Slice emittance measurements at the FLASH-linac with a transverse deflecting RF-structure

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Mini-Workshop on “Characterization of High Brightness Beams” in Zeuthen, May 2008
Outline: Slice emittance measurements at FLASH

• Setup
• Methods
• Results
  – On-crest operation
  – FEL operating conditions
• Error analysis
• Conclusions
The transverse deflecting structure (TDS)

- Installed in 2003, Collaboration DESY-SLAC
- Frequency: 2.86 GHz
- Length: 3.6 m
- Maximum deflecting voltage ~ 25 MV @ 20 MW input power
- Maximum induced divergence @ 500 MeV: ~1 mrad / ps
Setup

Installation in the FLASH-linac

Beam direction

RF gun

ACC1

~130 MeV

ACC2

ACC3

~400 MeV

ACC4

ACC5

ACC6

500 MeV

– 1 GeV

BC2

BC3

TDS

OTR screens

Dump

Undulator magnets
Setup for slice emittance measurements

- Camera: Basler 311f, 8 Bit, 480 x 640 pixels, 13 x 16 mm → ~25 µm / pixel
Methods

Optics for slice emittance measurements

\[ \Delta \phi_x = 180^\circ \]
Determination of the slice emittance

- Scan with typically 10 – 14 quadrupole settings
- 10 – 30 images with beam and 1 – 10 background images taken at each step (automatic adaption of the camera gain, automatic orbit-feedback)
- Image analysis:
  - Median filter applied to single high-intensity pixels
  - Subtraction of the background-offset (not images!)
  - Determination of a region of interest
- Subdivision of all beam images into slices of constant width
- Calculation of the RMS widths within slices (“100 % of the beam”)
- Averaging of slice-widths at each step and calculation of the RMS-emittance using a least-squares method, AND
  - Averaging of slice-profiles and determination of the phase space distribution using the MENT-algorithm (implementation by J. Scheins, 2004)
Image analysis: region of interest (ROI)

Simulation: OTR image with Gaussian noise (8 Bit):

- Bunch from start-to-end simulation
- TDS included
- Gaussian noise added (signal-to-noise ratio worse than in measurements)

→ Increase in signal-to-noise ratio by a factor of 10
2. Iterative determination of a ROI:
   • Add macro-pixel with maximum intensity to the ROI
   • Add nearest-neighbor macro-pixels, if intensity $> n \cdot \sigma_{noise}$ with typically $n=3$
   • Repeat this for new elements of the ROI until it stays unchanged

Result: *connected* ROI of arbitrary shape, “detectable” beam intensity included, minimum of noise

→ several iterations with different positions of the centers of the macro-pixels / different sizes of macro-pixels / entire boundary layers
→ union of all ROIs is taken
Image analysis: region of interest (ROI)

Methods

Processed image

Original image without noise

Accuracy of calculated slice widths:

original: calculated (μ and σ from 20 images)
Position jitter requires the determination of a reference point in the vertical (longitudinal) profile:

### Choice of the slice width:

- **Slice width 1.7 μm**
  - $\Delta \zeta_{\text{slice}} = 1.7 \mu m$

- **Slice width 3.4 μm**
  - $\Delta \zeta_{\text{slice}} = 3.4 \mu m$

- **Slice width 10.2 μm**
  - $\Delta \zeta_{\text{slice}} = 10.2 \mu m$
Results: measured slice emittance at on-crest operation

- Estimated accuracy: < 15% (RMS)
- Mean slice emittance: 2.1 µm
- Projected emittance: 3.8 µm

- Difference caused by
  - Centroid shifts
  - Beam deformation (``slice mismatch")
- Projected emittance after correction of centroid offsets: ~2.5 µm
Results

Tomographic reconstruction of phase space distributions

Single slice, $\Delta \zeta = 150\mu m$

$\gamma \epsilon_x = 1.6 \mu m$

Projected

$\gamma \epsilon_x = 3.8 \mu m$

490 MeV, 0.6 nC, on-crest operation

Tomography
Least squares
FEL-operating conditions: centroid offsets

494 MeV, 0.7 nC

CCD-image (head region)

Horizontal offset of the peak current region due to CSR within the second bunch compressor

Results
Results

Horizontal phase space

Centroid curve:

Projected distribution in horizontal phase space:

494 MeV, 0.7 nC

\[ \gamma \epsilon_x = 13 \, \mu m \]
FEL-operating conditions: slice emittance

Slice emittance

\[ \gamma e_x [\mu m] \]

\begin{align*}
\approx 2 \mu m \\
\approx 10 \mu m
\end{align*}

Longitudinal resolution \( \sim 8 \mu m \) (RMS)

Current profile

Head

Increase in slice emittance in the peak current region:

- Cause?
- FEL-criterion?
Comparison to numerical simulations

Current profile: Adaption of the RF-phase of module ACC1

Slice emittance

Simulations with ASTRA (K. Flöttmann) and CSRTrack (M. Dohlus)
Reconstructed phase space

Results

Reconstructed phase space:

Slice emittance

Tomography

Least squares

Current profile

Reconstructed phase space:

longitudinal slice position, thickness $\Delta \zeta = 8 \ \mu m$
Results

Reconstructed phase space

\[ \gamma \xi, x \text{ [\mu m]} \]

\[ I \text{ [kA]} \]

\[ \zeta \text{ [mm]} \]

\[ x' \text{ [mrad]} \]

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Results

Reconstructed phase space

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Reconstructed phase space

Results
Emittance analysis

Measured distribution in the peak current region

2-dimensional Gaussian fit to the peak

8 µm, 1.2 kA

2 µm, 0.7 kA

typical: 2-4 µm normalized emittance, 0.5 – 1.0 kA peak current

→ shot-to-shot fluctuations, coherence length ~1-2 µm << resolution, peak current may change downstream of the TDS, FEL radiation not saturated

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Error sources:
Horizontal slice emittance

- **Principle limitations of the method**
  - Shot-to-shot fluctuations in transverse phase space
  - Limitations of the longitudinal resolution

- **Errors in measured beam sizes:**
  - Resolution of the optical system (< 26 µm RMS)
  - Statistical errors of beam sizes (~10 % RMS)
  - Calibration errors (~2 % RMS)
  - Dispersion (from the kicker) (~< 10 % RMS)

- **Erroneous model for beam transfer** due to
  - Quadrupole gradient errors
  - Energy errors
  - Transverse space charge forces
  - The detailed energy distribution (“chromaticity”)

Emittance error < 20 % (RMS) for typical conditions

Simulation of a measurement using ASTRA
Simulation of an emittance measurement / a tomographic reconstruction

Start-to-end simulation

Initial distribution at the reconstruction point

Comparison

Reconstructed phase space / slice emittance

Particle tracking

Screen

Programs for data analysis

digital images + Gaussian noise
Simulation of a tomographic reconstruction: peak current region

Initial distribution:
Peak current region (25 µm length)

Reconstruction:
• Tracking: linear transfer matrices
  • no kicker

Reconstruction:
• Tracking: ASTRA (no space charge)
  • no kicker

Reconstruction:
• Tracking: ASTRA (incl. space charge)
  • with kicker

Error analysis
Error analysis

Simulation of a slice emittance measurement

- Tracking: ASTRA, incl. space charge
- Kicker included
- Longitudinal resolution: ~10 µm

Slice emittance of initial distribution

Reconstructed slice emittance

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Summary

- TDS successfully used to measure the horizontal slice emittance with a longitudinal resolution of ~10 μm (30 fs) and an accuracy of ~20 % (RMS)
- Strong increase in slice emittance observed in the high-current region, supposably due to CSR
- A tomographic reconstruction and a detailed phase space analysis are necessary in order to estimate the emittance of the “lasing fraction”, slice emittance not conclusive
Thank you for your attention!

Thanks to C. Gerth, H. Schlarb and the entire FLASH-team