Slice Parameter Measurements with RF Transverse Deflecting Cavities

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Issues

- Design parameters for RF power, length and wavelength for a specified resolution
- Measurement examples of longitudinal profile, slice emittance and slice energy spread
- Implementation and installation issues
- Modes of operation and triggering
- RF tolerance specifications
- Beam-based RF phase stabilization
- Calibration
- Image acquisition and controls integration
Bunch Length Measurements with the RF Transverse Deflecting Cavity

Bunch length reconstruction
Measure streak at 3 different phases

LoLa*
An S-band DLW structure with a TM<sub>11</sub> transverse deflecting mode at 2856 MHz

*Loew, Larsen 1964

Cavity on -180°

Asymmetric parabola indicates incoming tilt to beam

\[ \sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf} \sqrt{A}}{4C} \]

Cavity off

\[ \sigma_z = 90 \text{ \mu m} \]

\[ \text{rms} = 151 \text{ pixels} \]
Implementation and installation issues

- Vertical deflection orientation
- Measure horizontal slice emittance
  - Vertical slice emittance measurable with chirped beam and horizontal dispersion location
- Measure slice energy spread at horizontal dispersion location
- In combination with fast, pulsed magnet can selectively measure single pulses on an off-axis screen
Slice-Emittance Measurements in LCLS

3-screen method

LTU at 14 GeV with S-band RF-deflector at 24 MV

LTU slice-emit on OTR33 (CSR)

- = meas. sim.
- = calc.
- = \( y \) distribution
- = actual

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Modes of operation and triggering

- Usually want it to be active on a small fraction of the bunches.
- Normal conducting structure has a fill time of a few microseconds.
  - For single pulse machines can intercept a single bunch.
  - Otherwise in long pulse machines a bunch train will be deflected.
Slice resolution depends on TCAV amplitude

TCAV off

TCAV on

Bunch

Image

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Deflecting power and resolution

For the SLAC S-band structure

\[ V_0 \approx 1.6L \sqrt{P_0 \left[ \frac{MV}{m} \right]^{1/2}} \]

Centroid deflection

\[ \langle \Delta x \rangle = \frac{eV_0}{p\sigma} \sqrt{\beta_d \beta_s} \sin \Delta \psi \sin \phi \]

Beam size

\[ \sigma_x = \sqrt{\sigma_{x_0}^2 + \sigma_z^2 \beta_d \beta_s \left( \frac{2\pi eV_0}{\lambda p\sigma} \sin \Delta \psi \cos \phi \right)^2} \]

Requirement

\[ \left| eV_0 \right| \gtrsim \frac{\lambda}{\pi \sigma_z} \frac{1}{\sin \Delta \psi \cos \phi} \sqrt{p\sigma \cdot mc^2 \frac{\varepsilon_N}{\beta_d}} \]
# Typical operating parameters (LCLS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF deflector voltage</td>
<td>$V_0$</td>
<td>20</td>
</tr>
<tr>
<td>RF deflector length</td>
<td>$L$</td>
<td>2.44</td>
</tr>
<tr>
<td>Peak input power</td>
<td>$P_0$</td>
<td>25</td>
</tr>
<tr>
<td>RF deflector phase (crest at 90°)</td>
<td>$\varphi$</td>
<td>3.3</td>
</tr>
<tr>
<td>Nominal beam size</td>
<td>$\sigma_{x_0}$</td>
<td>80</td>
</tr>
<tr>
<td>Beam size with deflector on (two-phase mean)</td>
<td>$\sigma_x$</td>
<td>272</td>
</tr>
<tr>
<td>Beta function at deflector</td>
<td>$\beta_d$</td>
<td>58</td>
</tr>
<tr>
<td>Beta function at screen</td>
<td>$\beta_s$</td>
<td>63</td>
</tr>
<tr>
<td>Betatron phase from deflector to screen</td>
<td>$\Delta \psi$</td>
<td>60</td>
</tr>
<tr>
<td>Normalized rms emittance</td>
<td>$\varepsilon_{\text{N}}$</td>
<td>1</td>
</tr>
<tr>
<td>Beam energy at deflector</td>
<td>$E_d$</td>
<td>5.4</td>
</tr>
<tr>
<td>Beam energy at screen</td>
<td>$E_s$</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Slice-Emittance Measurement Simulation

*elegant simulation (M. Borland) courtesy P. Emma*

Quad can method: RF-deflector at 1 MV

\[
\sigma_y \approx \text{bunch length}
\]

\[
\sigma_z = 0.831 \text{ mm}
\]

\[
\langle y \rangle = -0.00113 \text{ mm}
\]

slice OTR 10 times

quad scanned
Slice-Emittance Measurement Simulation in the LCLS Injector

courtesy P. Emma

Injector at 135 MeV with S-band RF-deflector at 1 MV

(same SLAC slice-ε code used at BNL/SDL)

Slices have different emittance and phase space orientation

Slice #5: DL1 slice-emit on WS02
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\[ \sigma_0^2 \text{ vs } \xi \text{, } \gamma = A(X-B)^2 + C \]

\[ \chi^2/\text{NDF} = 0.561 \]

\[ \gamma_x = 0.692 \pm 0.030 \text{ (1.000)} \mu \text{m} \]
\[ \rho_x = 14.745 \pm 0.926 \text{ (11.410)} \mu \text{m} \]
\[ \sigma_x = -1.122 \pm 0.083 \text{ (-0.512)} \]
\[ \phi_x = 1.115 \text{ (1.000)} \]
\[ \gamma_{\chi}^2/\text{NDF} = 0.561 \]

\[ \sigma_0 = 158.927 \pm 7.946 \text{ (140.060)} \mu \text{m} \]
\[ \sigma_x = 108.650 \pm 5.433 \text{ (108.129)} \mu \text{m} \]
\[ \sigma_y = 59.407 \pm 2.976 \text{ (63.890)} \mu \text{m} \]
\[ \sigma_\phi = 45.580 \pm 2.279 \text{ (65.547)} \mu \text{m} \]
\[ \sigma_{\psi} = 72.157 \pm 3.608 \text{ (103.188)} \mu \text{m} \]
\[ \sigma_{\chi} = 45.203 \pm 2.161 \text{ (58.401)} \mu \text{m} \]
\[ \sigma_{\xi} = 45.288 \pm 2.661 \text{ (58.431)} \mu \text{m} \]

DL1 slice-emit on WS02

\[ \gamma_x / \mu \text{m} \]

\[ \text{Slice 5 Number} \]

= meas. sim.
= calc.
= \( \gamma \) distribution
= actual
Invasiveness and RF tolerances

- Transverse aperture and screen size determine maximum usable beam deflection
- RF phase jitter causes position jitter
  - Acceptable if whole image is within field of view
- RF phase tolerance is about equal to the designed temporal resolution
  - e.g. if the beam is streaked sufficiently to resolve 10 fs, then the beam can’t move by much more than 10 fs w.r.t. the TCAV RF phase

Phase deviations calculated from transverse kick measured by fitting BPM orbit downstream of cavity
Beam-based RF phase stabilization

- At downstream BPM measure beam position versus phase of deflecting cavity
- “steering” feedback will recenter the beam using RF phase
- But change sign at other phase 0-crossing

\[ y = B \sin \phi \]

\[ eV_{RF} = B \frac{E_0}{R_{34}} \]
Image size calibration versus RF phase

- Plot centroid position in screen pixels versus phase of deflecting cavity
- Gives image size in longitudinal units
- Absolute calibration based on wavelength of S-band
Slice Energy Spread Measurements in the LCLS

Screen located at dispersive location, $\eta_x = 10$ cm

LTU at 14 GeV with S-band RF-deflector at 24 MV

$\sigma_{E/E} \approx 10^{-4}$

$\sigma_{x} \approx 12 \, \mu m$

FEL goal