs or even sub-fs x-ray pulses.
- LCLS operating at ~20 pC or using slotted-foil has delivered x-rays to the users, with estimated duration of a few fs.
- However, the resolution of the present e-beam diagnostics at LCLS is about 10 fs rms.
- The characterization on the x-ray pulse duration is also very challenging, even at 100s fs scale.
- Need techniques with 1-fs resolution, for both e-beams and x-rays.
Overview: e-beams (I)

Existing methods of e-beam longitudinal diagnostics

- S-band/C-band transverse deflector:
  \[\sim 10 \text{ fs rms resolution at LCLS, time-domain, direct measurement; (LCLS, FLASH, Spring-8, …)}\]

- Single-shot spectrometer:
  \[\text{frequency-domain; (FLASH, LCLS (under construction), …)}\]

- Relative bunch length monitor (BLM) from coherent edge radiation or diffraction radiation:
  \[(\text{LCLS, FLASH, …})\]

- Electro-optic (EO) method: \[(\text{FLASH, …})\]
Overview: e-beams (II)

New techniques have been proposed/developed*:

- **longitudinal-to-transverse mapping:**
  chicane + deflector (Xiang and Ding, PRSTAB13 094001 (2010))

- optical streaking or deflecting

- **RF + optical deflecting:**
  two orthogonally oriented deflecting (Andonian et al., PRSTAB14 072802 (2011))

- **optical replica synthesizer:** Saldin et al.

- **longitudinal mapping: time ➔ energy** (this talk)

* Just pick a few examples here.
Overview: x-ray pulses*

- **X-ray auto-correlation**
  Difficult due to vanishingly small cross-sections in nonlinear processes
  Geloni et al., two undulators + fresh bunches

- **x-ray gas interaction + laser or THz fields streaking**
  *next talk, A. Maier*

- **Statistical analysis**
  J. Wu et al. FEL10; A. Lutman et al. WEOA2, FEL11.

- **Optical afterburner**
  N. Stojanovic, WEOA4, FEL11

- **X-band transverse deflector** *(this talk)*

* Just pick a few examples here.
Longitudinal mapping with a high-resolution energy spectrometer*:

- Review of the method
- Experimental setup and results

*Z. Huang et al., PRSTAB 13, 092801 (2010), Presented at FEL10.
* Z. Huang et al., PAC11, THP183
Apply this method to measure fs bunches

Slightly adjust BC2 $R_{56}$
add a diagnostic chicane $R_{56}'$

BC2 4.3 GeV
Run L3 at zero crossing (-90 deg) $h_3$

L2 ($\phi_2$)

To high-resolution energy spectrometer

Final energy spread/profile corresponds to short bunch length/profile
Wakefield of long linac must be taken into account

Diagnostic chicane can be part of BC2

Over-compression
Zero-crossing

$z_3 = \begin{pmatrix} 1 & 0 \\ h_3 & 1 \end{pmatrix} \begin{pmatrix} R'_{56} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix}$

$= \begin{pmatrix} 1 & R'_{56} \\ h_3 (1 + h_3 R'_{56}) \end{pmatrix} \begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix}$

$z_2 = \frac{\delta_3}{h_3}$

$=0$
A-line as a high-resolution spectrometer

Updated the screen from aluminum to ZnS (Zinc Sulfide), ~0.1 mm thickness. Measured resolution of 250 μm in \( \sigma_x \) with the new screen.

\[ \eta_x = -6.4 \text{ m} \]
\[ \beta_x = 100 \text{ m} \]
Energy resolution 
\[ \sim 1 \times 10^{-5} \]
Calibration and Benchmark

- Calibration factor: $\approx 770-840 \, \mu m / \mu m$ bunch length
  - Measure PR18 horizontal central position vs L3 phase;
  - OR, use measured dispersion and chirp.

- TCAV3 runs out of resolutions at about $\approx 3 \, \mu m$ (10 fs) bunch length level

40 pC measured data*

* With an old aluminum screen.
Measurement examples on PR18 (new screen)

- **40 pC, under-compression**
  - $\sigma_x = 1908 \, \mu m \rightarrow \sigma_z = 2.47 \, \mu m$

- **10 pC, full-compression**
  - $\sigma_x = 327 \, \mu m \rightarrow \sigma_z = 0.27 \, \mu m$
    (after subtracting 250 $\mu m$
    
  - resol. ~1 fs (rms)

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Measurement vs. simulation (40 pC)

- BC2 R56=-24.7mm to get $\sigma_z$, and R56=-35 mm and L3 -90 deg to get $\sigma_\delta$
- Shifted L2 phase to compare measurement with simulations (5% cut area)
X-band transverse deflector for both e-beam and x-ray pulse measurement*:

- Basic principle
- System layout and requirements
- Resolution
- Simulation examples

* Y. Ding et al., SLAC-PUB-14534, submitted to PRSTAB.
* Poster WEPB14, FEL11.
How to get the x-ray temporal profile

- The E-loss scan for measuring x-ray pulse energy:

\[ \Delta E = \Delta E_f - \Delta E_i \]

We propose to streak the beam in time using a transverse deflector to measure the \textit{time-resolved} energy loss, and energy spread, where the x-ray profile has been imprinted in the e-beam time-energy phase space.
Layout and deflector parameters

- XTCAV streaks horizontally;
- Dipole bends vertically.

Deflector Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure length</td>
<td>2 x 1 m</td>
</tr>
<tr>
<td>Frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Maximum kick</td>
<td>48 MV@40MW</td>
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<tr>
<td>Max rep. rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Phase stability</td>
<td>&lt;0.1 deg rms</td>
</tr>
<tr>
<td>Amplitude stability</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

(Juwen Wang)
Resolution and optics optimization

Temporal resol. = \( \frac{\sigma_{x0}}{cS} \propto \frac{\lambda_{rf}}{V_0} \sqrt{E} \frac{\varepsilon_{N,x}}{\beta_{xd}} \)

Energy resol. = \( \frac{\sigma_{y0}}{\eta_y} \propto \sqrt{\frac{\beta_{ys}}{E} \frac{\varepsilon_{N,y}}{\eta_y}} \)

\( S \) is the calibration factor:

\[
S = \frac{\sigma_x}{c\sigma_t} = \frac{eV_0}{pc} \sqrt{\beta_{xd}\beta_{xs}|\sin\Delta\Psi|} \frac{2\pi}{\lambda}
\]

**HXR: (14GeV)**

- \( \varepsilon_{N,x} = 0.6\mu m \)
- \( S = 128, \sigma_{t,R} \sim 2\text{ fs}; \sigma_{\delta,R} = 7.3e-6 \text{ (100keV)}; \)

**SXR: (4.3GeV)**

- \( \varepsilon_{N,x} = 0.6\mu m \)
- \( S = 400, \sigma_{t,R} \sim 1\text{ fs}; \sigma_{\delta,R} = 1.3e-5 \text{ (56keV)}; \)

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Simulation example: hard x-ray S2E beam, 250pC
Simulation example: soft x-ray S2E beam, 20pC

Reconstruction e-beam profile

Reconstruction x-ray profile
Advantages of the X-band deflector method

- High resolution, ~ few fs;
- Applicable for all radiation wavelength;
- Wide diagnostic range, few fs to few hundred fs;
- Profiles, single shot possible;
- No interruption with LCLS operation;
- Both e-beam and x-ray profiles.

Generally applicable to other FEL facilities…
Jitter discussions …

- Calibration requires small arrival time and X-band deflector rf phase jitters:
  - use larger dump screen;
  - use phase cavity signal to correct;

- Electron energy jitter correction with BPMs:
  - energy correction with BPMs;
  - using energy spread is less sensitive than E-loss;

- Current (bunch length) jitter correction:
  - cause difference on wake loss;
  - correction by correlation (same as E-loss scan).
Streaking at optical frequencies?

- **Optical streaking with a Ti:Sa laser**
  - use the slope of the intensity envelope to distinguish the different modulation periods.
  - calibrated with the laser wavelength. *Poster WEPB22.*

- **Optical deflecting of the ionized low-energy electron beam with a circularly-polarized long-wavelength laser (~10 µm)**
  - No synchronization problem;
  - calibrated with the laser wavelength.
Thanks all my SLAC colleagues for helps and supports;
Thanks C. Behrens for X-band transverse deflector work;
Thanks the support from DOE Early-Career Award Program.

We have postdoc position open at SLAC on this ultrashort diagnostic topic.
Wakefield compensation by shifting L2 phase

- Real bunch length
- E-spread/chirp
- E-spread/chirp (shift $\phi_2$ by 1°)

\[ R_{56} = -7.18 \text{ mm} \]

Phase shift agrees with theory

Wake effect can be corrected empirically by identifying full compression phase through CSR bunch length monitor