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

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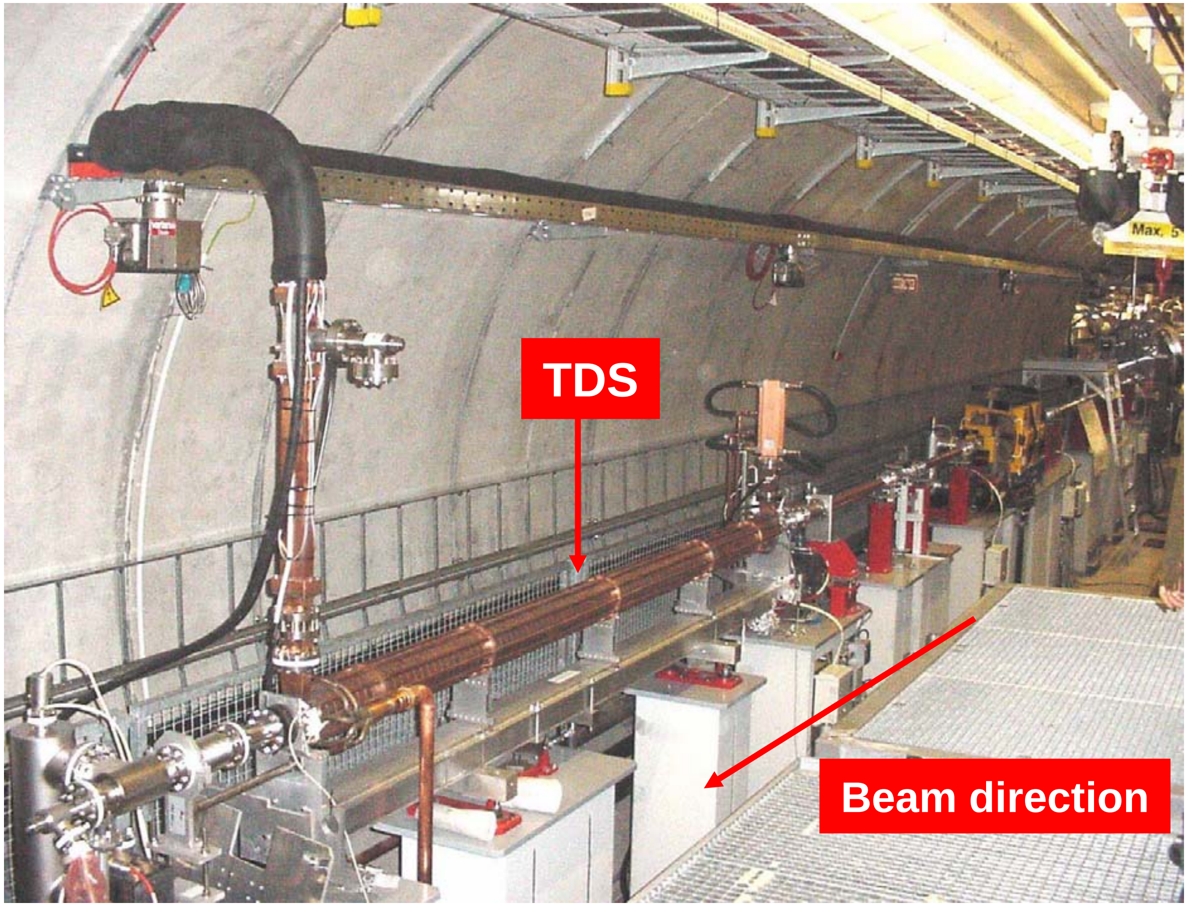
Mini-Workshop on “Characterization of High Brightness Beams” in Zeuthen, May 2008

Outline: Slice emittance measurements at FLASH

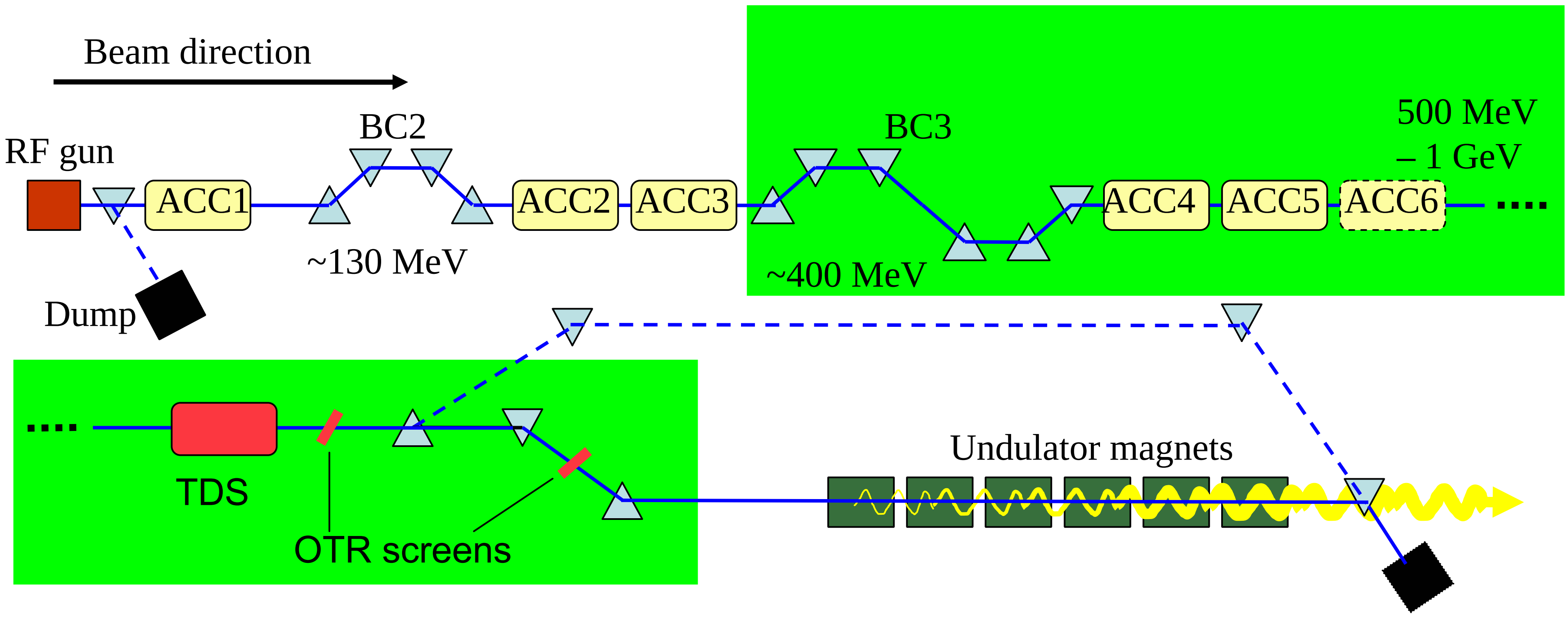
- Setup
- Methods
- Results
  - On-crest operation
  - FEL operating conditions
- Error analysis
- Conclusions

The transverse deflecting structure (TDS)

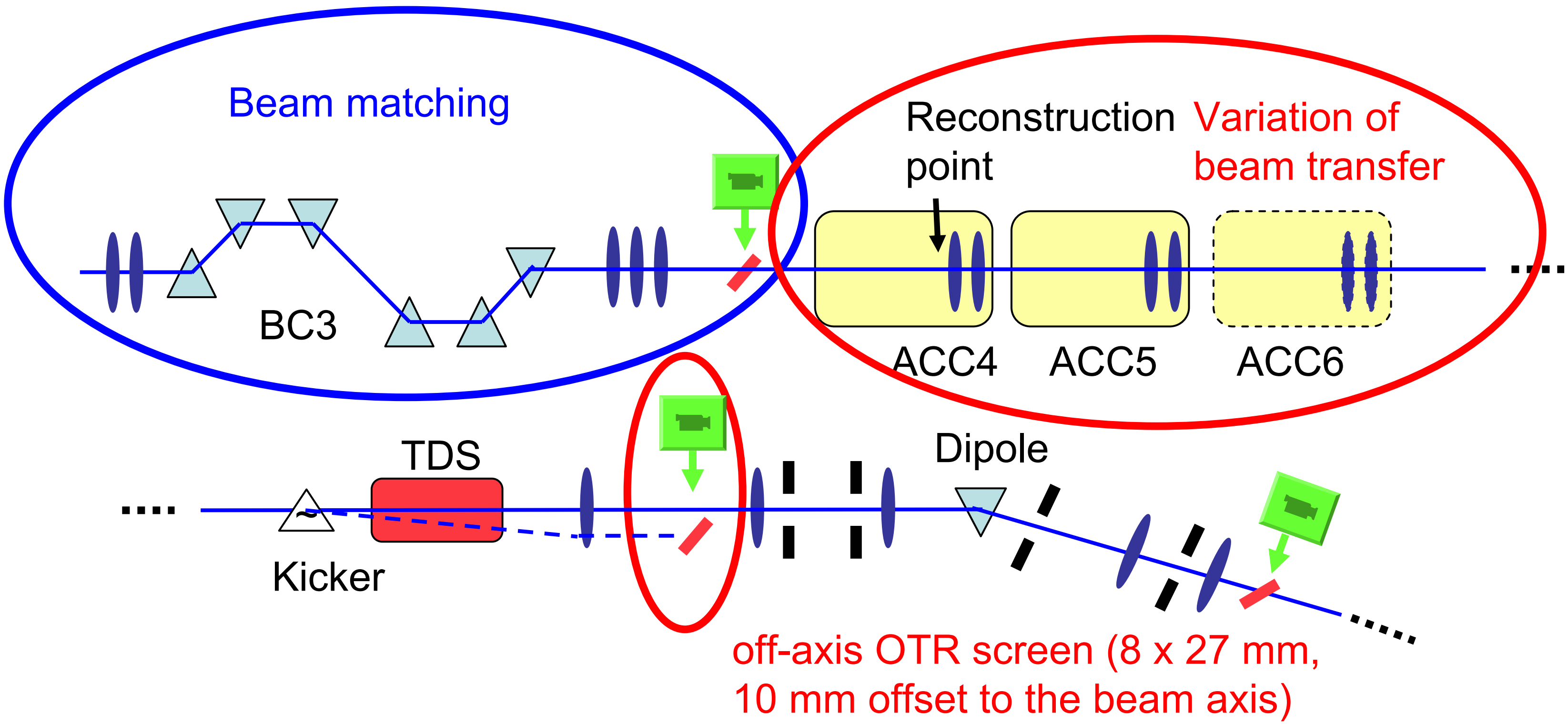


- Installed in 2003, Collaboration DESY-SLAC
- Frequency: 2.86 GHz
- Length: 3.6 m
- Maximum deflecting voltage ~ 25 MV @ 20 MW input power
- Maximum induced divergence @ 500 MeV: ~1 mrad / ps

Installation in the FLASH-linac



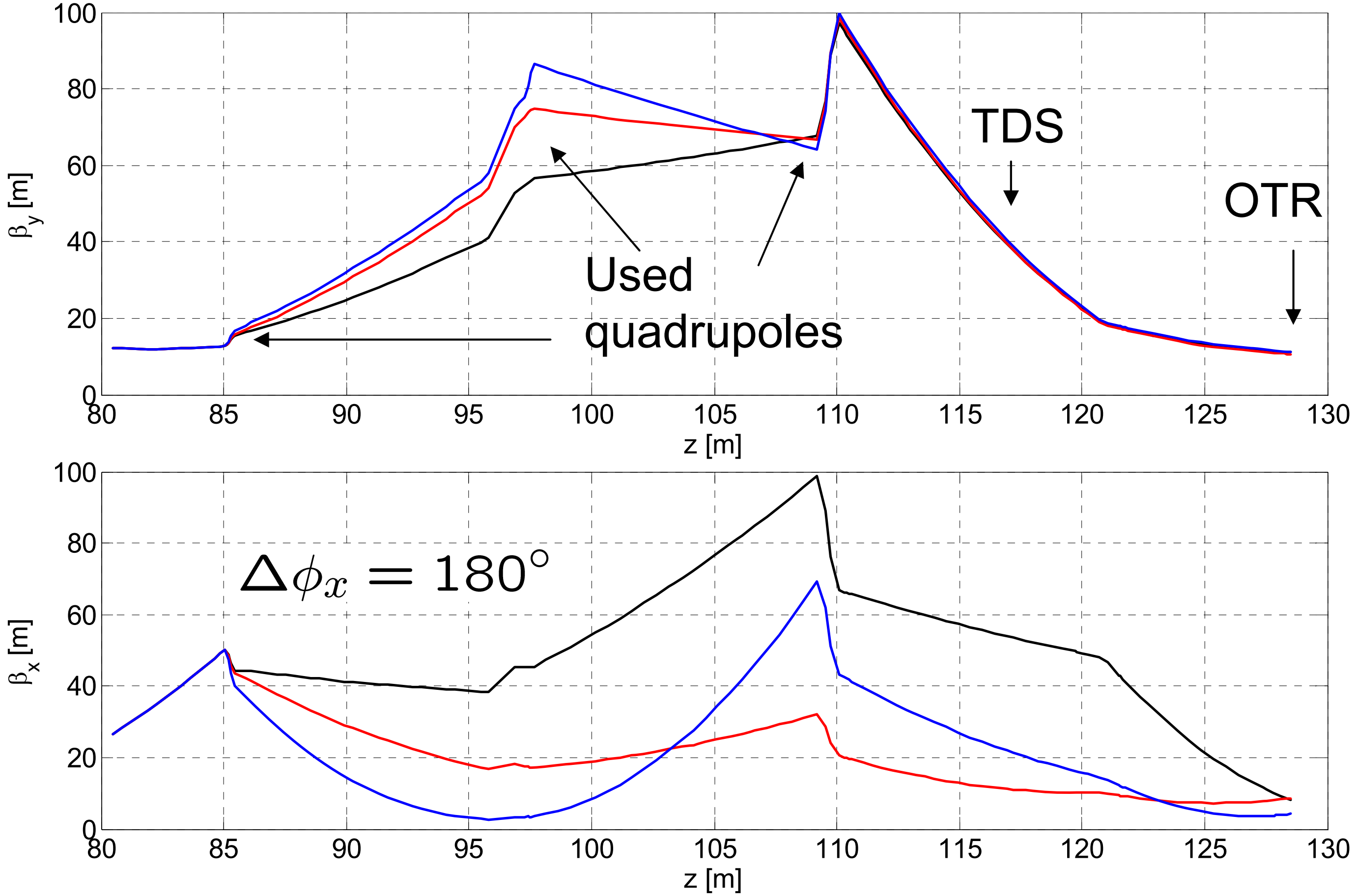
Setup for slice emittance measurements



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

Methods

Optics for slice emittance measurements



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,

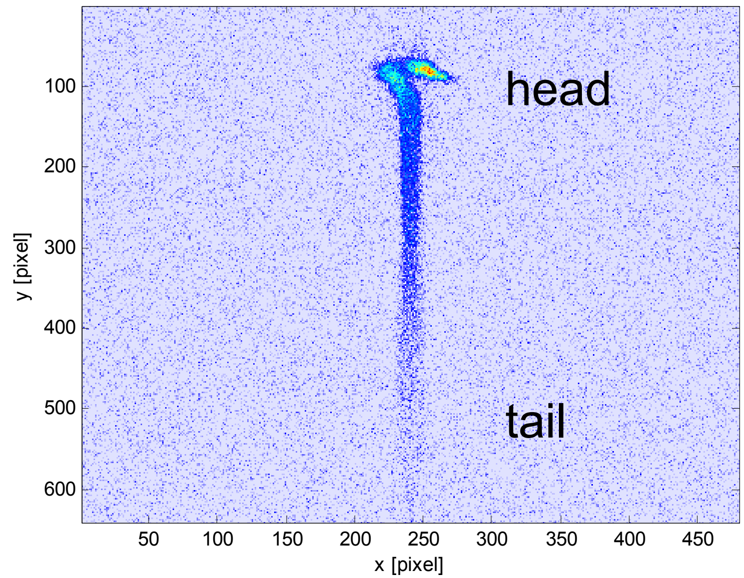
  AND

  averaging of slice-profiles and determination of the phase space distribution using the MENT-algorithm (implementation by J. Scheins, 2004)

Methods

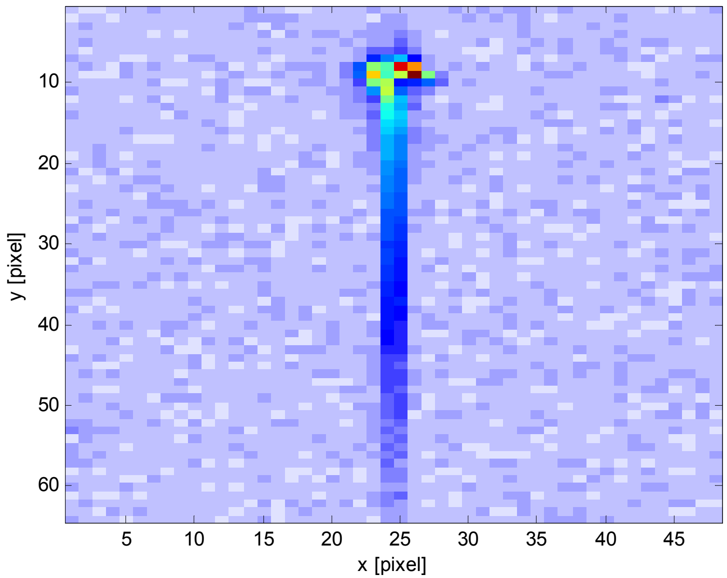
Image analysis: region of interest (ROI)

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)

1. Coarsened image, 10x10 “macro-pixels”



→ Increase in signal-to-noise ratio by a factor of 10

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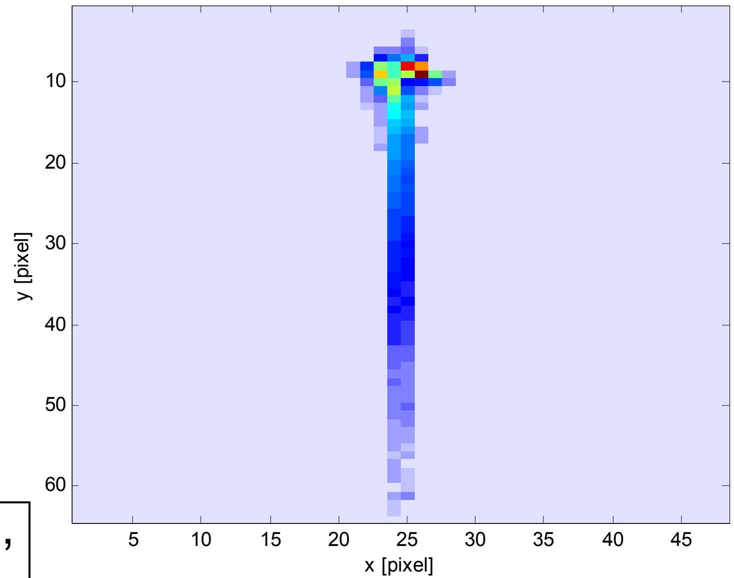
Image analysis: region of interest (ROI)

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

Example for a ROI:



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

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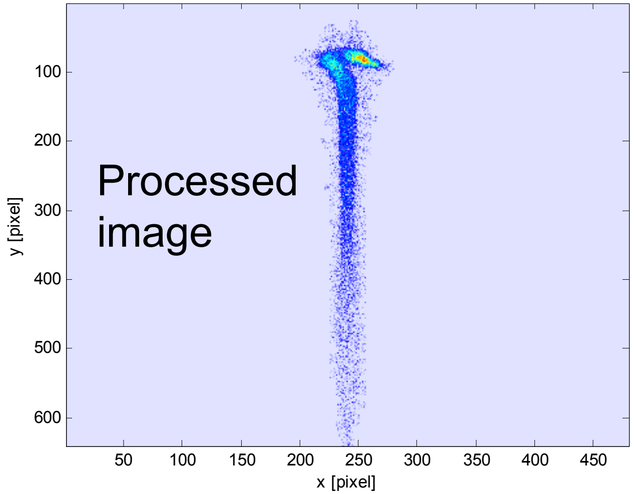
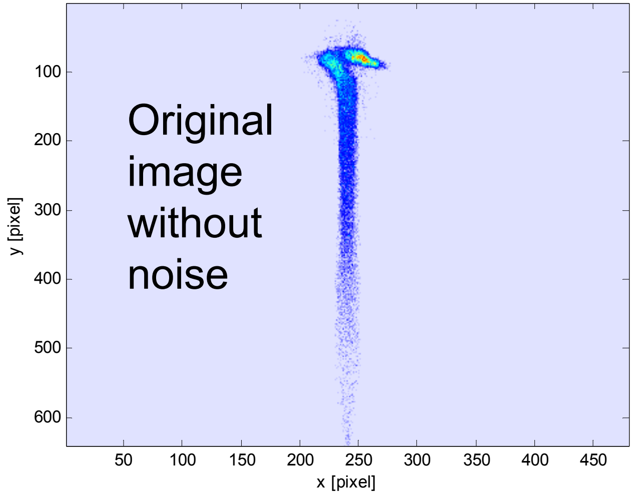
Image analysis: region of interest (ROI)





Accuracy of calculated slice widths:

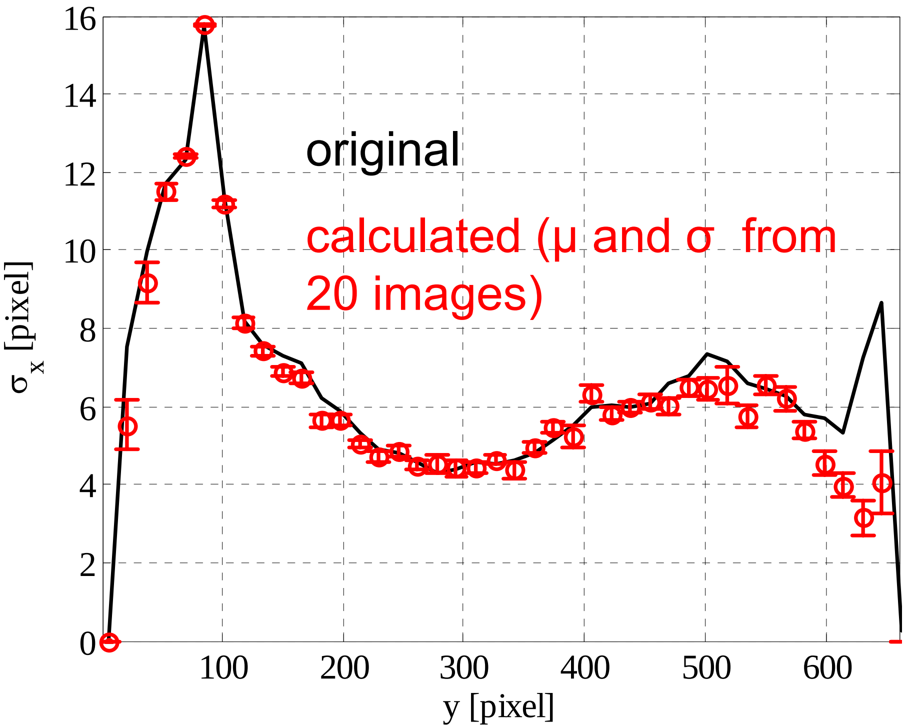
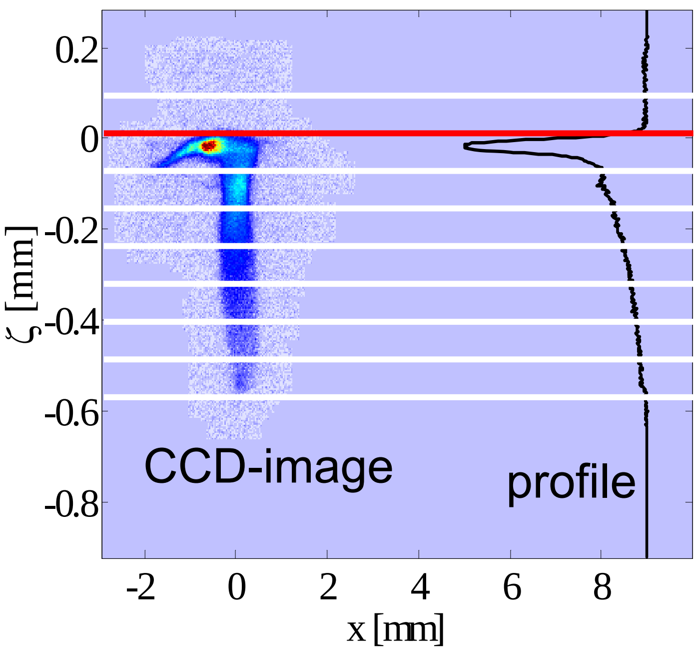
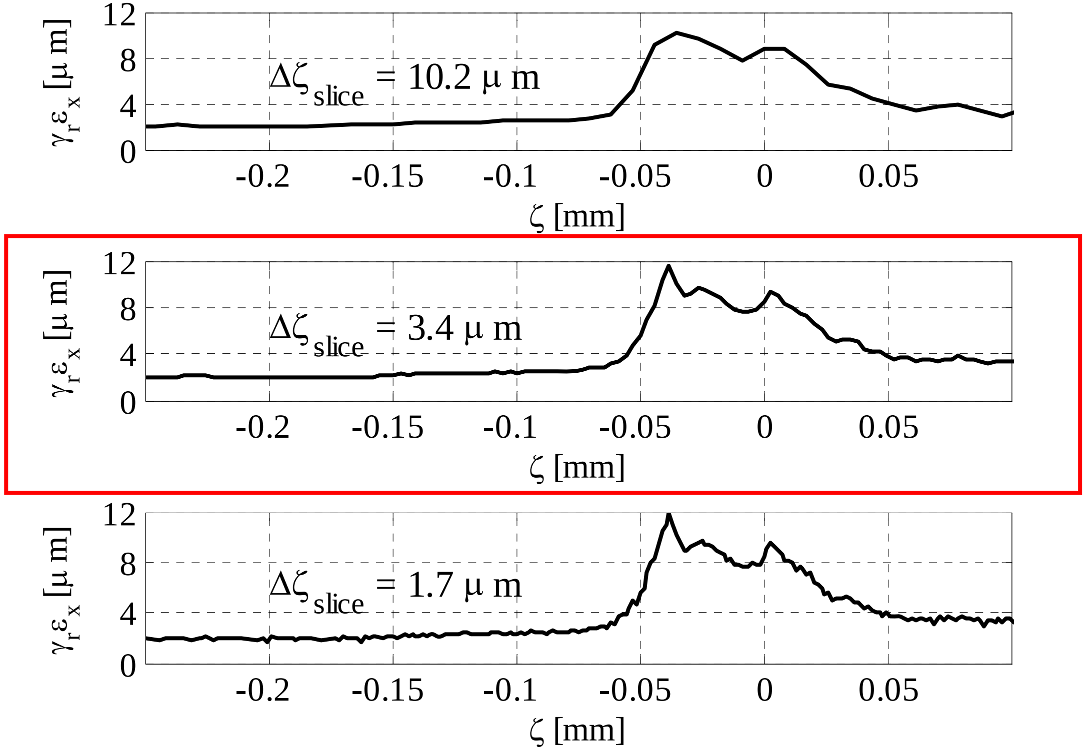


Image analysis: Subdivision into slices

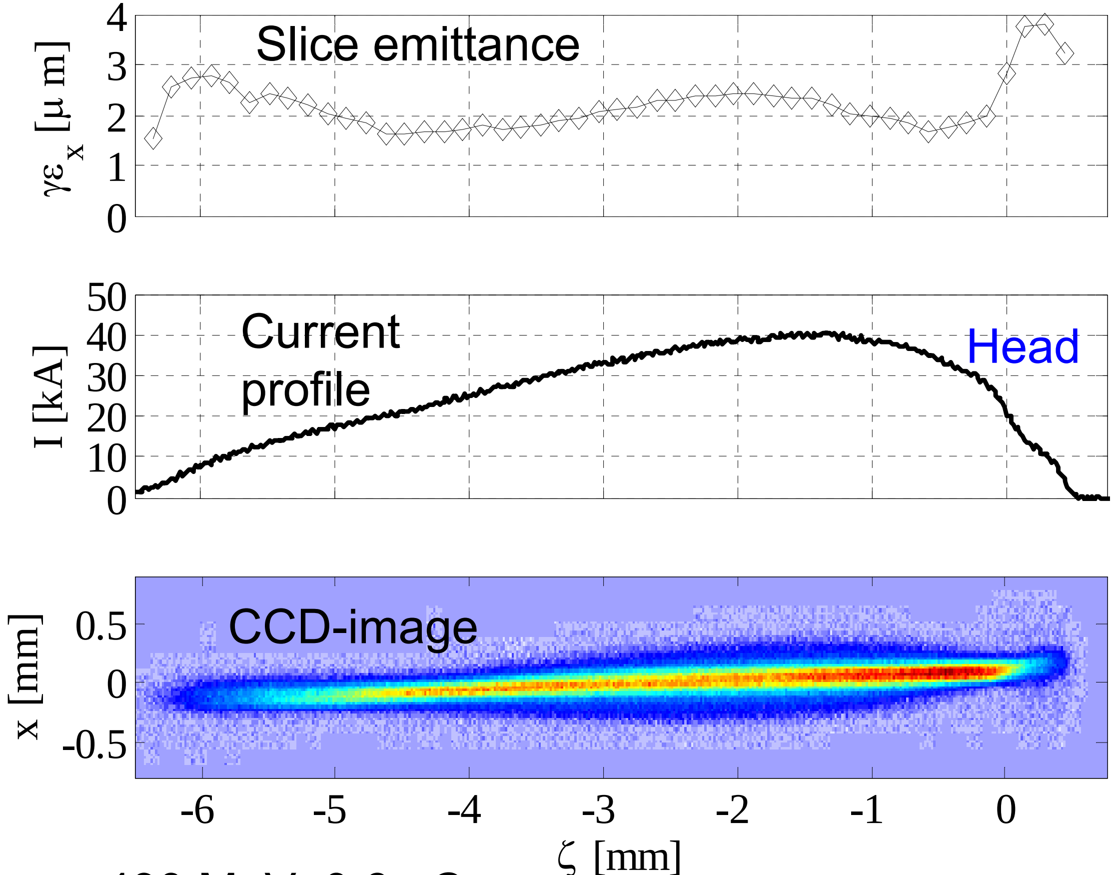
Position jitter requires the determination of a reference point in the vertical (longitudinal) profile:



Choice of the slice width:



Results: measured slice emittance at on-crest operation

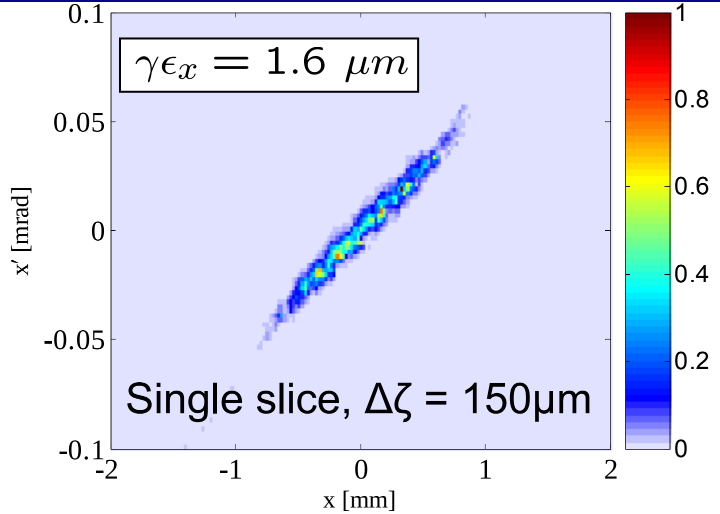


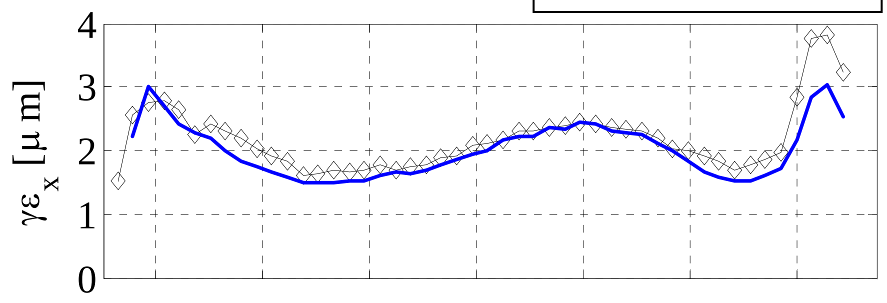
490 MeV, 0.6 nC

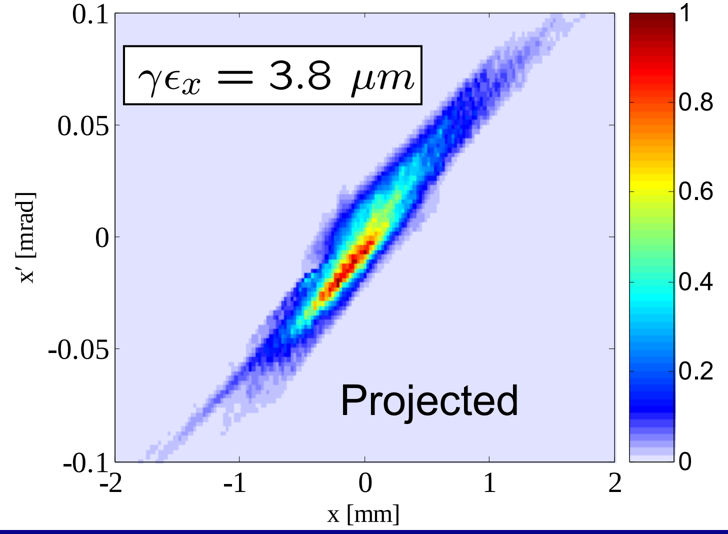
- Estimated accuracy: < 15% (RMS)
- Mean slice emittance: **2.1μm**
- Projected emittance: **3.8 μm**

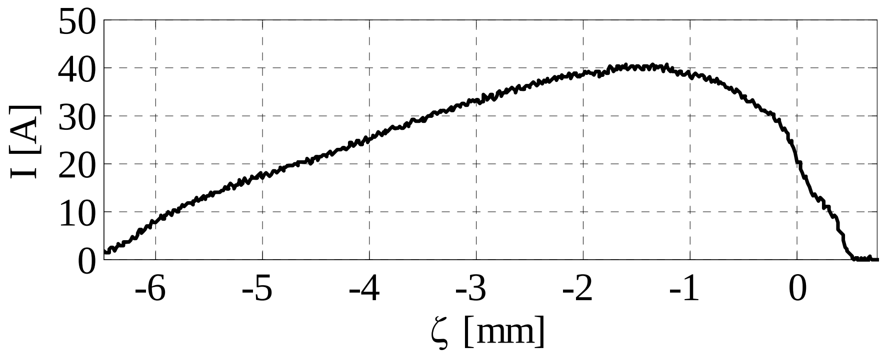
- Difference caused by
  - Centroid shifts
  - Beam deformation (``slice mismatch")
- Projected emittance after correction of centroid offsets: **~2.5μm**

Tomographic reconstruction of phase space distributions





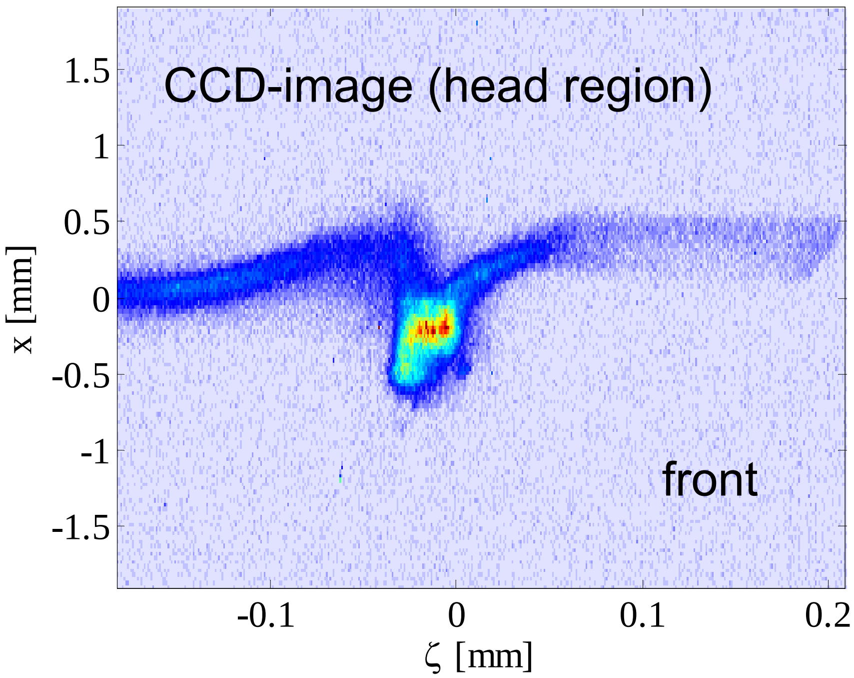


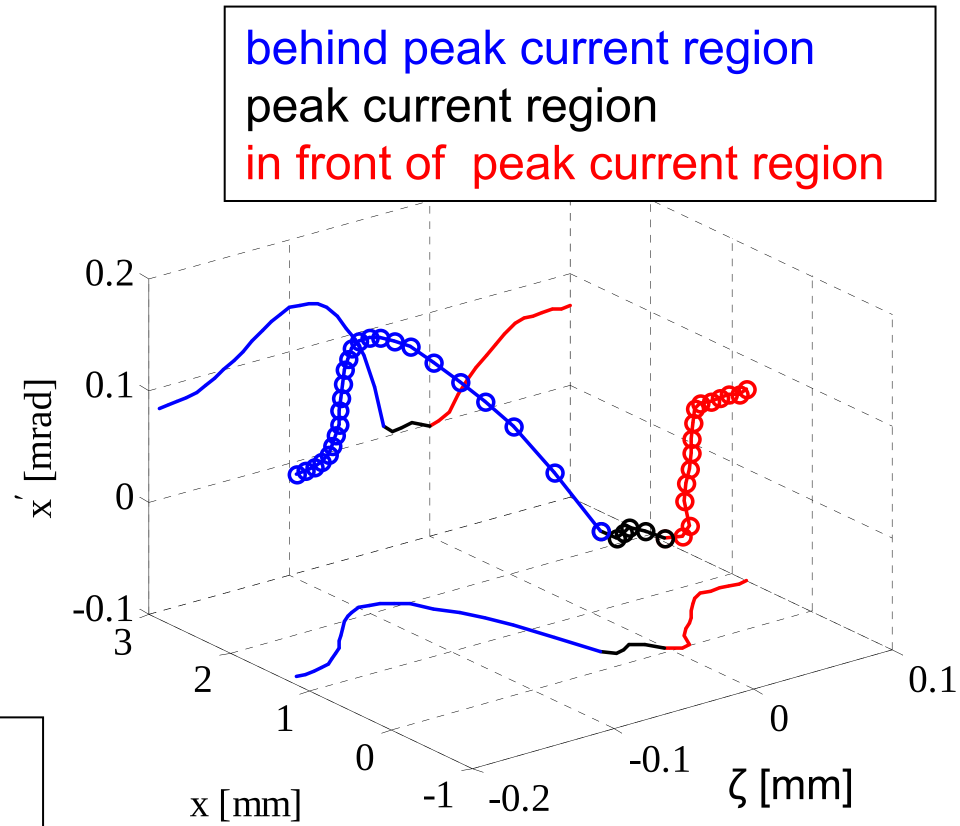


490 MeV, 0.6 nC, on-crest operation

FEL-operating conditions: centroid offsets

494 MeV, 0.7 nC

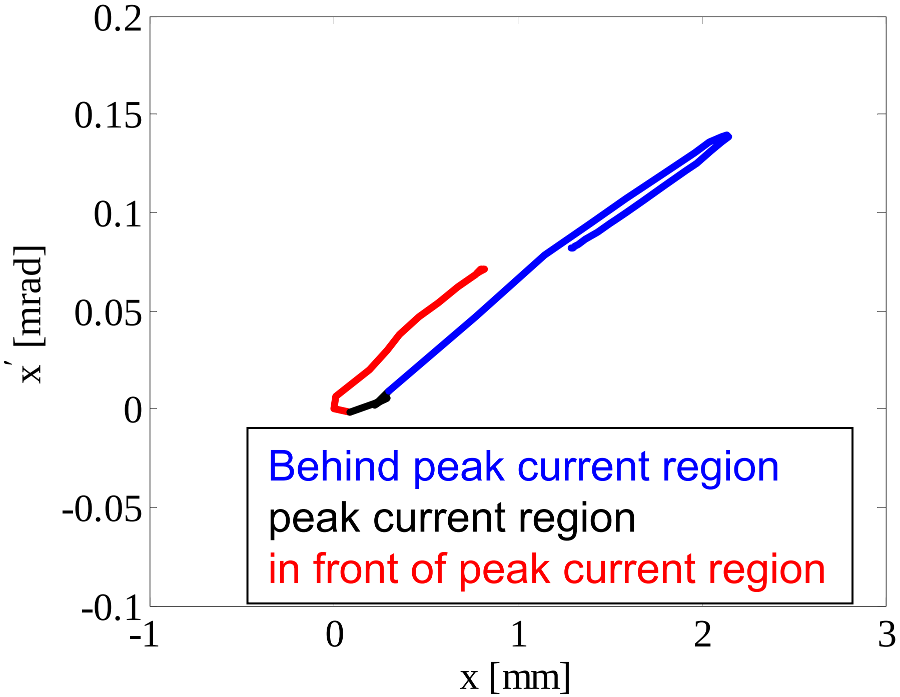




Horizontal offset of the peak current region due to CSR within the second bunch compressor

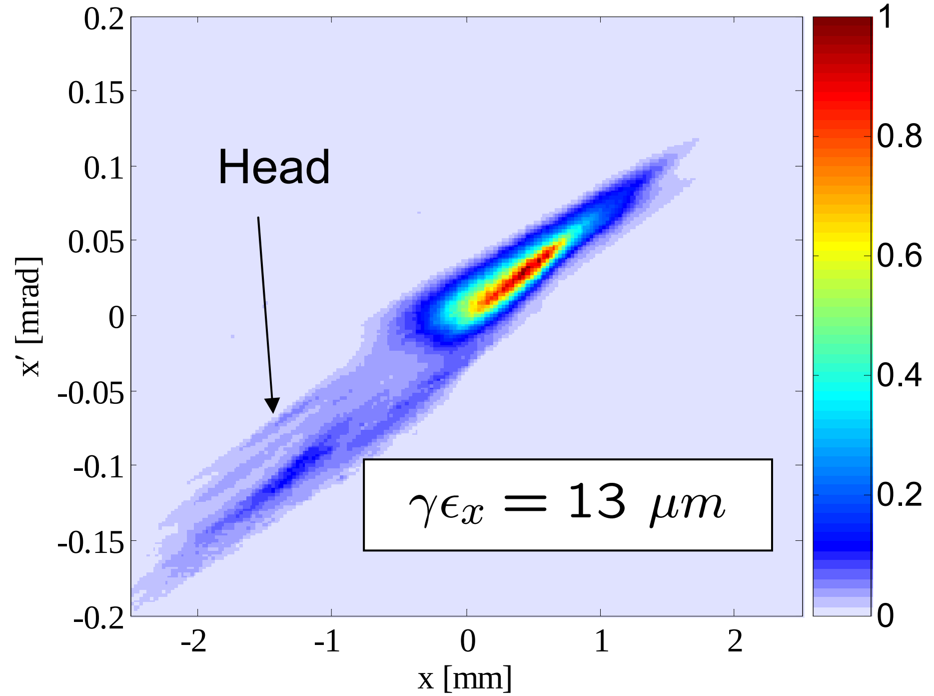
Horizontal phase space

Centroid curve:

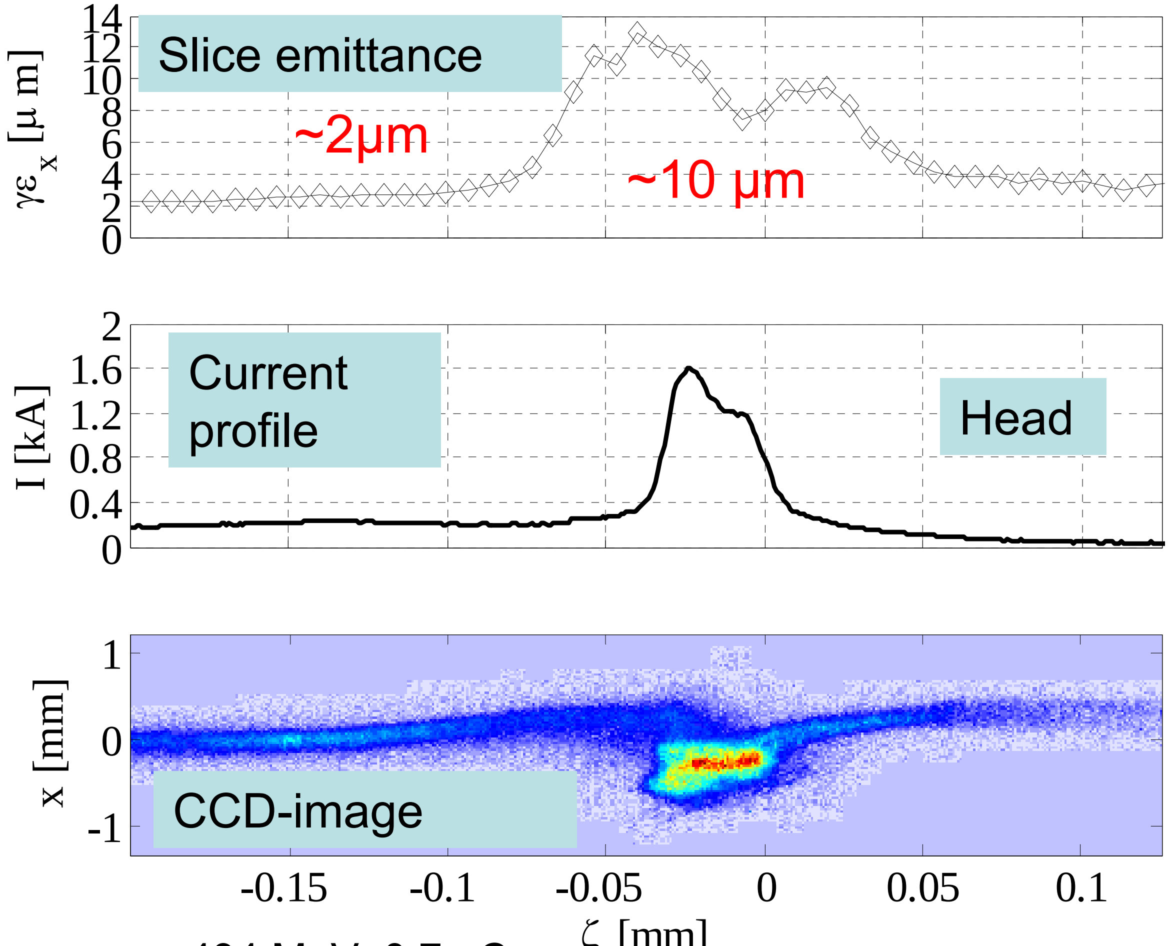


494 MeV, 0.7 nC

Projected distribution in horizontal phase space:



FEL-operating conditions: slice emittance



494 MeV, 0.7 nC

Longitudinal resolution ~ 8 μm (RMS)

Increase in slice emittance in the peak current region:

- Cause?
- FEL-criterion?

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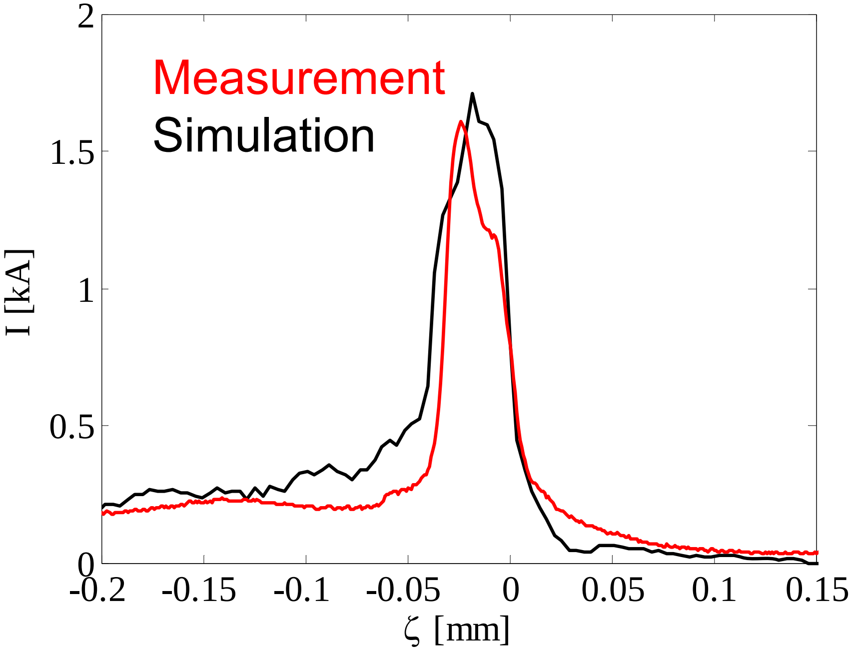
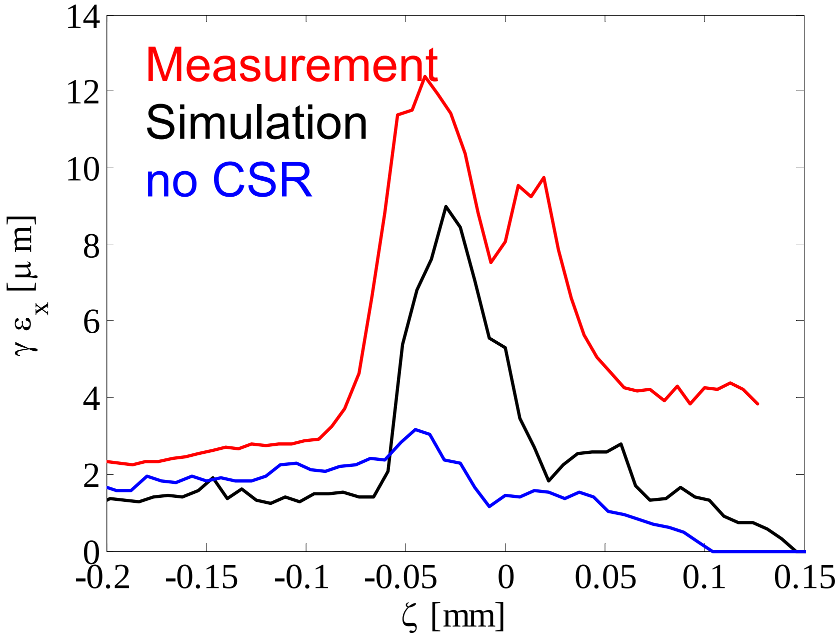
Comparison to numerical simulations

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



Slice emittance



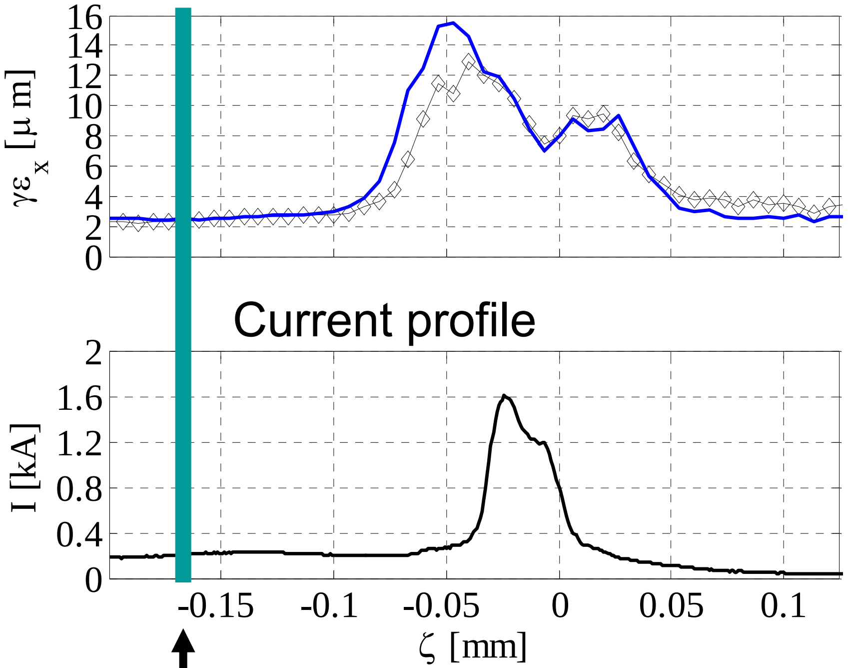
Simulations with ASTRA (K. Flöttmann) and CSRTrack (M. Dohlus)

Results

Reconstructed phase space

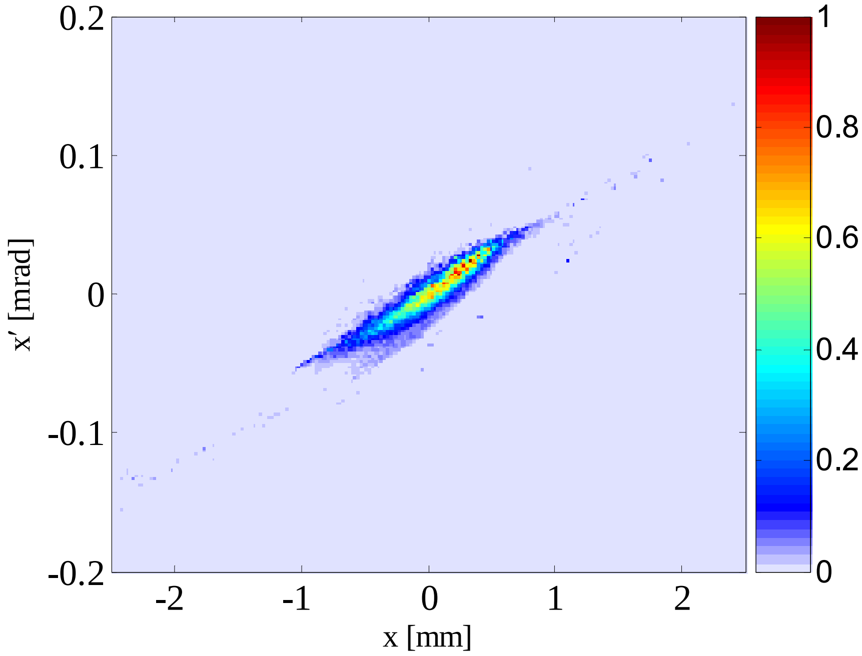
Slice emittance

Tomography
Least squares

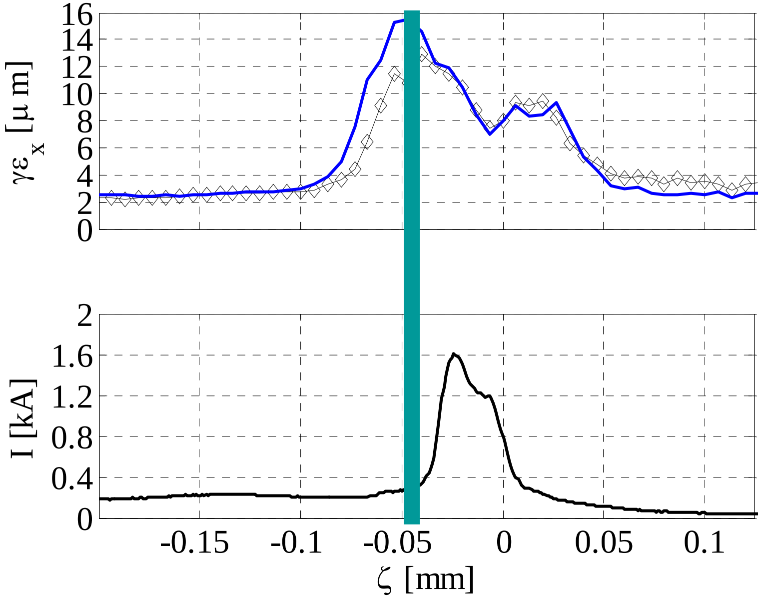


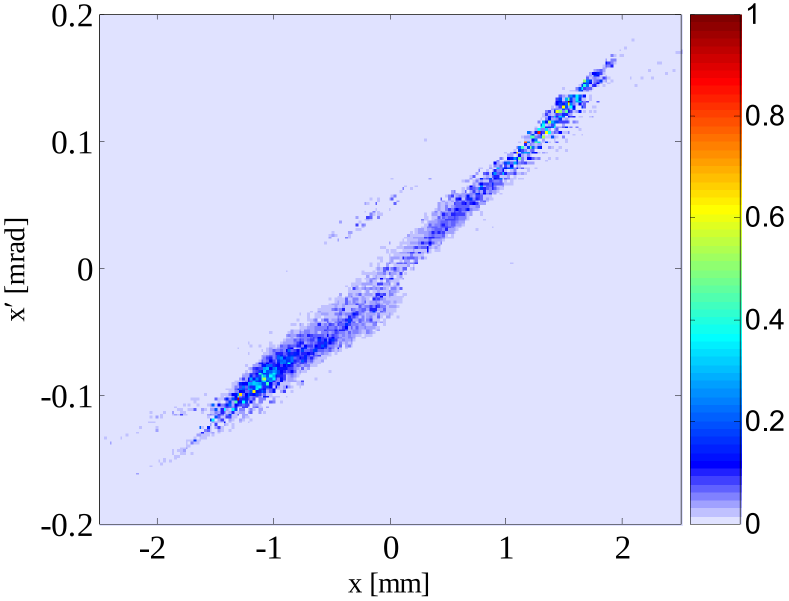
longitudinal slice position,
thickness Δζ = 8 μm

Reconstructed phase space:

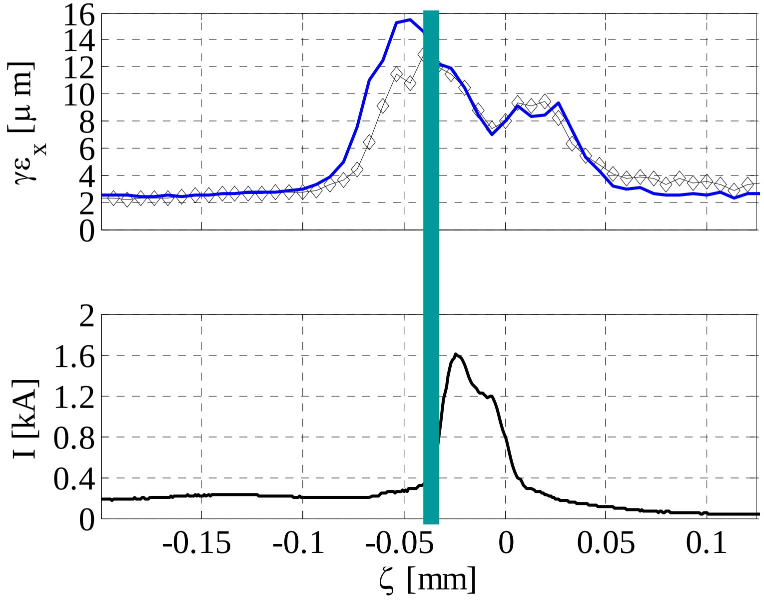


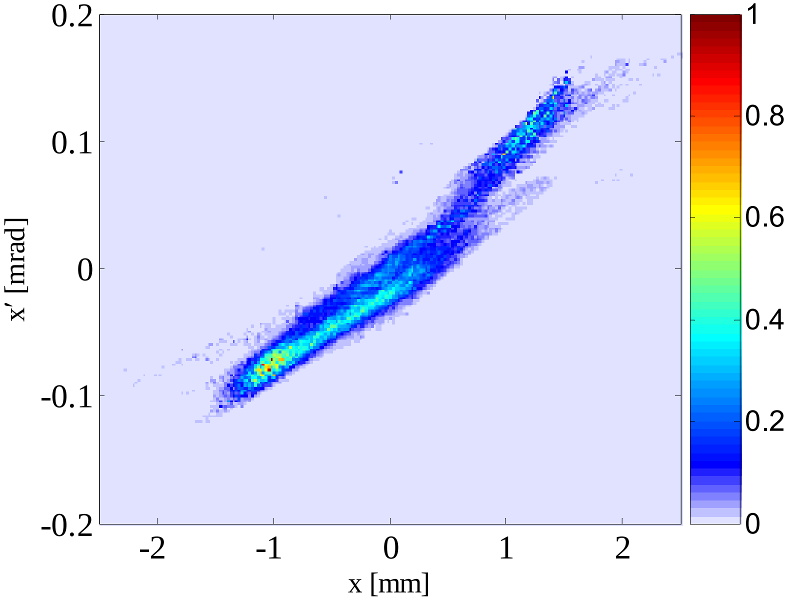
Reconstructed phase space



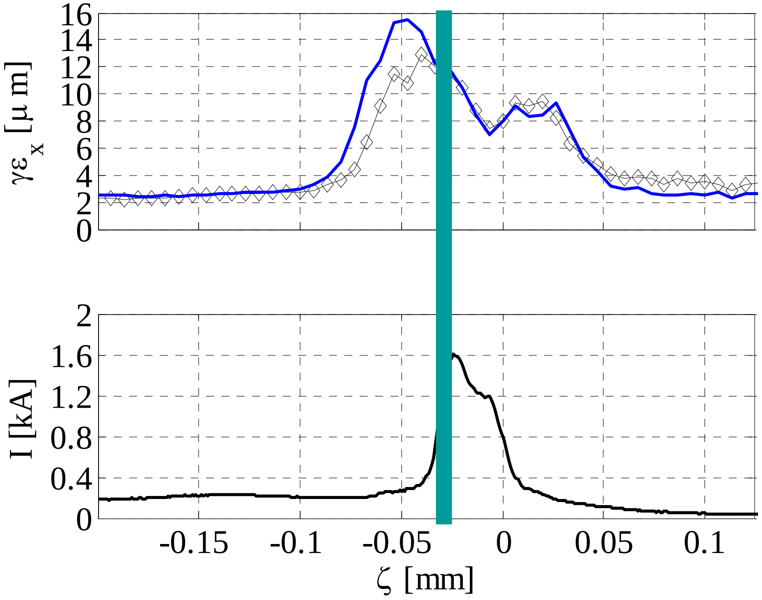


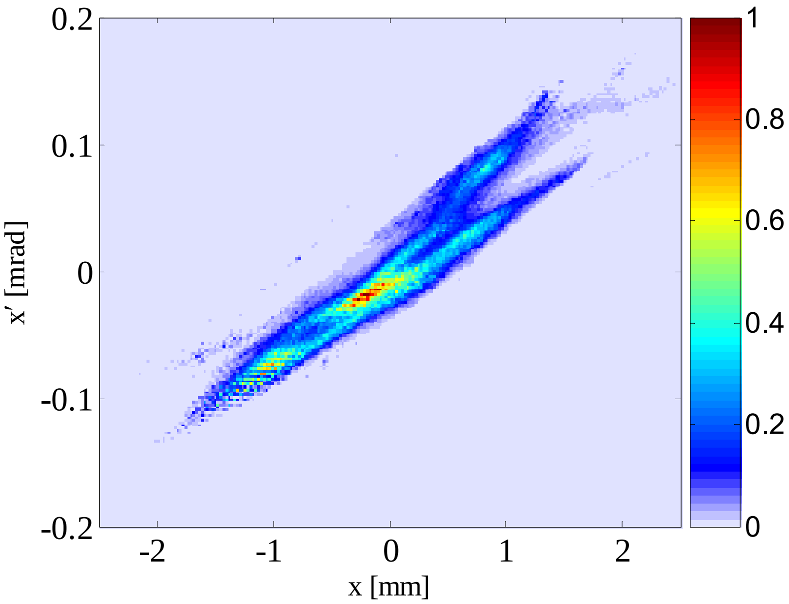
Reconstructed phase space





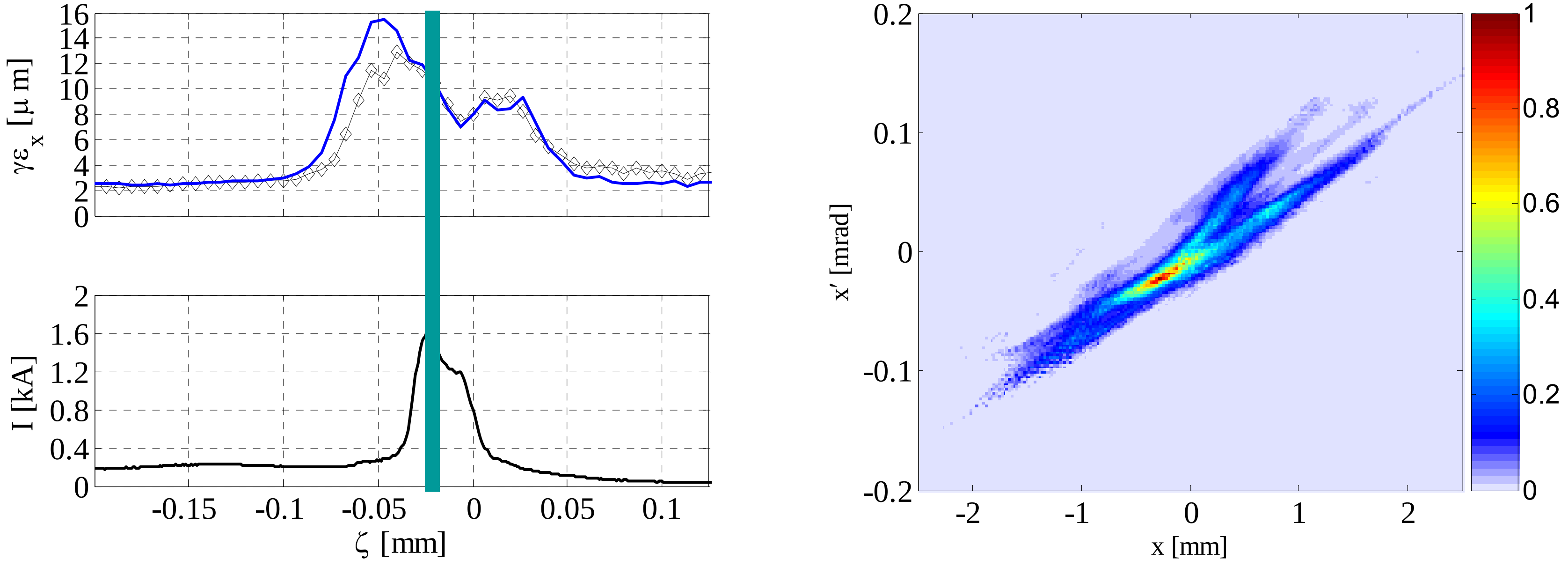
Reconstructed phase space





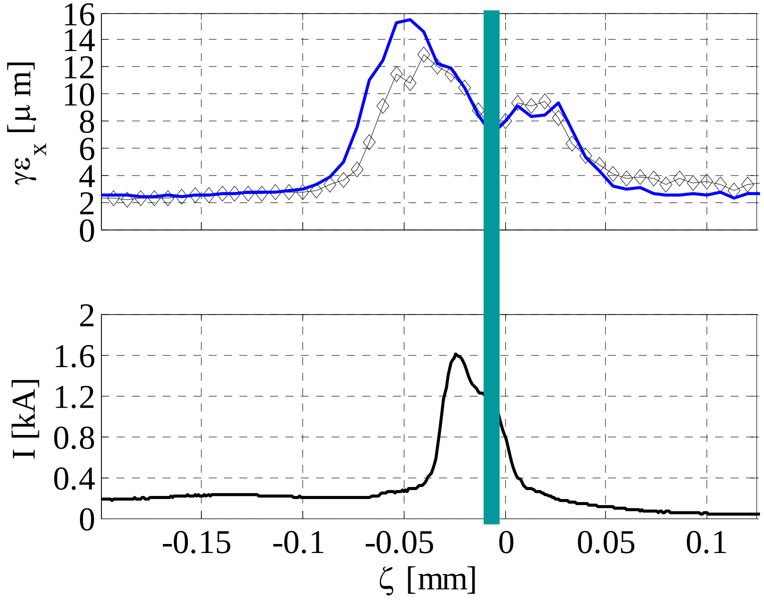
Results

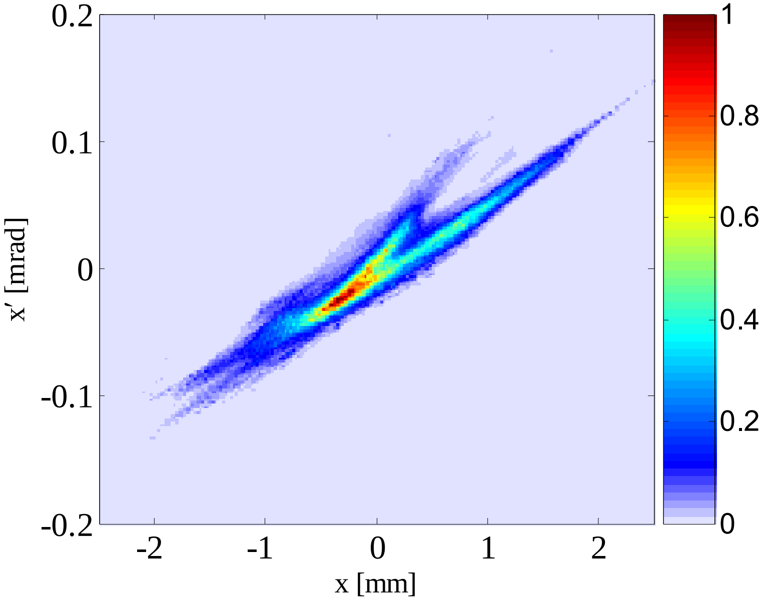
Reconstructed phase space



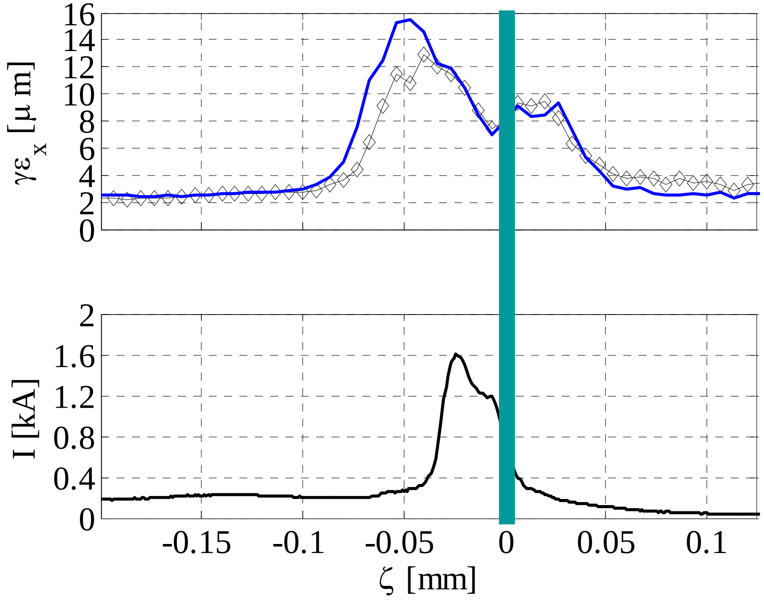
Results

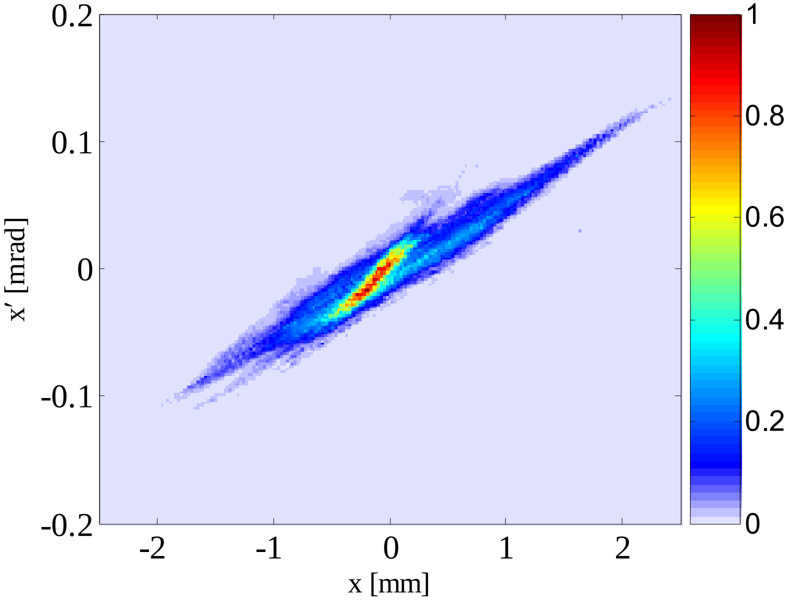
Reconstructed phase space





Reconstructed phase space





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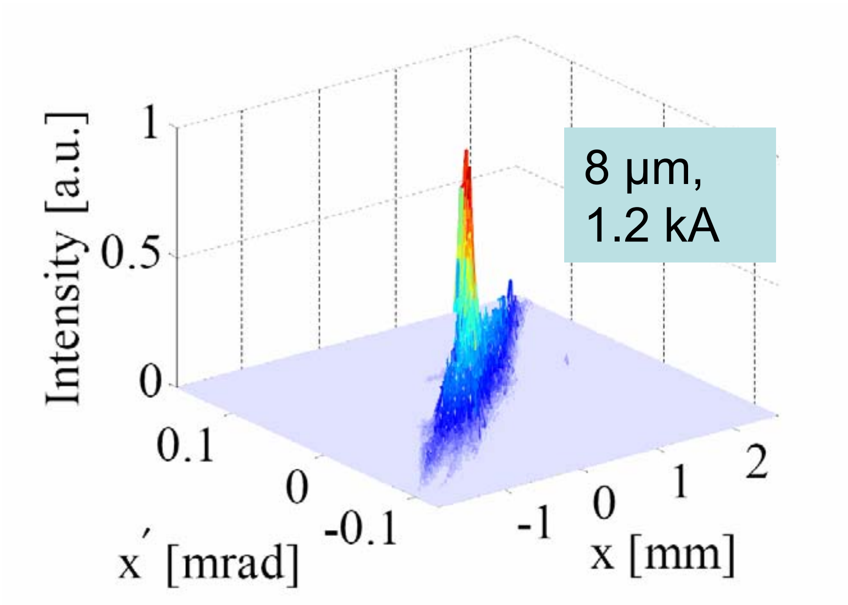
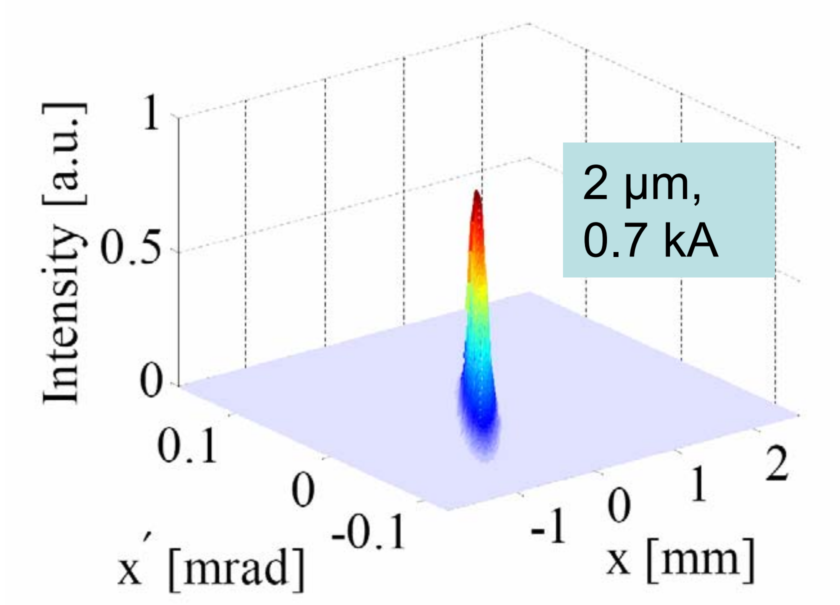
Emittance analysis

Measured distribution in the peak current region



2-dimensional Gaussian fit to the peak



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

→ ???

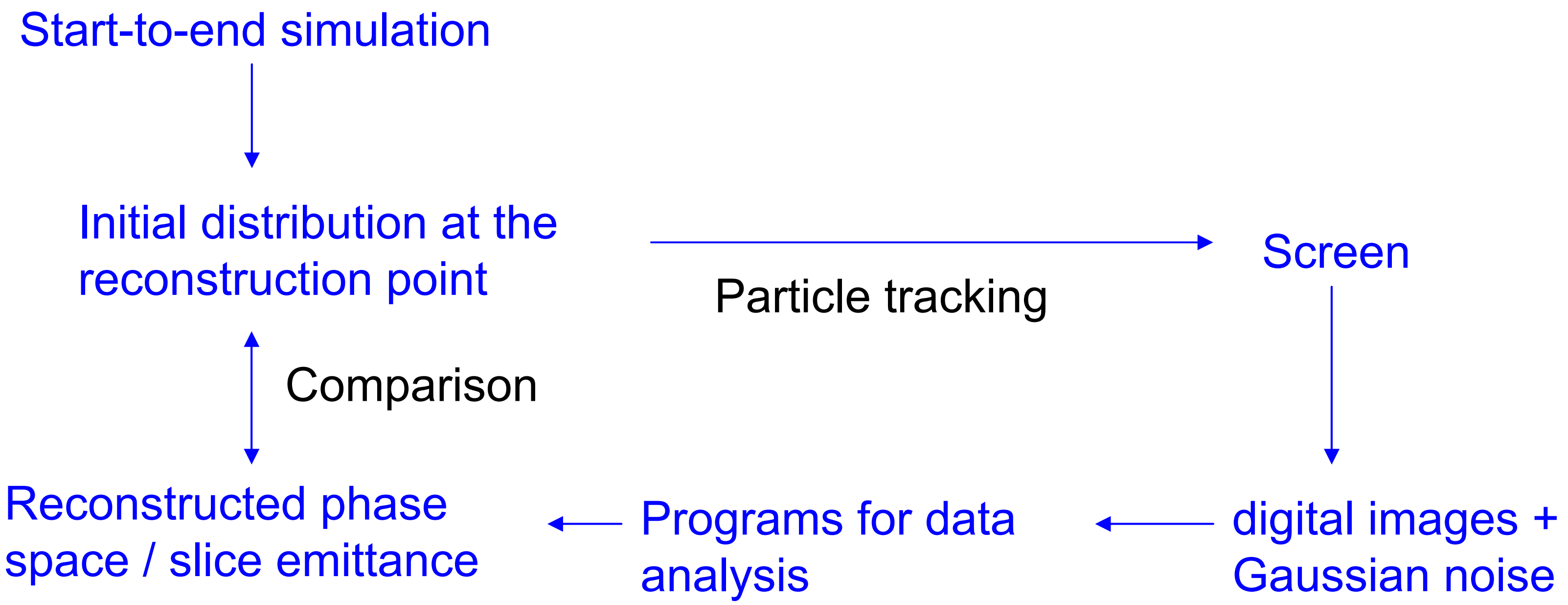
- Errors in measured beam sizes:
  - Resolution of the optical system (< 26 µm RMS)
  - Statistical errors of beam sizes (~10 % RMS)
  - Calibration errors (~2 % RMS)
  - Dispersion (from the kicker) (~< 10 % RMS)
- Erroneous model for beam transfer due to
  - Quadrupole gradient errors
  - Energy errors

→ Emittance error < 20 % (RMS) for typical conditions

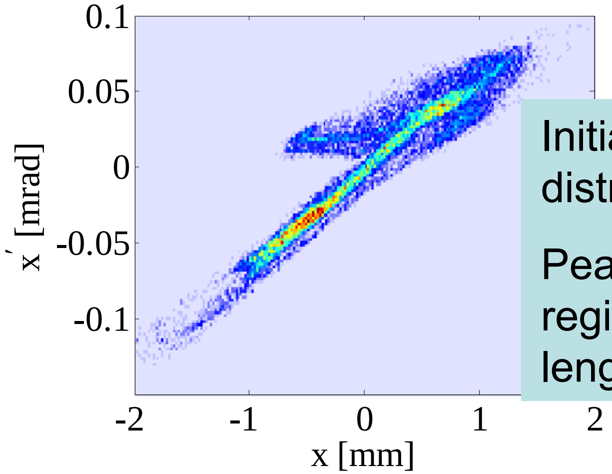
  - Transverse space charge forces
  - The detailed energy distribution ("chromaticity")

→ Simulation of a measurement using ASTRA

Simulation of an emittance measurement / a tomographic reconstruction

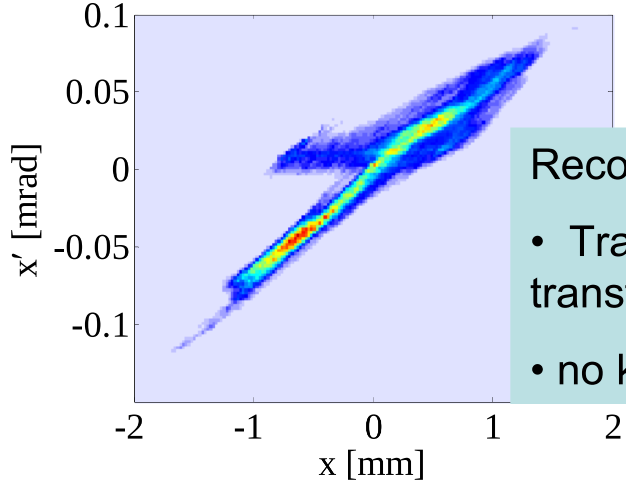


Simulation of a tomographic reconstruction: peak current region



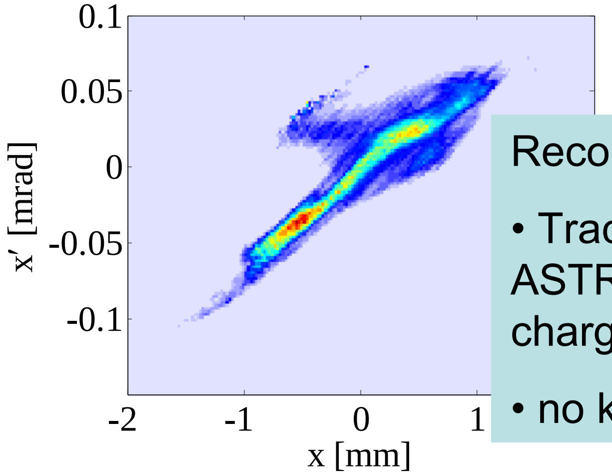
Initial distribution:

Peak current region (25 μm length)



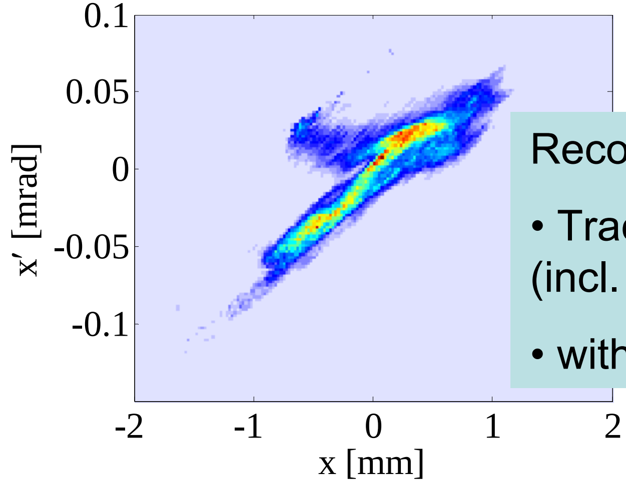
Reconstruction:

- Tracking: linear transfer matrices
- no kicker



Reconstruction:

- Tracking: ASTRA (no space charge)
- no kicker

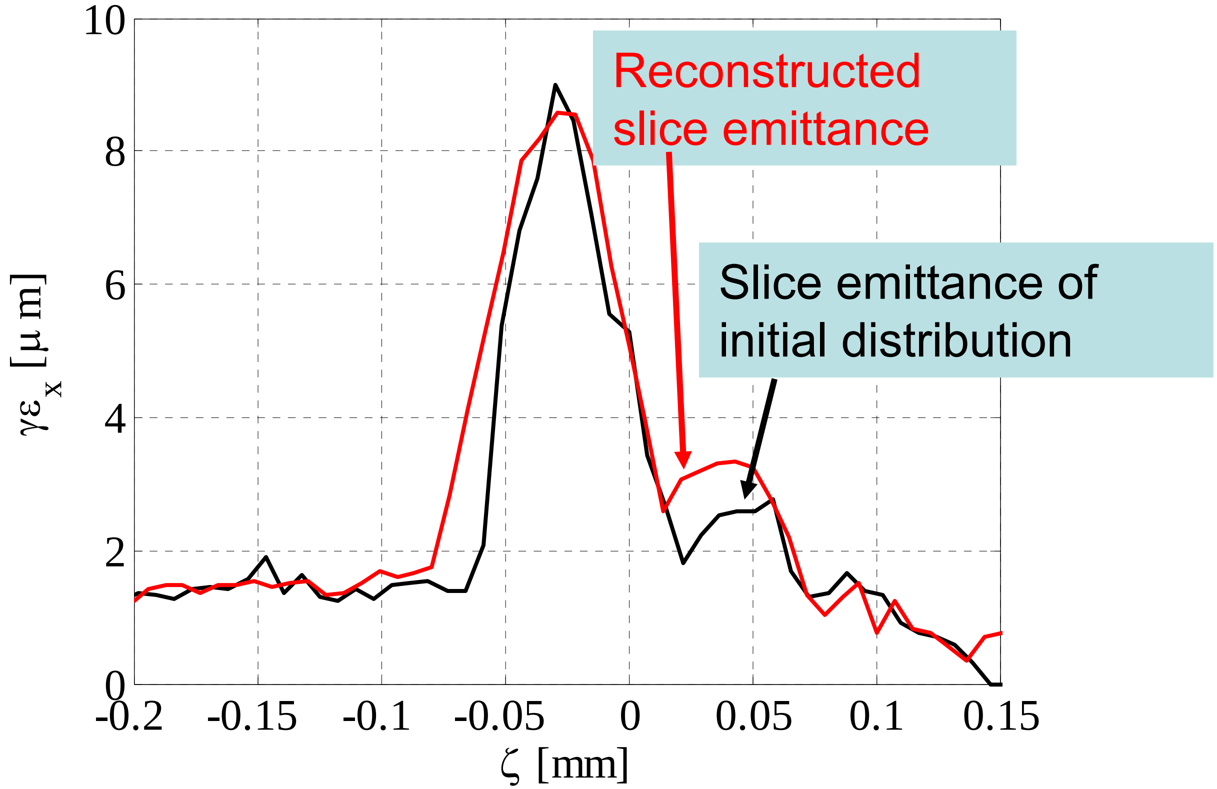


Reconstruction:

- Tracking: ASTRA (incl. space charge)
- with kicker

Simulation of a slice emittance measurement

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



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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