Longitudinal Diagnostics for Short Electron Beam Bunches

Henrik Loos, SLAC
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Motivation

- Bunch length diagnostic for X-Ray free electron lasers
- FEL gain scales with charge density
- X-Ray FEL saturation (1 Å) in < 100 m undulator needs kA of peak current at 1 \( \mu \)m norm. emittance
- For bunch charges of 1 nC or less, bunch lengths of sub-100 fs or 10s of \( \mu \)m are required and need diagnostics

<table>
<thead>
<tr>
<th></th>
<th>Energy (GeV)</th>
<th>Undulator length</th>
<th>Bunch Charge</th>
<th>Peak Current</th>
<th>Bunch Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCLS</td>
<td>13.6</td>
<td>100m</td>
<td>0.25-1nC</td>
<td>3kA</td>
<td>8-20( \mu )m</td>
</tr>
<tr>
<td>SCSS</td>
<td>6</td>
<td>100m</td>
<td>1nC</td>
<td>3kA</td>
<td>25( \mu )m</td>
</tr>
<tr>
<td>XFEL</td>
<td>17.5</td>
<td>130m</td>
<td>1nC</td>
<td>5kA</td>
<td>25( \mu )m</td>
</tr>
</tbody>
</table>
Bunch Length Measurement Principles

Electro-Optic
- Laser
- Crystal

Coherent Radiation
- THz Pulse
- Spectrometer

Incoherent Radiation
- Streak Camera/Fluctuation

Field Based
- Coulomb Field
- Electron Bunch

Deflecting Cavity/Zero Phasing
- RF Cavity
- Screen

Beam Based
- Modulator
- Chicane
- Radiator
- Optical Replica
- FROG

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Bunch Length Overview

- **Field based**
  - Direct electro-optic field detection
    - Scanning and single shot methods
  - Coherent radiation generation
    - Transition, synchrotron, edge, diffraction, …
    - Power or spectrum measurement
  - Incoherent radiation
    - Transition, Cherenkov, undulator, synchrotron, …
    - Time based measurement with streak camera
    - Analysis of spectrum fluctuations

- **Beam based**
  - Phase space manipulation
    - Zero-phase acceleration and spectrometer
    - Transverse deflector cavity

- **Beam & field based**
  - Optical replica synthesizer
    - Optical phase space modulation
    - Coherent radiation generation
Transverse Deflector Cavity

\[ V_0 > 20 \text{ MV} \]
\[ f_{RF} = 2856 \text{ MHz} \]
\[ E_S = 13.6 \text{ GeV} \]

\[ \sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left( \frac{k_{RF} e V_0}{E_s} \sin \Delta \psi \cos \phi \right)^2 \]

- Map time axis onto transverse coordinate
- Simple calibration by scan of cavity phase
Transverse Deflector Cavity Setup

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Calibration by phase scan
- Shortest bunch is only 2% change in beam size
- Limited resolution from phosphor screen, only 1 Hz operation
- Phase jitter at full RF power
- Beam based FB implemented

Calibration

Beam position (μm)

89.6 89.8 90 90.2

TCAV Phase (Degree)

σz = 5515 ± 244 μm/degree

Bunch Length, 250 pC

σz = 7.28 ± 0.452 μm

σz = 17.89 ± 0.792 μm/μm

Normal compression

Full compression
Scan of BC2 bunch compressor strength

Bunch length measurement with TCAV agrees well with Elegant simulation

Shortest bunch of 2 μm supported by simulation

- Measured
- Elegant

250 pC

σ\(_z\) (μm)

BC2 R56 (mm)

K. Bane et al., FEL08

Scan of BC2 bunch compressor strength

Bunch length measurement with TCAV agrees well with Elegant simulation

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COTR Diagnostics Problem

- Planned pulse stealing mode for TCAV after 2\textsuperscript{nd} BC
- Use horizontal kicker and off-axis OTR screen
- Camera saturated with coherent OTR from micro-bunching instability
- Increased energy spread from laser heater does not mitigate coherent radiation
- OTR diagnostics not usable for ultra-short bunch lengths near visible wavelengths

See Poster WE5RFP041 and talk R. Fiorito
LCLS Transverse Deflector Summary

- TCAV at LCLS provides absolute bunch length measurement
- Injector TCAV used for
  - bunch length & slice emittance
  - longitudinal phase space
  - laser heater optimization
- Present TCAV use invasive to operation
  - Parasitic use on off-axis screen spoiled by COTR
  - Need to investigate alternative transverse diagnostics
  - Use of wire scanner with beam-based phase feedback tested
  - Wire scanner not single shot, at high compression profiles fluctuate due to CSR beam break-up
- Time resolution inadequate for shortest bunch operation
  - Implementation of X-band structure studied to improve time resolution
Beam interaction with beam-line impedance (foil, iris, bend magnet, …)

Used at many accelerator labs for ps and sub-ps bunch length diagnostics

Depends on Fourier transform of temporal bunch shape

Radiation spectrum

- Low-frequency cut-off from apertures
- High-frequency cut-off from bunch length

Bunch length from spectrum $\lambda > 2\pi \sigma_z$
LCLS Relative Bunch Length Monitor

- BC2 Range 1 mm – 20 μm, broadband pyro-detector & Si-window
- Best stability at BC2 with 100 μm low pass scattering filter
- Removes visible & NIR coherent μ-bunching radiation
- Calibration with TCAV
- Fit of empirical function of peak current to detector signal used for longitudinal feedback

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Single-shot IR grating spectrometer at FLASH
- Wavelength range 3 \( \mu \text{m} \) to 65 \( \mu \text{m} \) accessible
- CTR transport over 20 m from linac to spectrometer
- NIR micro-bunching enhancement observed
- Form factor consistent with 15 fs bunch spike

Fit \( \sim 15 \) fs rms

B. Schmidt et al., EPAC08
LCLS 20pC, 1μm bunch length?

Only NIR photodiode signal

NIR single-shot spectrum measurement needed

Bunch shape reconstruction possible with 20 channel spectrum from 1-20 μm
Coherent Radiation Summary

- Simple to implement as relative bunch length monitor
- Non-intercepting radiation sources available
  - Synchrotron, edge, diffraction radiation
- For absolute bunch length and shape measurement
  - precise knowledge of emission spectrum, transfer line and detector efficiency required
  - Calibration feasible from independent absolute measurement
  - Single-shot measurement needs multi-channel spectrometer with spectral range factor 10 or more in wavelength
- Single-shot device in use at FLASH and implementation at LCLS being studied
Electro-Optic Techniques

- Transient birefringence in EO crystal induced by Coulomb field of beam
- Probe with laser beam and polarizer
- Scanning, spectral & spatial decoding
- Temporal decoding: retrieve temporal shape with SHG
- Requires amplified fs laser synchronized to RF
- Time resolution limited by phonon resonance in EO crystal, highest in GaP at 11 THz

EO Response Function

G. Berden et al., PRL 93, 114802 (2004)

S. Casalbuoni et al., PRSTAB 11, 072802 (2008)
EOTD and Deflector installed at FLASH
Signals from same pulse train

- TDS signal of 40 fs broadens to 60 fs in EOTD
- Good agreement between measured EOTD signals and simulation using bunch shape from deflector cavity
- Physics of detector response well understood

EO Detection Summary

- Non-interceptive single-shot absolute bunch length diagnostics
- Can be located anywhere in accelerator
- Needs transport of synchronized fs laser system to beam line
- Application to ultra-short bunches limited by available EO materials
- Simplified in future with fiber-laser based EO detection
- Shorter time scales may be accessible with new organic materials

- Energy modulation with laser in first undulator
- Convert to density modulation in chicane
- Generate coherent light pulse at laser wavelength in second undulator
- Maps 3D electron beam distribution onto optical pulse
- Single shot laser temporal diagnostics, FROG, determines time resolution
- Principle demonstrated at FLASH for ps time scale
- Bunch form factor at laser wavelength to be incoherent

Summary

- Matured bunch length diagnostics available for lengths > 20 fs
- Deflector cavities successfully implemented at LCLS & FLASH and provide absolute length
- Coherent radiation diagnostics at many accelerator labs
- Single-shot techniques for ultra-short fs long bunches need development
- Fluctuation analysis of x-ray spectra considered
- New materials (organic) for EO-method investigated
Thanks to the entire LCLS Commissioning Team for their many contributions!

See Talk Paul Emma, TH3PBI01

LCLS 1.5 Å