Investigation of the Longitudinal Electron Bunch Structure with LOLA

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Outline

• Description of the measurements
• Results:
  – Longitudinal profile
  – Longitudinal phase space distribution
  – Slice emittance
• Error considerations for the measured slice emittance values
LOLA in the FLASH linac

Beam direction

- UND6
- UND1
- Dogleg
- LOLA
- ACC45
- BC3
- ACC23
- BC2 ACC1 GUN
- Q9 ACC7
- Q9/10 ACC6
- Sextupol
- OTR screen
- Collimators
- Off-axis screen
- Horizontal Kicker

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Accelerator settings

- Energy: 677 MeV
- Charge: 0.5 nC
- SASE signal at 13.7 nm with 5 µJ average radiation energy per bunch
  → optics downstream of BC3 changed before the measurements!
- ACC1-phase: -9°
- ACC23-phase: -25°
- ACC45-phase: 0°
Longitudinal profile

Spike width: \(
\approx \Delta t_{\text{spike}} \approx 65 \text{ fs} \text{ (FWHM)}
\)
Resolution: \(
\approx \Delta t_{\text{spike}} \approx 50 \text{ fs} \text{ (FWHM)}
\)
Charge in spike: \(
\approx Q_{\text{spike}} \approx 0.12 \text{ nC} \text{ (23\%)}\)
spike current: \(
\approx I_{\text{spike}} \approx 1.7 \text{ kA}
\)

Spike width statistics (100 bunches):

\[
\begin{align*}
\Delta t_{\text{spike}} & \approx 65 \text{ fs} \text{ (FWHM)} \\
Q_{\text{spike}} & \approx 0.12 \text{ nC} \text{ (23\%)}
\end{align*}
\]
Longitudinal phase space

Dispersion: 233 mm;
Time resolution: ~ 50 fs;
Energy spread resolution: ~ 0.06%
(380 keV)

Profile of the head

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Slice emittance

- Resolution \( \sim 60 \) fs
- Proj. emittance: 13.5 mm mrad
- Slice mismatch < 1.5

\[ \Delta x \text{ [mm]} \quad \Delta t \text{ [ps]} \]

\[ \epsilon_x \text{ [mm mrad]} \quad \Delta t \text{ [ps]} \]

\leftrightarrow \text{ SASE signal?}

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Slice emittance: comparison of different methods

Comparison of different methods

Tail:
Comparison of different methods

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Reconstructed phase space

Entire bunch:
Main part of the bunch
\[ \varepsilon_x^{\text{norm}} = 12.8 \mu \text{m} \]
\[ Q = 0.5 \text{nC} \]

Part of the head

Single slice (~60 fs) within the head:
Main part of the bunch
\[ \varepsilon_x^{\text{norm}} = 15.2 \mu \text{m} \]
\[ Q = 0.07 \text{nC} \]

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Emittance of substructures in phase space

Single slice (~60 fs) within the head

90% of the total charge (low intensity regions are cut):

75% of the total charge:

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Dispersion

Reconstructed horizontal dispersion during the quadrupole scan:

Tilt of the tail due to dispersion(?)

Tilt and long. Phase space distribution can me utilized to estimate dispersion

→ Very large values
→ Tilt not solely due to dispersion?

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Dispersion-corrected slice emittance

Slice energy spread < 50keV assumed
Large Dispersion because of optics?

Measured and reconstructed tilt due to dispersion:

Reconstructed beta-functions during the scan (single slice):

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Quadrupole gradient errors

- Monte Carlo simulation for 3% quadrupole gradient errors (1000 seeds, emittance of one slice):

- Comparison of measured and reconstructed slice widths:

\[ S = \sum_{i=1:N} (\sigma_i^{\text{meas.}} - \sigma_i^{\text{reconstr.}})^2 \]

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Quadrupole gradient errors

Comparison of reconstructed and measured slice widths for random gradient errors:

Number of runs: 1000

Used transfer function

Errors from erroneous transfer matrices much smaller than expected

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Image analysis

• Algorithm to detect the image region covered by the bunch

• The remainder of the image is set to zero

→ nearly no influence of noise
Resolution limitation

- Pixel size: ~25 µm

- Minimum slice widths during the scan:

![Graph showing slice widths and relative beam size error](image)

- Effect of binning on the calculated rms width for a gaussian distribution with standard deviation $\sigma$

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Conclusions

• Dispersion seems to be a significant error source for slice emittance measurements
  – Measure and correct dispersion before slice emittance measurements if possible → smaller emittance values?
  – Measurement of dispersion during the scan
  – Apply different optics?
Image analysis 1

Original image with noise (background subtracted):

1. Local averaging; new pixel size e.g. 5x5 pixels

Bad signal to noise ratio in single slices, noise largely influences calculated rms widths

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Image analysis 2

2. Determine mean value and variance $\sigma^2$ of noise from an intensity histogram.

3. Find pixel with maximum intensity.

4. Loop: add nearest neighbour pixels, if intensity $> n*\sigma$ (e.g. $n=3$).

Connected area with intensities above the noise level.

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5. Transformation back to original pixel size

Optional:

- Boundary layers around the bunch area
- Iterative determination of the noise level, e.g. in case of synchrotron radiation
- Splitting of the image in case of inhomogenous background