Measurement of slice emittance and energy-time correlation with LOLA

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Outline

• Introduction
• Preparation of the measurements
• Some results:
  – Energy-time correlation / slice energy spread
  – Slice emittance
• Outlook
Introduction

Measurements:
- Longitudinal density profile
- Horizontal slice widths
- Horizontal slice emittance
- Horizontal slice centroid positions
- Dispersive section: energy-time correlation / slice energy spread

Optics-requirements:
- $\sigma_{y\text{streaked}} >> \sigma_y$ → small $\beta_y^{OTR}$
- Vertical offset at the screen:

$$\Delta y \approx \sqrt{\beta_{ini} \beta_{end}} \cdot \sin(\phi_y) \cdot y'_{LOLA}$$

Courtesy: H. Schlarb, M. Nagl, M. Ross et al.
LOLA in the FLASH beamline

- Beam direction
- Q9ACC7
- Q9/10ACC6
- Q9/10ACC5
- Q9/10ACC4
- Horizontal Kicker
- Off-axis screen

Energy-time correlation measurements

Courtesy: H. Schlarb
Section used for energy-time correlation measurements

- Collimators were opened
- Sextupole was switched off
Optics for energy-time correlation measurements

Objectives: small beta function values (~3m), maximum streak, large dispersion at the screen (~290mm),

Standard optics:

Optics for the measurements:

LOLA

OTR
Optics for slice emittance measurements

- Scan of horizontal phase advance (~210 deg range) using the 6 quadrupoles Q9ACC4 – Q10ACC6 upstream of LOLA
- Streak at the screen is held constant
- Values of the beta functions at the screen: ~5m - 10m
Screen Calibration

- **Time axis (vertical):**
  Measurement of the vertical beam position for different phases \( \phi = \omega_{LOLA} \cdot \Delta t \)

  \[ \Delta y \approx y'_{LOLA} \]
  \[ y'_{LOLA} = \frac{eV_0}{E} \cdot \sin(\phi) \]

- **Energy axis (OTR 5ECOL):**
  Measurement of the horizontal dispersion by variation of the current in the dipole

Dispersion at 5ECOL; reference current \( I_0 \) of D1ECOL: 111.5 A

Data points
- Fit: \( D = -29386.4972 \) pixel = -290.9263 mm
Overview: LOLA measurements

• **Slice emittance**
  - $E = 630$ MeV, BC2 on, BC3 on, ACC1: 0 deg, ACC23: 0 deg
  - $E = 630$ MeV, BC2 on, BC3 on, ACC1: -20 deg, ACC23: 0 deg
  - $E = 630$ MeV, BC2 on, BC3 off, ACC1: -14.1 deg, ACC23: 0 deg
  - $E = 630$ MeV, BC2 on, BC3 on, ACC1: 0 deg, ACC23: -26.2 deg
  - $E = 650$ MeV, BC2 off, BC3 on (5.4 deg), ACC1: 0 deg, ACC23: -26 deg
  - $E = 445$ MeV, BC2 on, BC3 on, ACC1: -6.5 deg, ACC23: 0 deg (2005)

• **Energy-time correlation/ Slice energy spread**
  - $E = 650$ MeV, BC2 off, BC3 on (5.4 deg), ACC1: 0 deg, ACC23: -26..-32
  - $E = 630$ MeV, BC2 off, BC3 off, ACC1: 0 deg, ACC23: 0 deg (+ scan of gun phase)

• **ACC1/23 Phase scans**

• **Tomography**
Energy-time correlation: Both BCs by-passed, ACC1: 0 deg, ACC23: 0 deg

On-crest operation, BCs by-passed; LOLA on/off

LOLA off
LOLA on

Dispersion: $D = 290 \text{ mm}$
Energy: $650 \text{ MeV}$

\[
\sigma_{t} = 4.8 \pm 0.05 \text{ ps} \\
\sigma_{\delta} = 0.09 \pm 0.003\% \\
\sigma_{E} \approx 585 \text{ keV}
\]
**Slice energy spread: BCs by-passed**

Measured slice energy width: < 325 keV

Expected: < 10 keV → slice width not dominated by dispersion

Distribution in the (s,x)-plane at the gun

$E = 650$ MeV

$\sigma_x = 261 \pm 7 \, \mu m$

$\sigma_y = 4.8 \pm 0.05 \, ps$

$\delta_{tot} = 0.09 \pm 0.003 \%$

$\delta_{tot} = 4.8 \pm 0.05 \, ps$
Simulation: Bunch properties at the gun

Slice emittance

Slice energy spread

Distribution in the (s,x)-plane

Number of Particles: 19999  Charge: 5.5 nC
Length: 12,002 m  Beam Energy: 106 MeV

FWHM (distance between green bars): 4.4 x 10^-3 m (14.7 ps)
Charge within FWHM: 50.5 %
Projected Emittance: \( \varepsilon_x = 1.95 x 10^-3 \) m, \( \varepsilon_y = 2.05 x 10^-3 \) m
Order @ FWHM: \( \beta_x = 0.95 \beta = 0.95 \), \( \alpha_x = 0.95 \beta_x = 0.95 \beta_x \)

RMS values for all particles:
- \( x = 5.13 x 10^-3 \) m, \( y = 1.32 x 10^-3 \) m
- \( x' = 1.32 x 10^-3 \) m, \( y' = 1.32 x 10^-3 \) m

RMS values within FWHMA:
- \( x = 5.32 x 10^-3 \) m, \( y = 1.12 x 10^-3 \) m
- \( x' = 1.12 x 10^-3 \) m, \( y' = 1.12 x 10^-3 \) m

Courtesy: B. Beutner
Slice energy spread: BC2 off, BC3 on, ACC1: 0 deg, ACC23: 0 deg

Compression at the front side: 4.8 ps → 3.7 ps

Caused by dispersion?
Slice emittance: $E = 630$ MeV, BC2 on, BC3 on, ACC1: 0 deg, ACC23: 0 deg

- projected emittance larger by a factor of 2
- tilt caused by Dispersion? → $D \sim 15$ cm
- wake fields?
- BC2-section: 4.3 mm mrad (100%)
- coupler kicks?
Energy-time correlation: BC2 off, BC3 on, ACC1: 0 deg, ACC23: -26..-32 deg
Energy-time correlation: BC2 off, BC3 on, ACC1: 0 deg, ACC23: -29 deg

Simulation (slightly different settings): CSR/ longitudinal space charge forces

Courtesy: B. Beutner
Energy-time correlation/ slice energy spread: scan of ACC23: -32 deg

Phase of ACC23: -32 deg.

3.25 MeV
Energy-time correlation/ slice energy spread: scan of ACC23: -31 deg

3.25 MeV
Energy-time correlation/ slice energy spread: scan of ACC23: -30 deg

3.25 MeV
Energy-time correlation/slice energy spread: scan of ACC23: -29 deg

Phase of ACC23: −29 deg.

3.25 MeV
Energy-time correlation/ slice energy spread: scan of ACC23: -28 deg

2.6 MeV

Phase of ACC23: -28 deg.

average
single image
Energy-time correlation/ slice energy spread: scan of ACC23: -27 deg

2.3 MeV
Energy-time correlation/ slice energy spread: scan of ACC23: -26 deg

1.6 MeV
Slice emittance: $E = 650$ MeV, BC2 off, BC3 on, ACC1: 0 deg, ACC23: -26 deg

Tilted bunch:

increasing slice emittance in the bunch center with moderate current and no overcompression
Slice emittance / slice mismatch: BC2 on, BC3 on, ACC1: -20 deg, ACC23: 0 deg

Caused by CSR

Simulation with similar settings:

E = 630 MeV, BC2 on, BC3 on, ACC1: -20 deg, ACC23 0 deg

Courtesy: B. Beutner
Strongly distorted bunch

- Strong variations from bunch to bunch
- Slice emittance measurements not reasonable
Outlook

• The results have to be compared more precisely with simulations
• Measurement of slice emittance, energy-time correlation and slice energy spread under SASE-conditions (planned for August)
• Development of a fast tool for slice emittance measurement available for every operator
Slice emittance: $E = 630$ MeV, BC2 on, BC3 off, ACC1: $-14.1$ deg, ACC23: 0 deg
Slice emittance: $E = 630$ MeV, BC2 on, BC3 on, ACC1: 0 deg, ACC23: -26.2 deg
Slice mismatch, Slice emittance and energy-time correlation

Mismatch phase for large mismatch parameter (arbitrary Twiss parameters)

Mismatch parameter with respect to one selected slice

Chromaticity along the machine?

E = 650 MeV, BC2 off, BC3 on (~5.4 deg), ACC1: 0 deg, ACC23: −26 deg
Slice emittance: ACC1: -6.5 deg

132 fs (FWHM);
0.23 nC (1nC bunch charge)
Measurements with LOLA: Slice centroid shifts

- Energy-loss due to coherent synchrotron radiation in the dipoles of the bunch compressors lead to horizontal slice centroid shifts
- Comparison with simulations (Bolko Beutner)

BC2 off, BC3 on, overcompression
Measurements with LOLA: Tomography

- Scanning the LOLA power allows to reconstruct the 3-dimensional spatial particle distribution
  → reconstruction of the vertical slice emittance?
  → combination with phase space tomography?
Image analysis
Reference point for slicing

Chromat. + centroid shifts/dispersion
## Parameters of LOULA IV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Type of structure</td>
<td>Constant impedance structure</td>
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<tr>
<td>Mode type</td>
<td>TM 11 (Hybrid Mode)</td>
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<tr>
<td>Phase shift / cell</td>
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<td>Cell length</td>
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<tr>
<td>Design wavelength</td>
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<td>Nominal operating frequency</td>
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<td>Nominal operating temperature</td>
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<td>Quality factor</td>
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<td>Relative group velocity</td>
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<td>Filling time</td>
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<td>Attenuation</td>
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<tr>
<td>Transverse shunt impedance</td>
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<tr>
<td>Deflecting voltage</td>
<td>$V_o = 1.6 \text{ MV} \cdot \text{L/m} \cdot (P_o/\text{MW})^{1/2}$</td>
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<tr>
<td>Nominal deflecting voltage</td>
<td>26 MV at 20 MW</td>
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<tr>
<td>Maximum operating power</td>
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<td>Length of structure</td>
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<td>Disk thickness</td>
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<td>Iris aperture</td>
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<td>Cavity inner diameter</td>
<td>116.34 mm</td>
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<tr>
<td>Cavity outer diameter</td>
<td>137.59 mm</td>
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</table>

*Courtesy: M. Nagl*