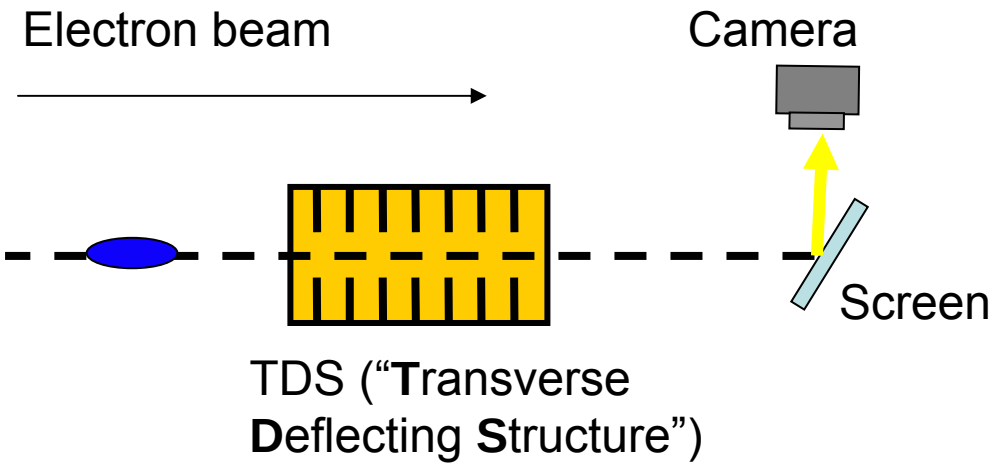
Investigation of the Phase Space Distribution of Electron Bunches at the FLASH-Linac Using a Transverse Deflecting RF-Structure

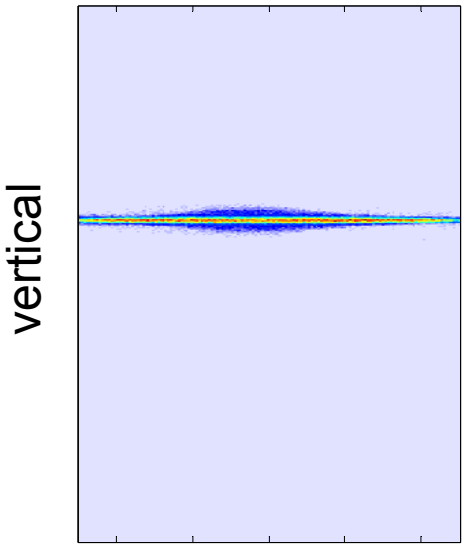
Michael Röhrs

Paul Scherrer Institut, June 2008

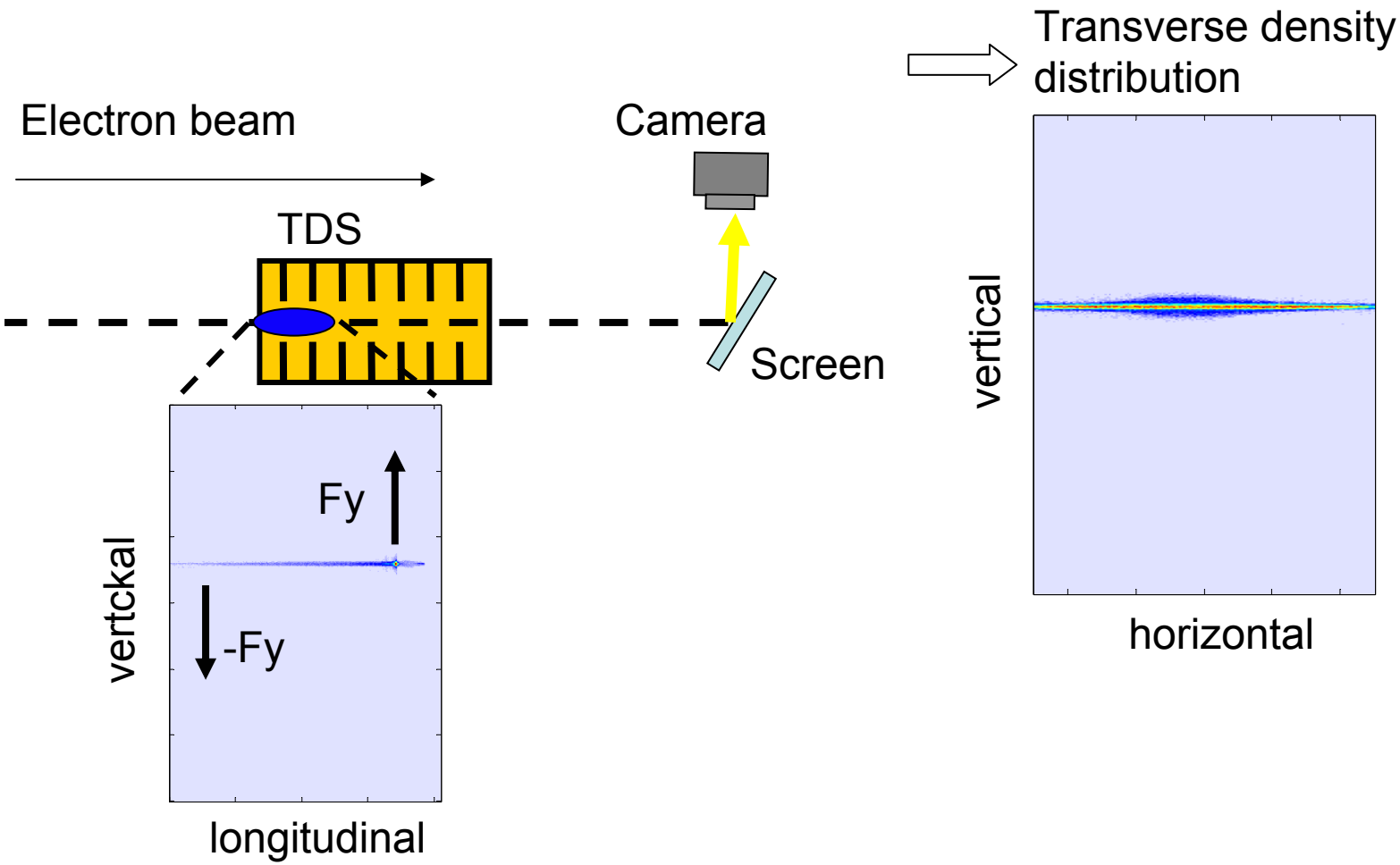
Introduction



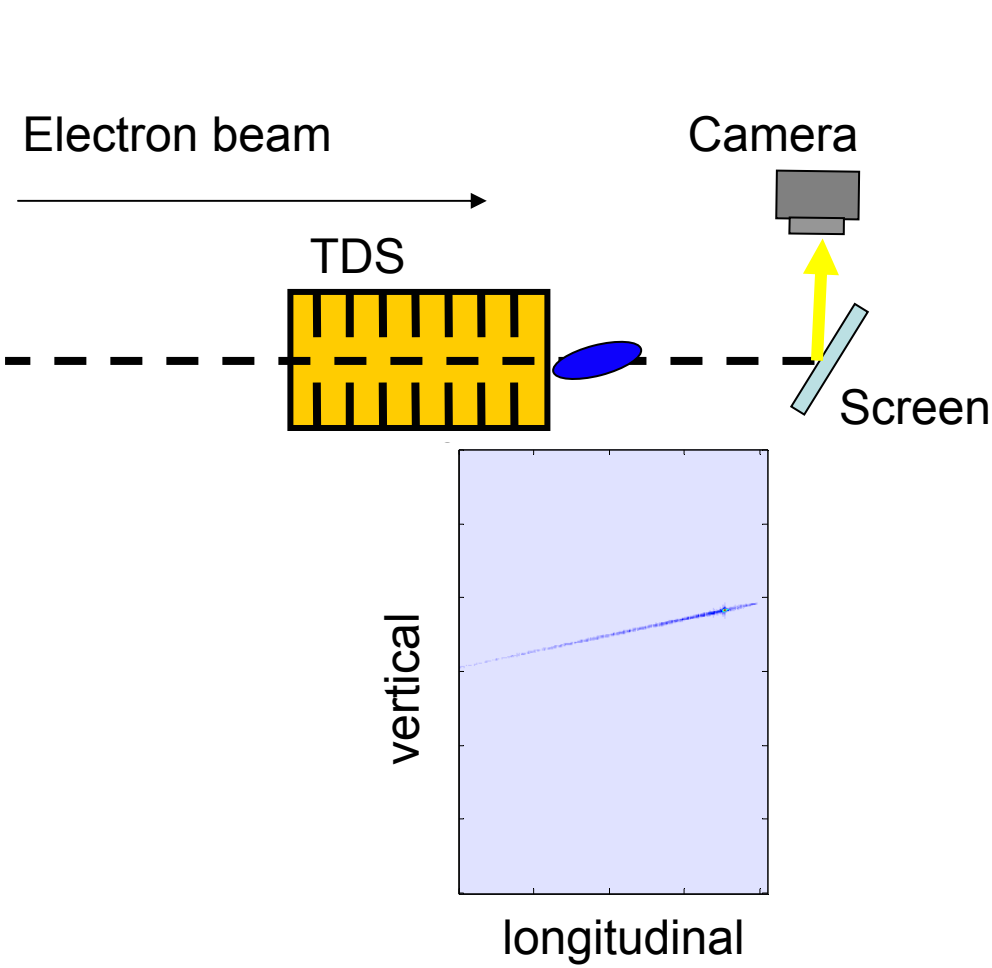
Transverse density distribution:



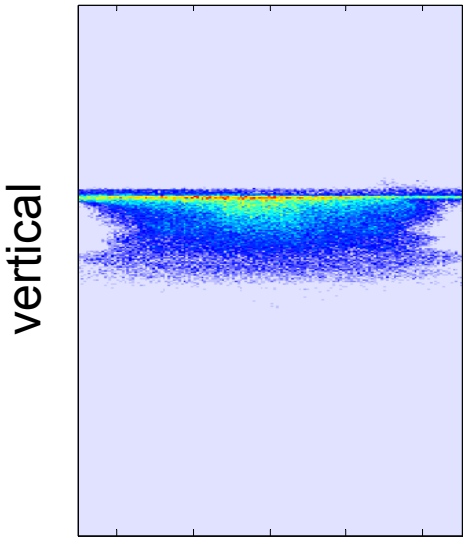
Introduction



Introduction



Transverse density distribution:



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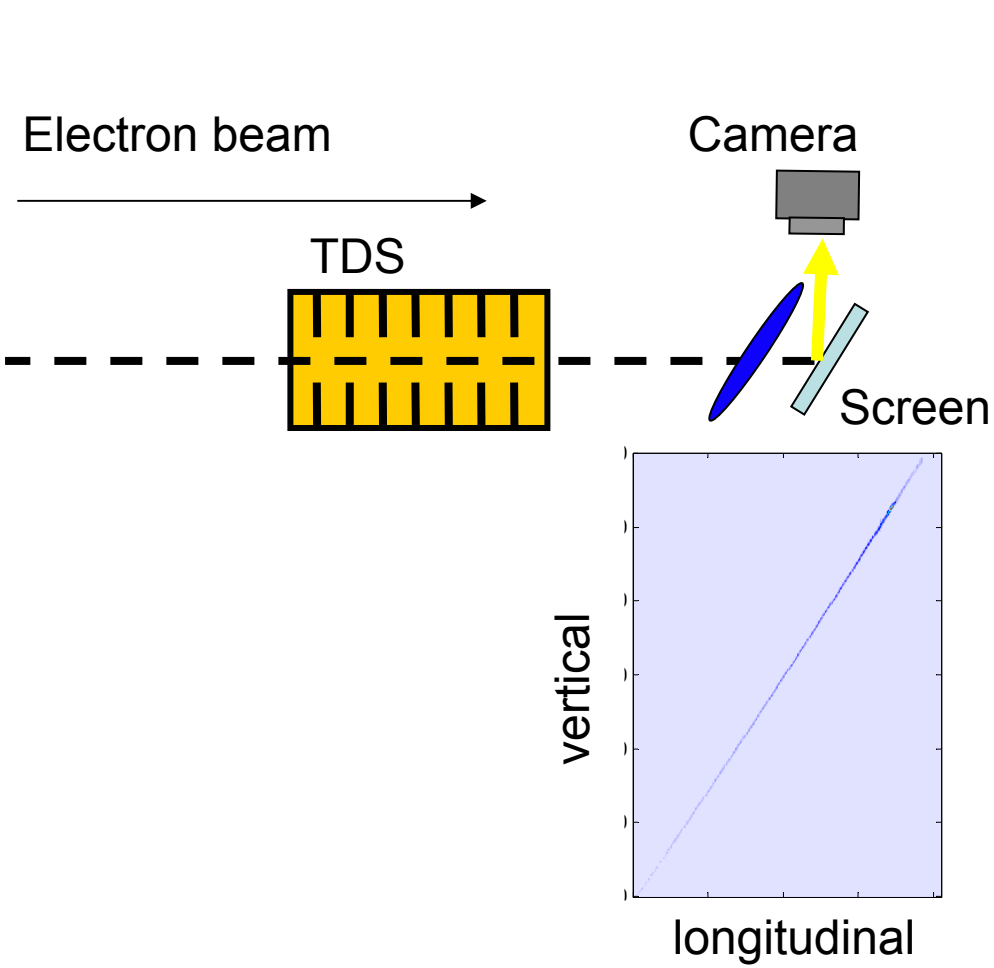
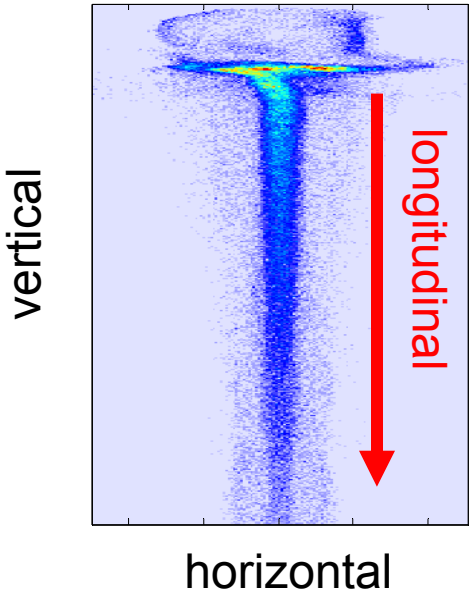


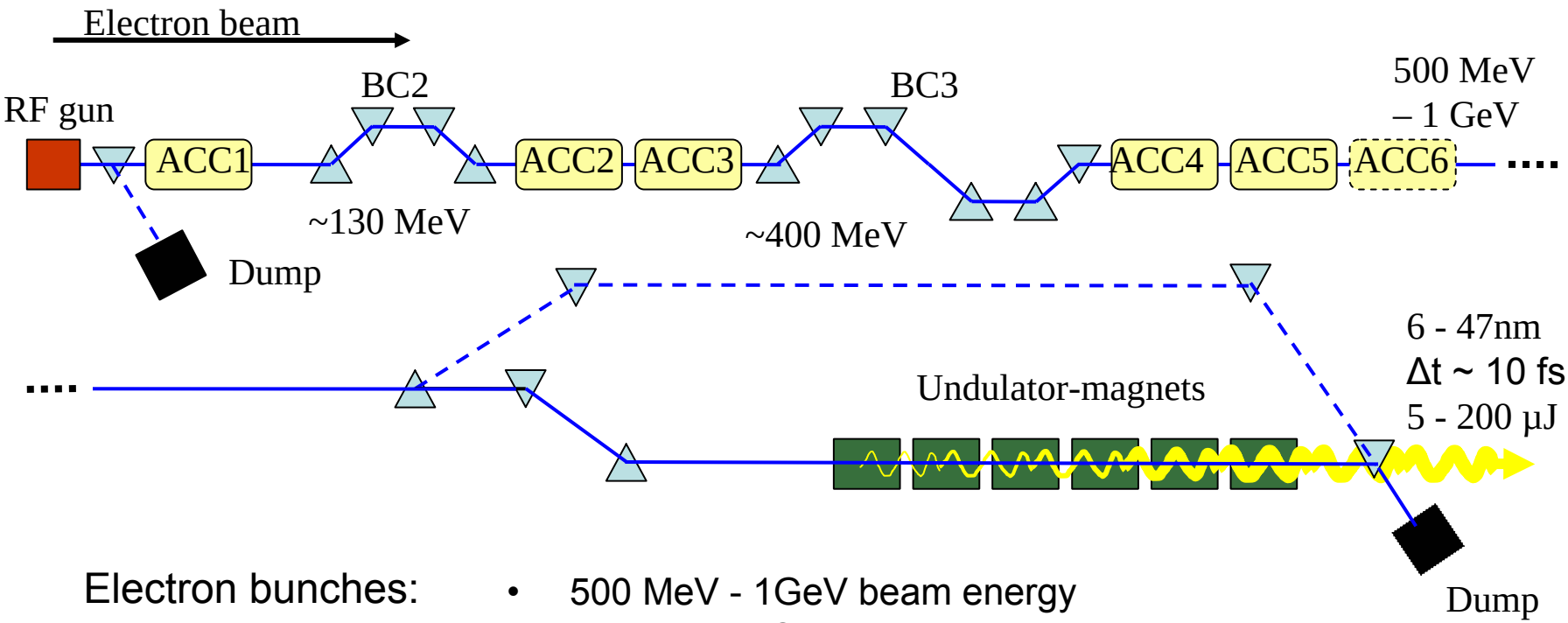
Transverse density distribution



Outline

- Setup at FLASH
- Measurement methods
- Results under FEL operating conditions
- Error sources
- Summary

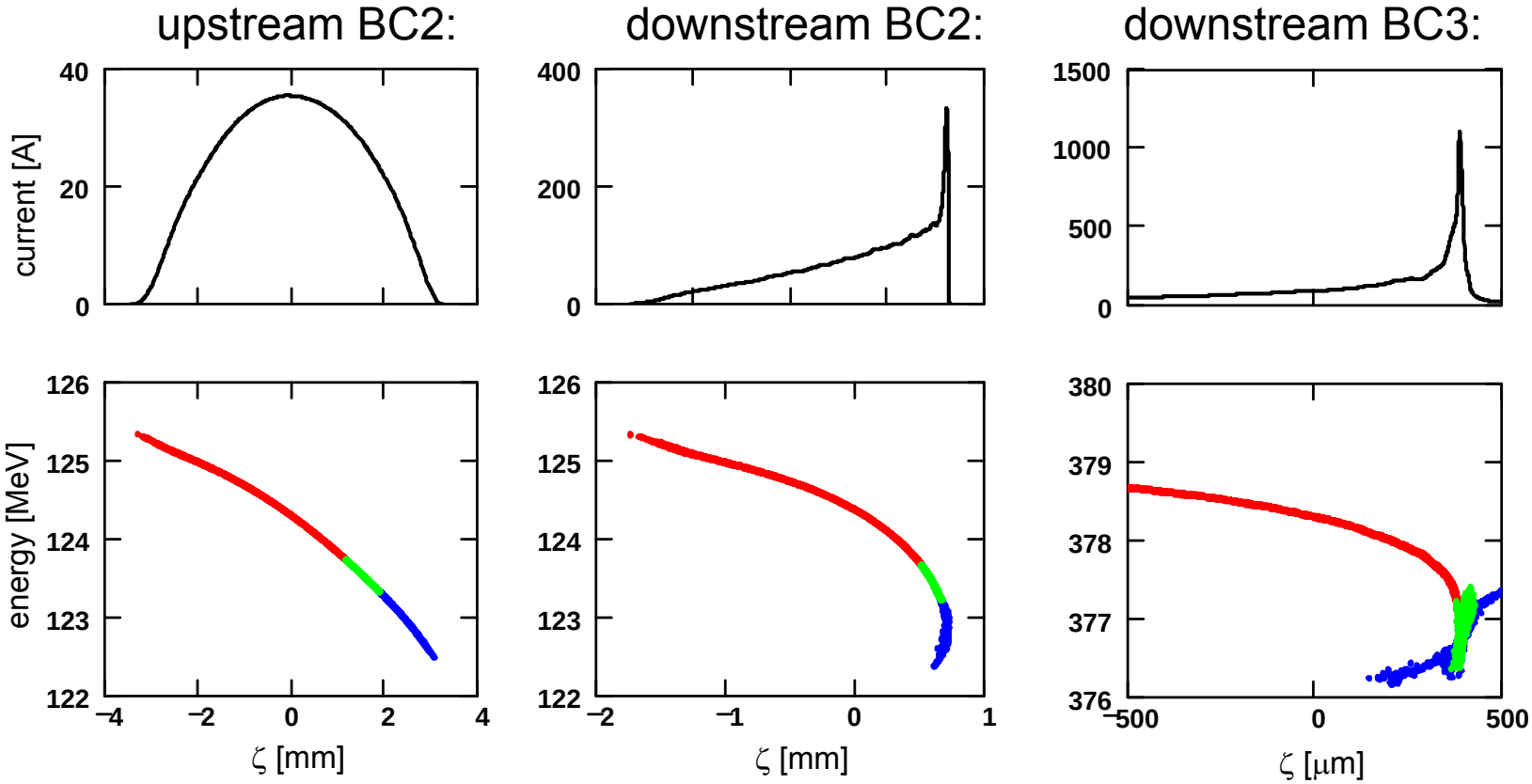
The Free-Electron Laser in Hamburg (FLASH)



Electron bunches:

- 500 MeV - 1GeV beam energy
- ~0.5 – 1.0 nC charge
- ~1-3 kA peak current
- ~1-4 µm normalized emittance
- Relative energy spread ~10^{-3}

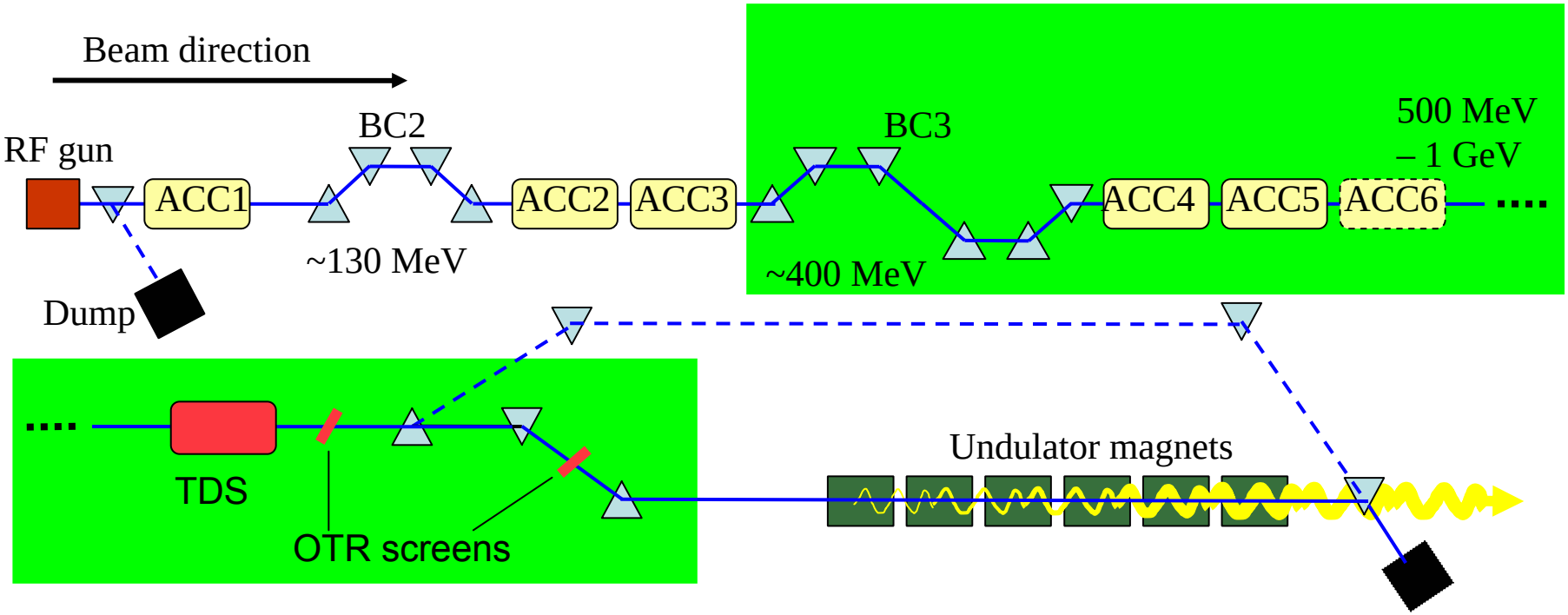
Beam dynamics



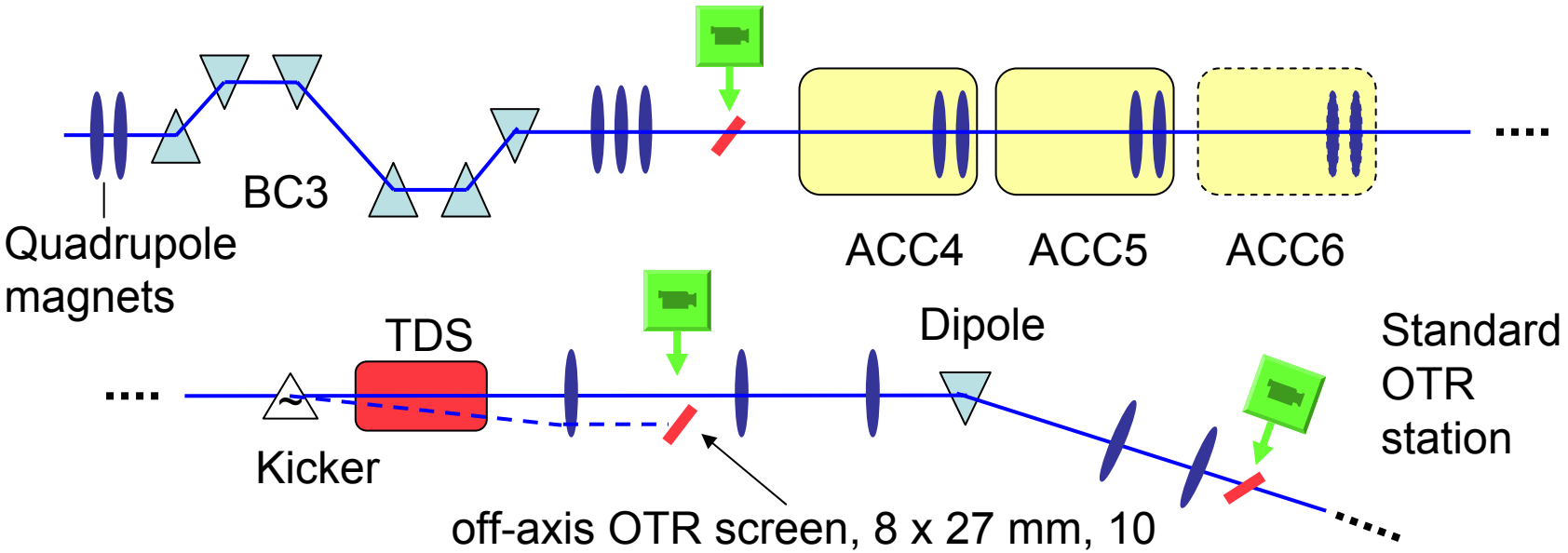
Calculations by M. Dohlus

The TDS allows to investigate the peak current region

Integration into the FLASH-linac



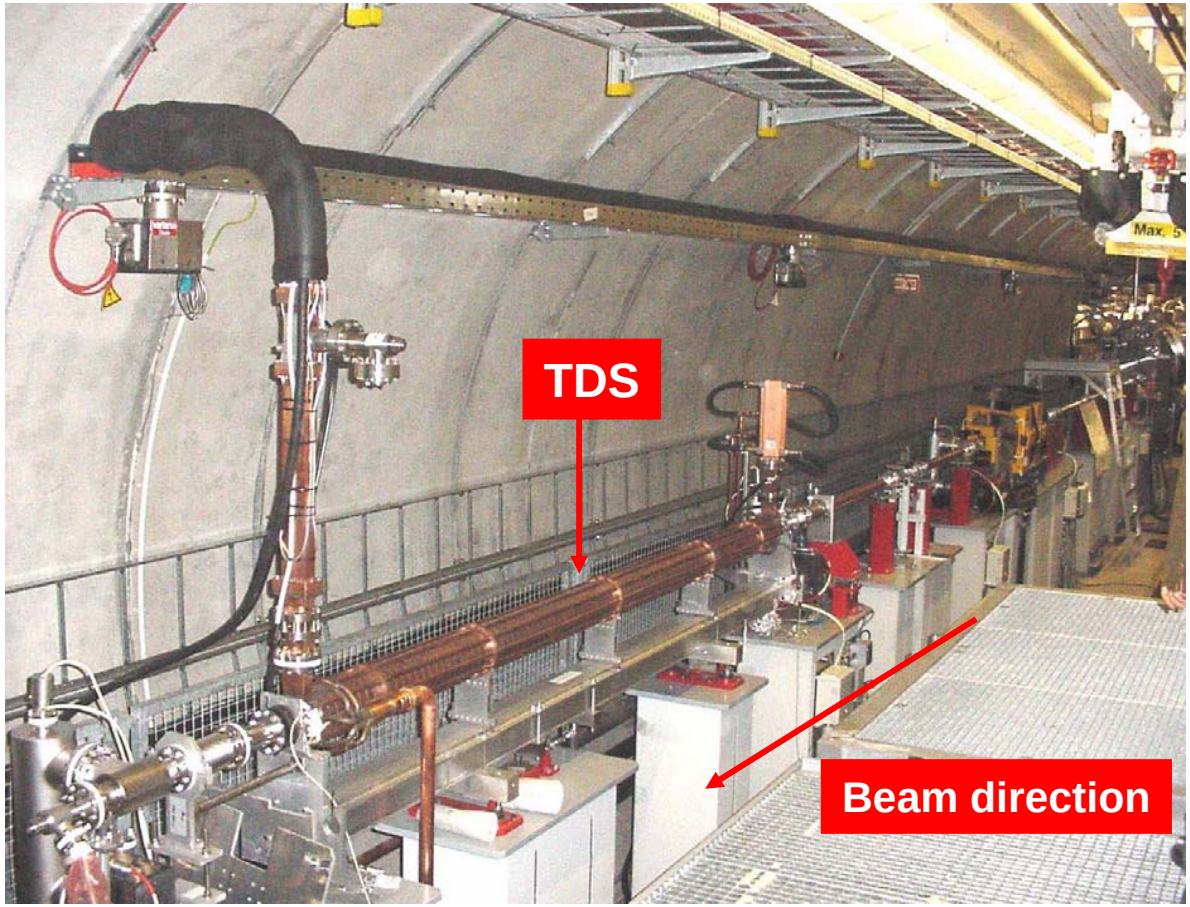
Integration into the FLASH-linac



off-axis OTR screen, 8 x 27 mm, 10 mm offset to the beam axis)

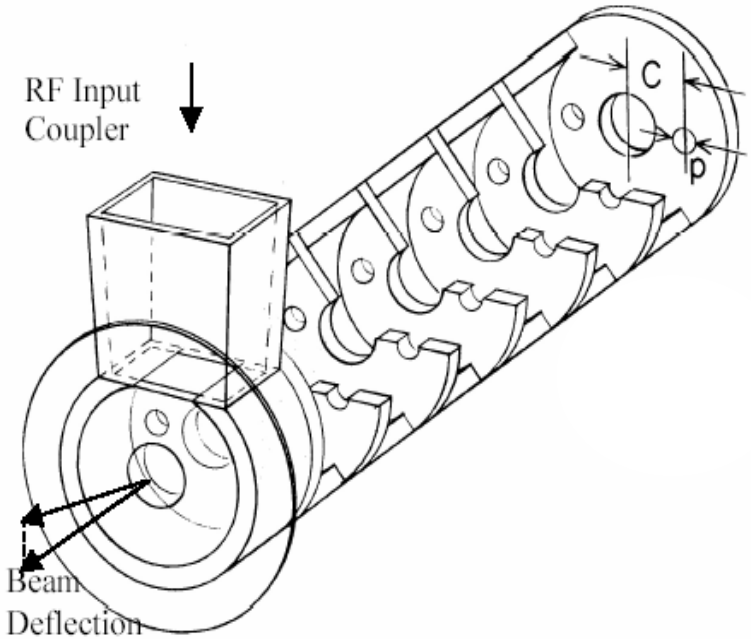
Camera: Basler 311f , 8 (12) Bit,
480 x 640 pixels, 13 x 16 mm
→ ~25 µm / pixel

The transverse deflecting structure (TDS)



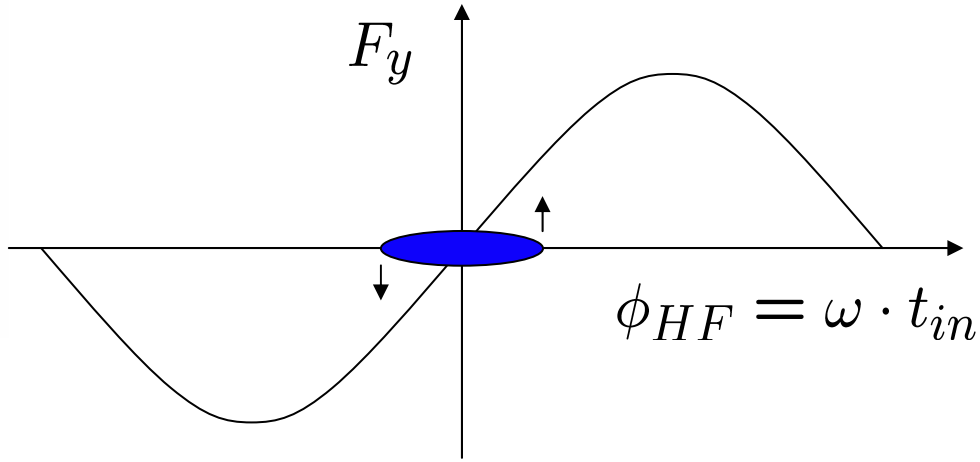
- Installed in 2003, Collaboration DESY-SLAC
- Frequency: 2.86 GHz
- Length: 3.6 m
- Maximum deflecting voltage ~ 25 MV @ 20 MW input power
- Maximum induced divergence @ 500 MeV: ~1 mrad / ps

The TDS



- RF traveling wave structure, $v_{ph} = c$
- Iris-loaded, cell length : 3.5 cm
- A relativistic electron experiences a constant force during its passage:

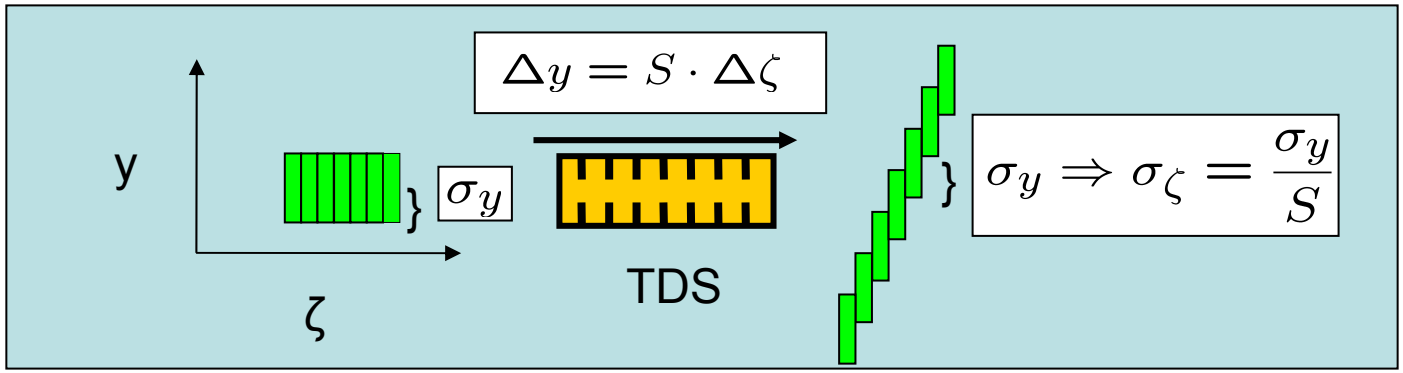
$$F_y = F_0 \cdot \sin(\phi_{HF})$$



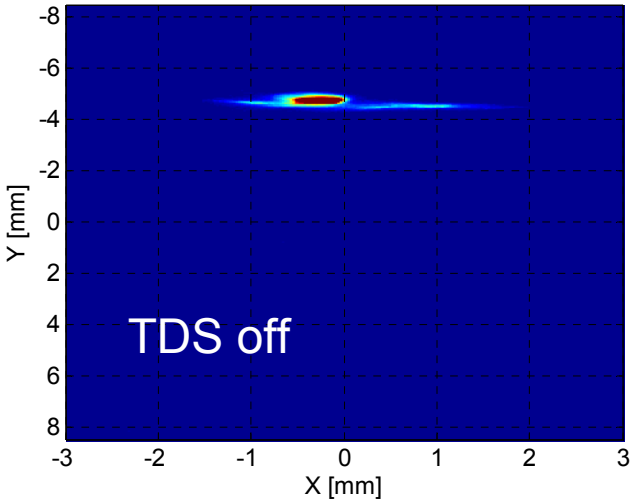
Outline

- Setup at FLASH
- Measurement methods
  - Calibration
  - Current profile
  - Longitudinal phase space
  - Horizontal slice emittance and phase space
  - Slice centroid offsets
- Results under FEL operating conditions
- Error sources
- Summary

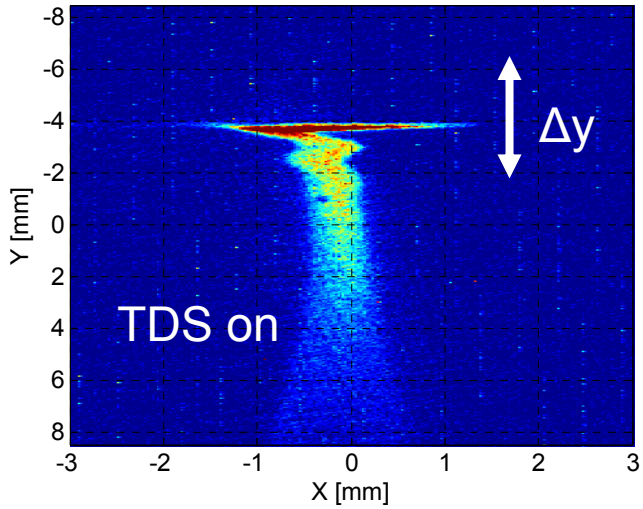
Longitudinal resolution and calibration measurements



Estimation of σ_y



Measurement of Δy as a function of the RF-phase $\Rightarrow S$



Typical values:

$S = 15$

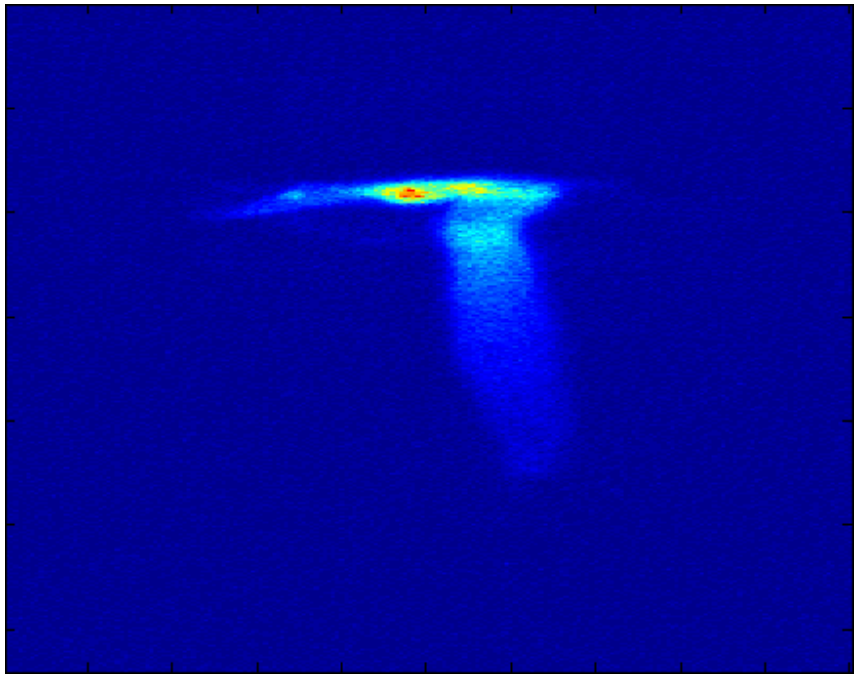
$\sigma_y = 150\ \mu\text{m}$

$\Rightarrow \sigma_\zeta = 10\ \mu\text{m}$

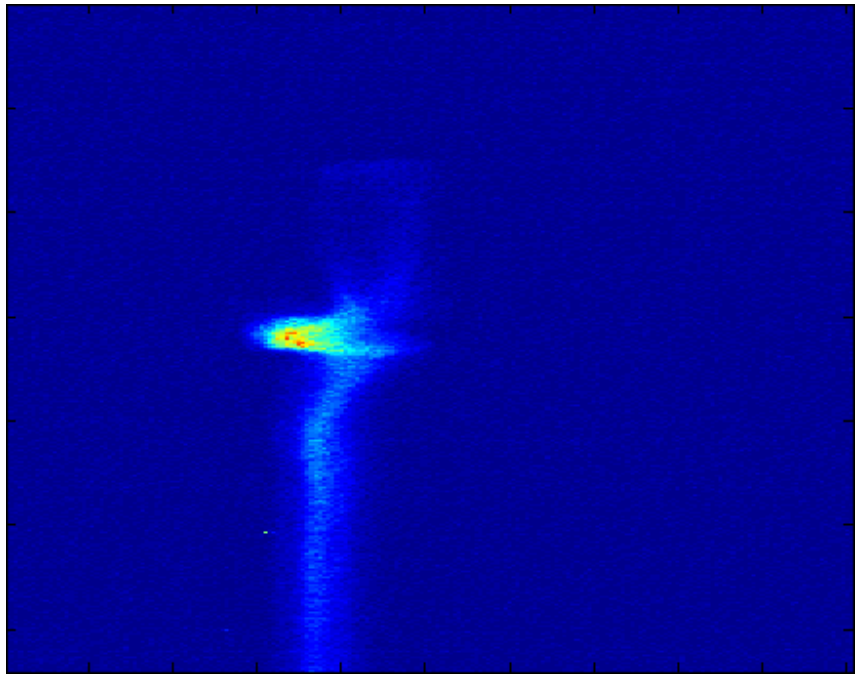
(30 fs)

Position jitter

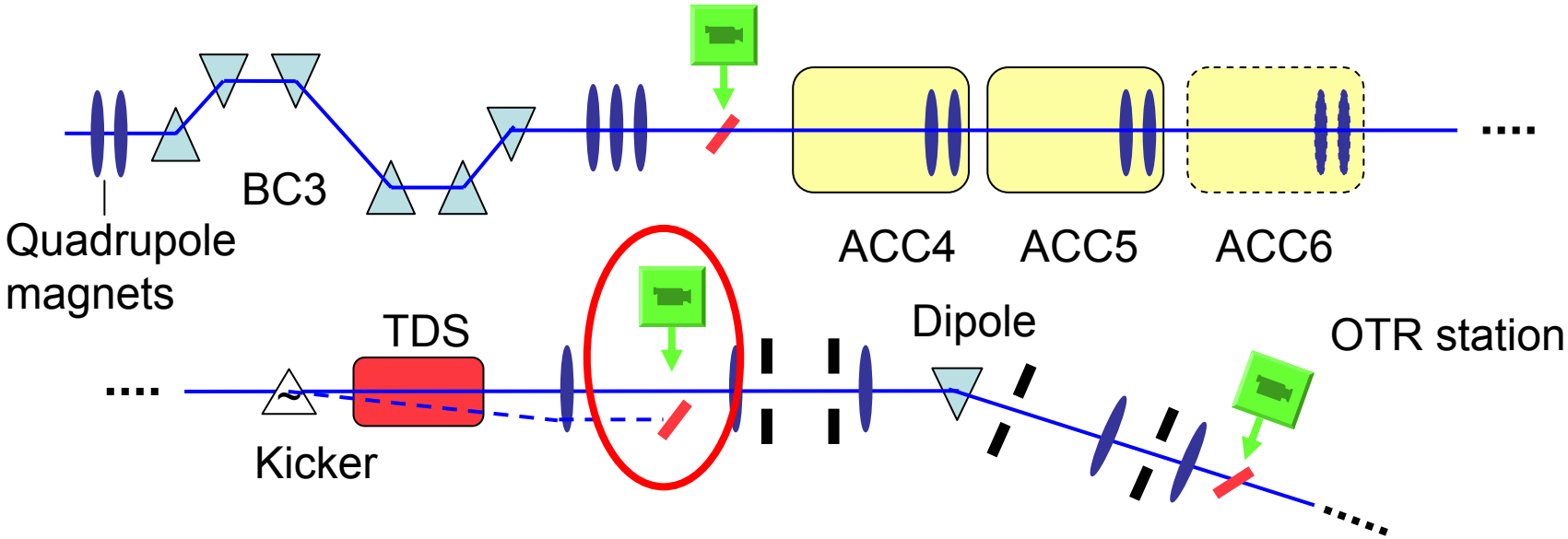
Moderate input power:



High input power:



Measurement of the current profile

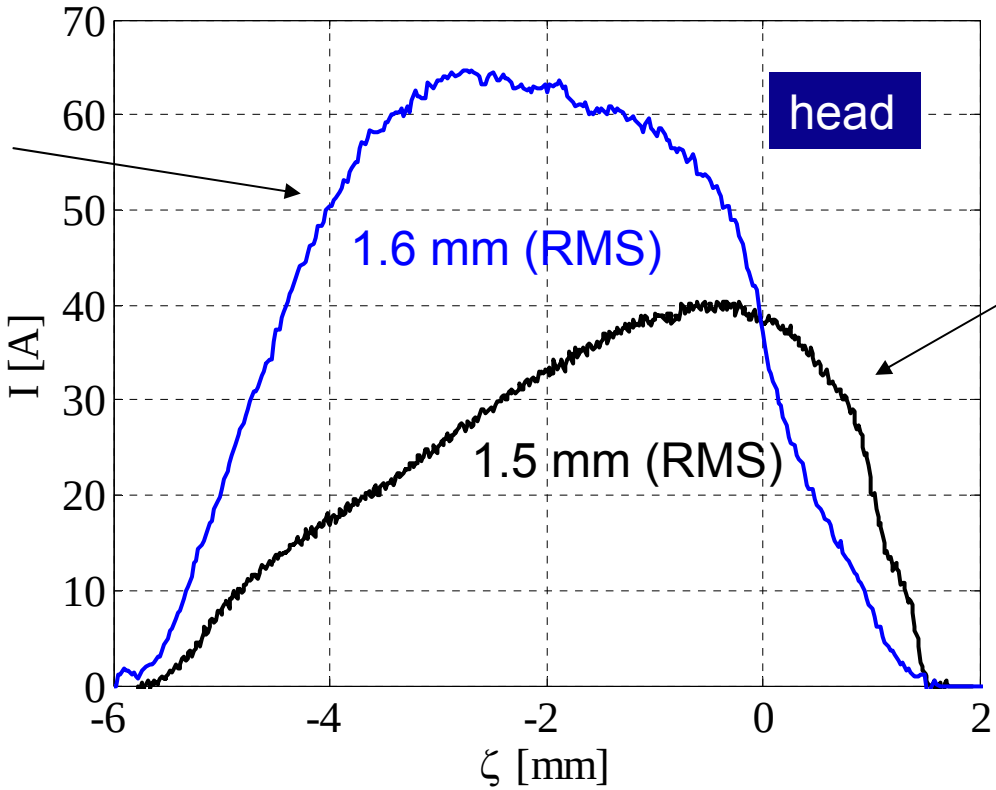


Measurement of current profiles

- Calibration of longitudinal distances
- Calibration of a charge density scale

Measured current profiles of uncompressed bunches

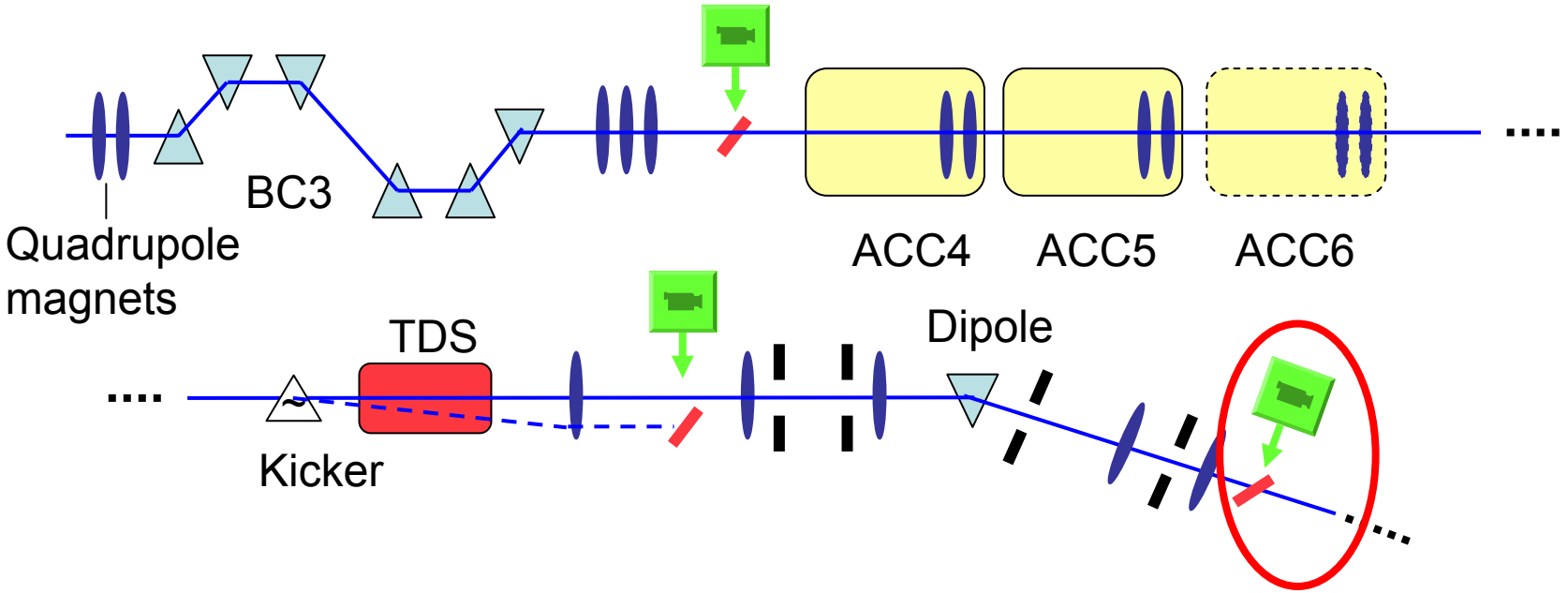
650 MeV, 1.0 nC, no deflection in the compressor chicanes



490 MeV, 0.6 nC

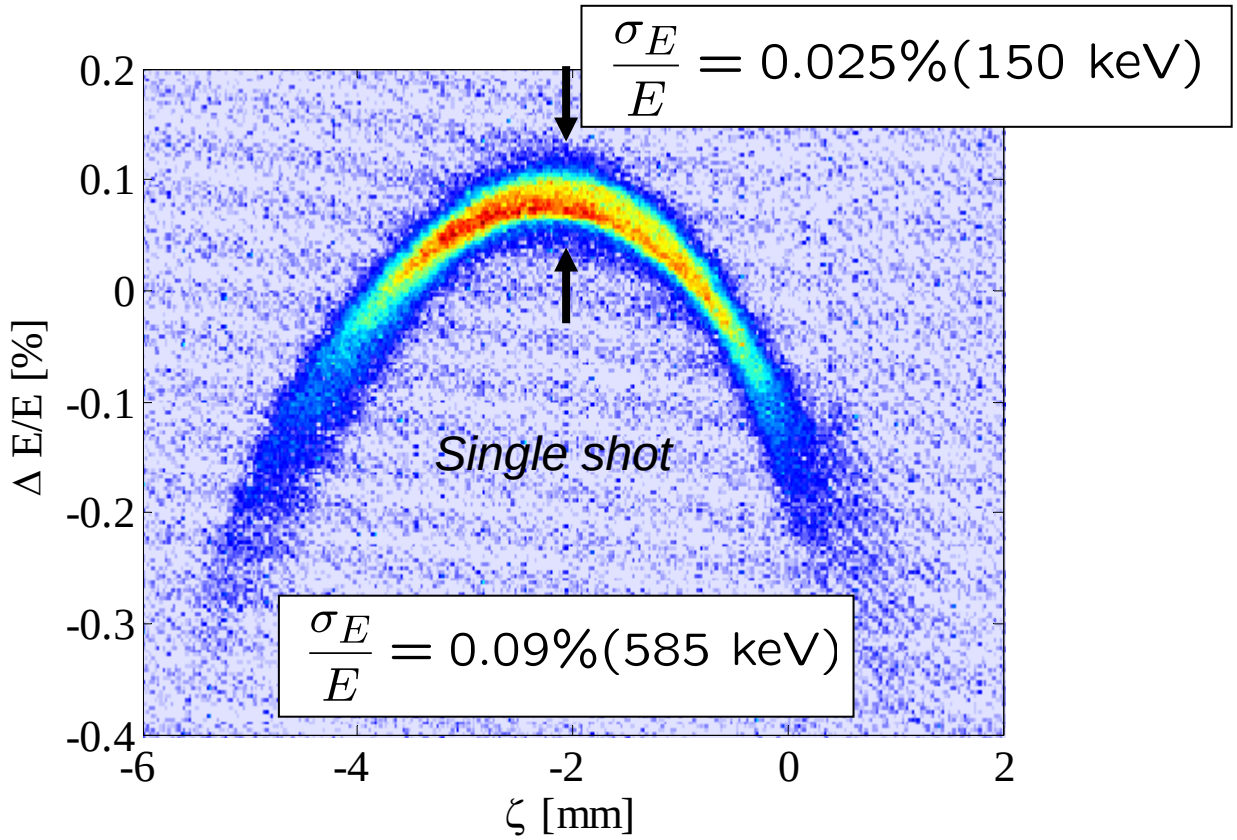
Profiles: averaged over 30 shots

Measurement of the distribution in longitudinal phase space



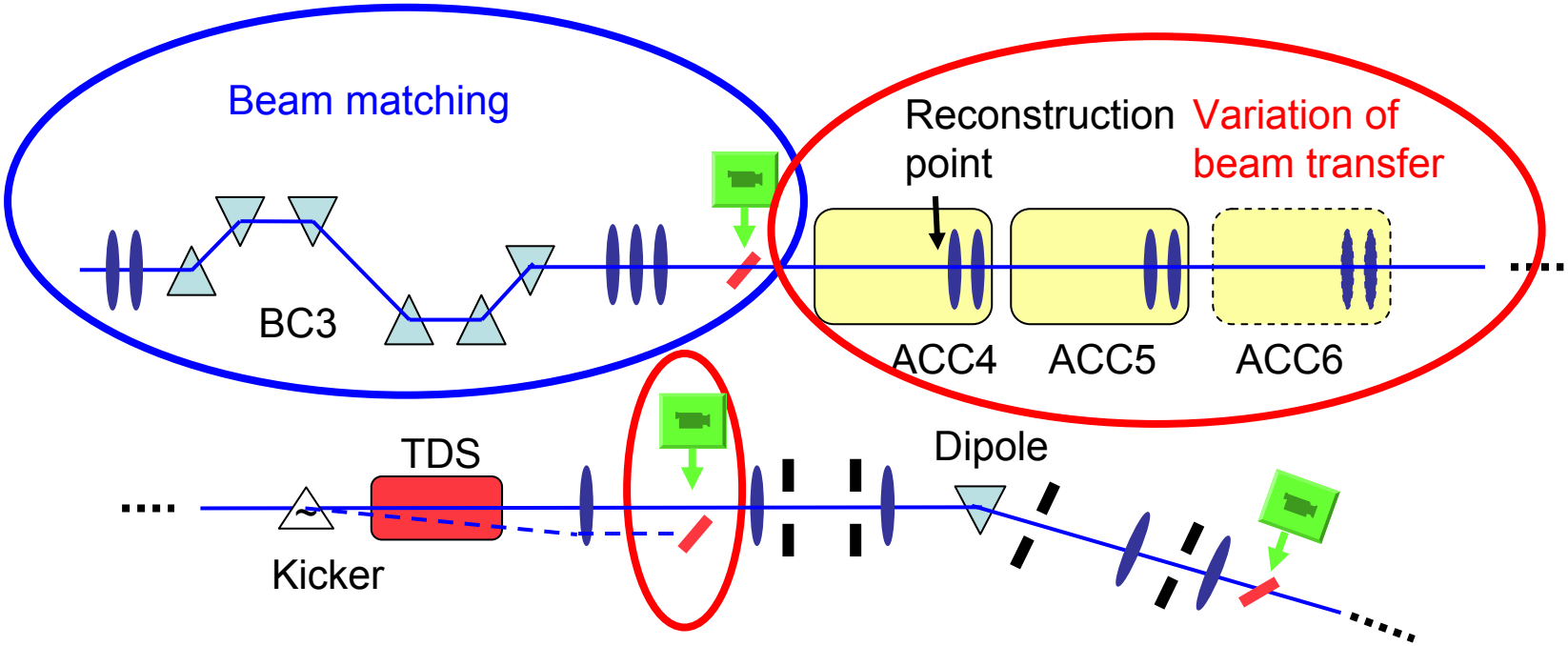
- energy-dependent position on the screen: $\Delta x = D \cdot \frac{\Delta E}{E}$
- typical values: $D \sim 30\ \text{cm},\ \sigma_x = 100\ \mu\text{m} \Rightarrow \frac{\sigma_E}{E} \approx \frac{\sigma_x}{D} \sim 3 \cdot 10^{-4}$

Measured distribution in longitudinal phase space of uncompressed bunches

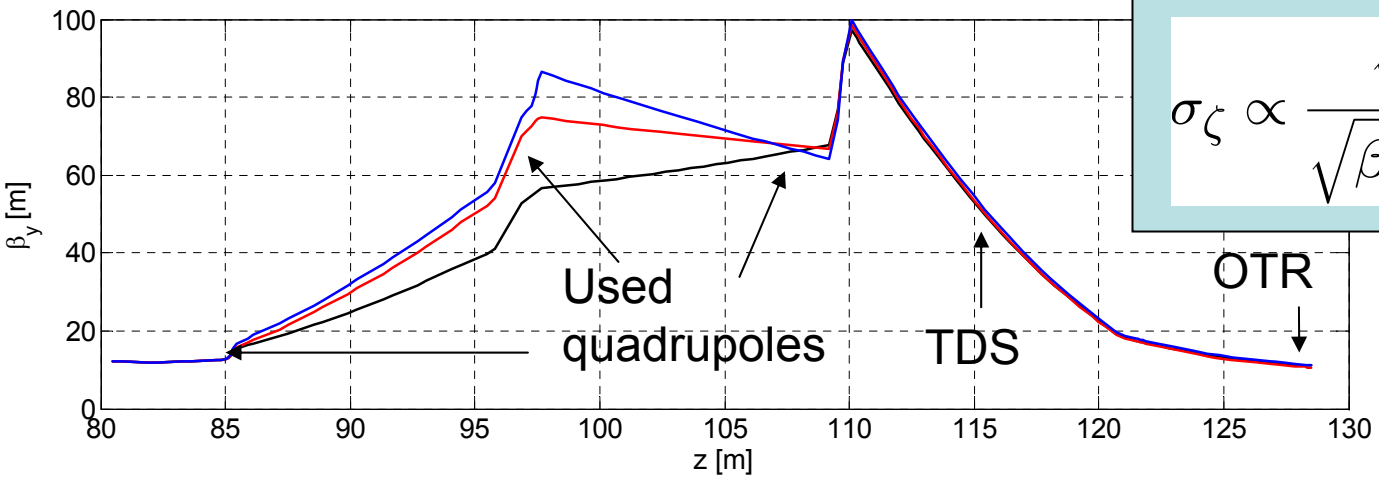


650 MeV, 1nC, compressor chicanes switched off

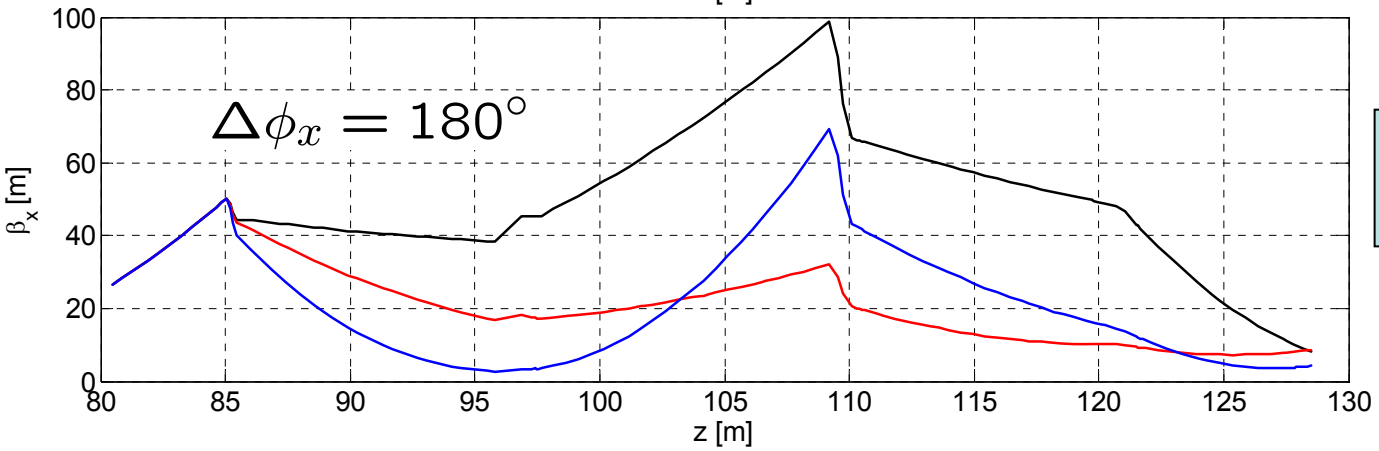
Slice emittance measurements



Optics for slice emittance measurements

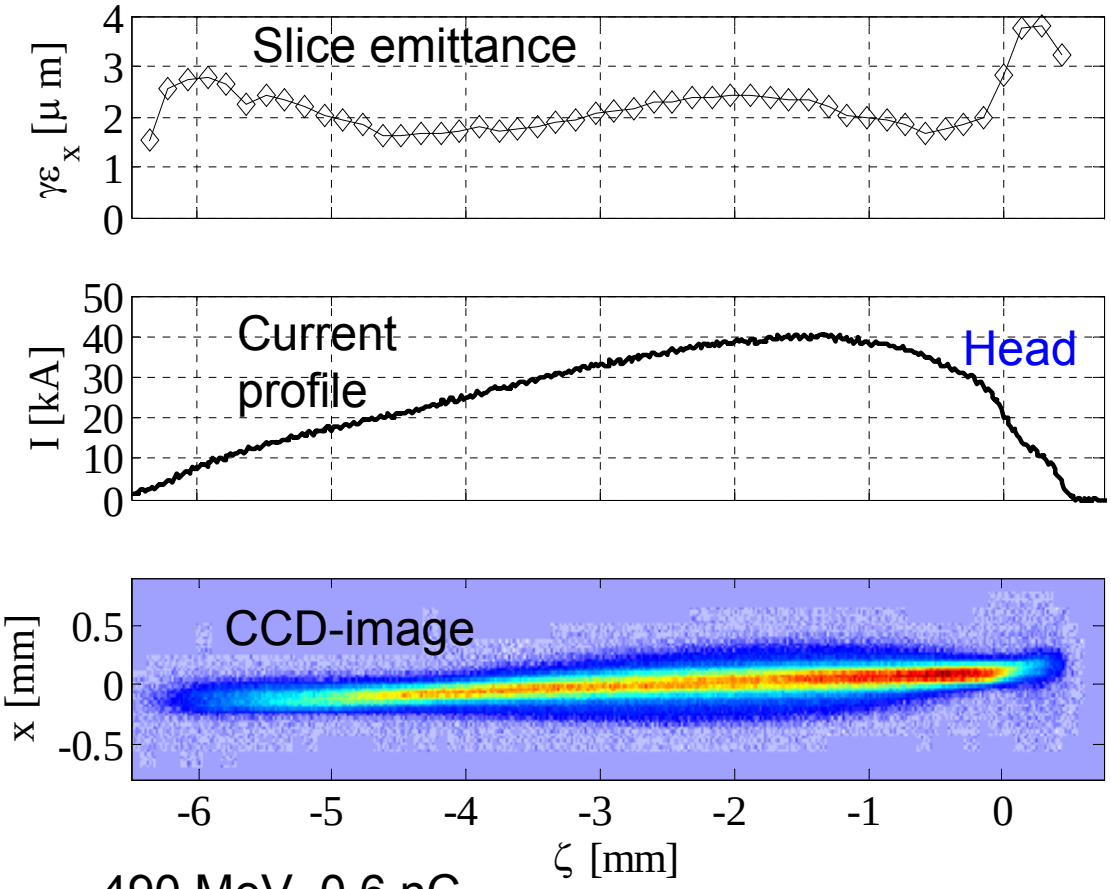


$$\sigma_\zeta \propto \frac{\sqrt{\epsilon_y^{norm}} \cdot \sqrt{\gamma}}{\sqrt{\beta_y^{TDS}} \sin(\Delta\phi_y)}$$



10-14 steps per measurement

Results: measured slice emittance at on-crest operation

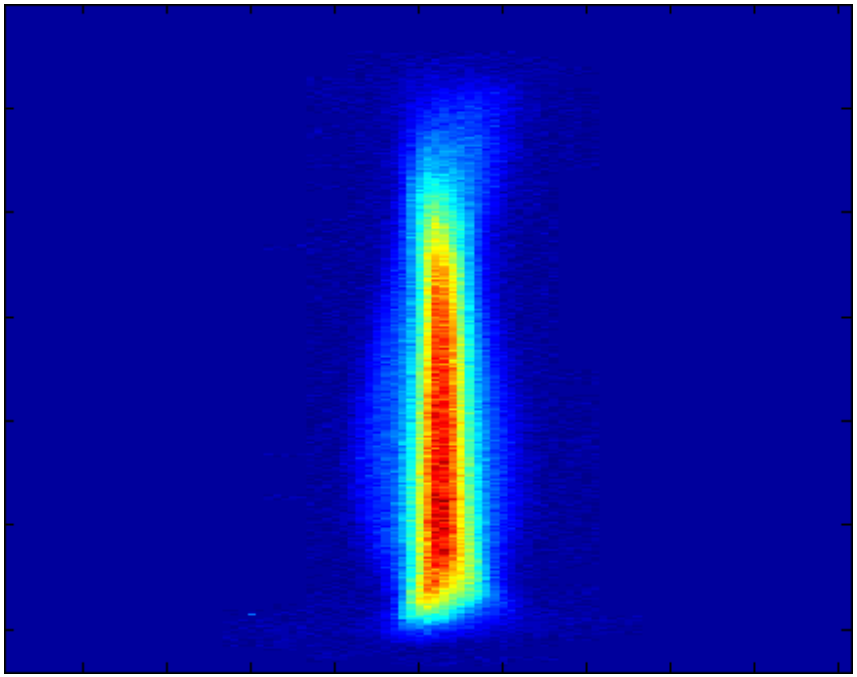


- Estimated accuracy: < 15% (RMS)
- Mean slice emittance: **2.1µm**
- Projected emittance: **3.8 µm**

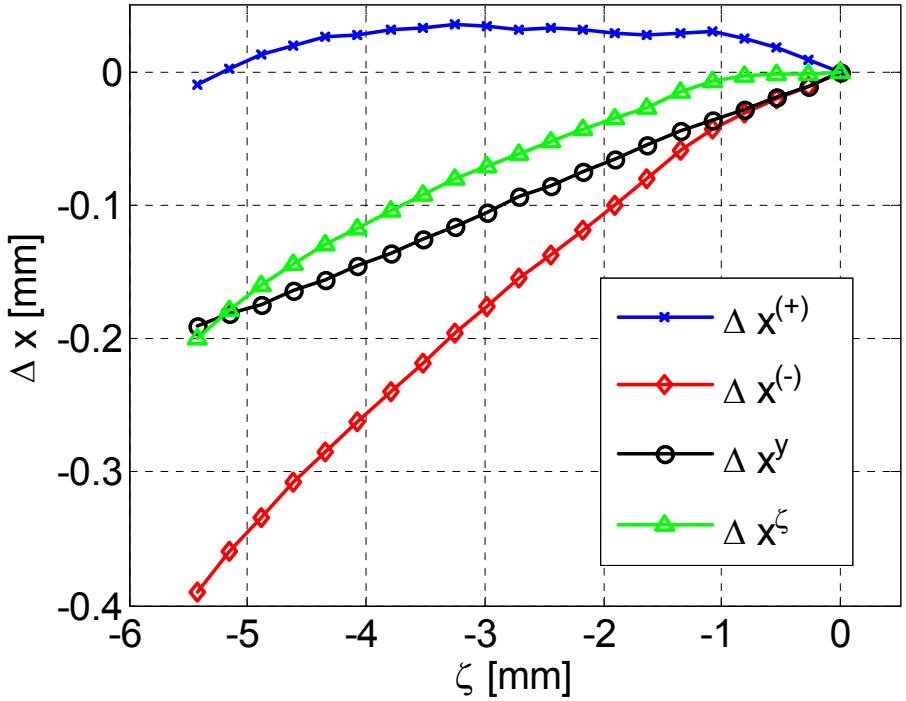
- Difference caused by
  - Centroid shifts
  - Beam deformation (``slice mismatch")
- Projected emittance after correction of centroid offsets: **~2.5µm**

Slice centroid offsets

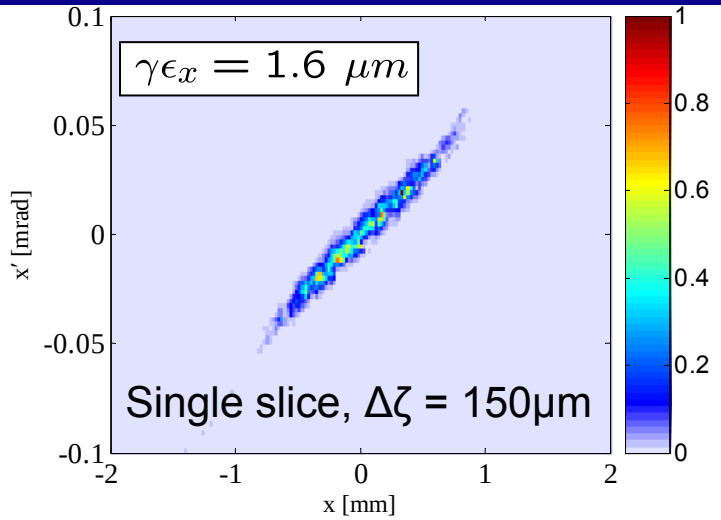
Development during a scan of quadrupole magnets:

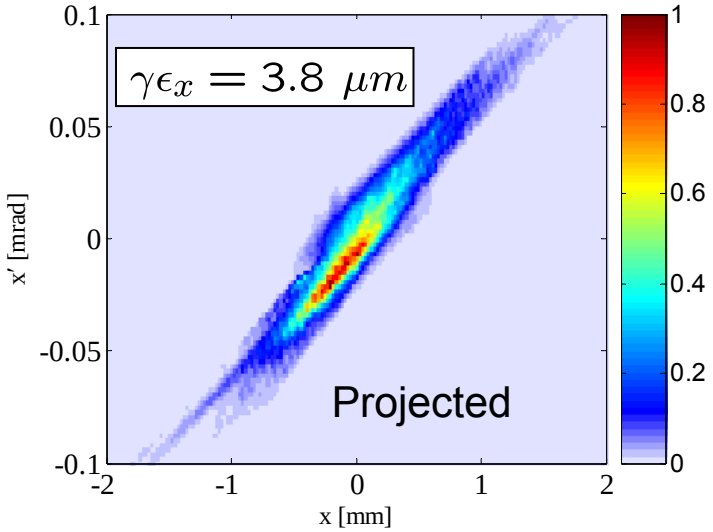


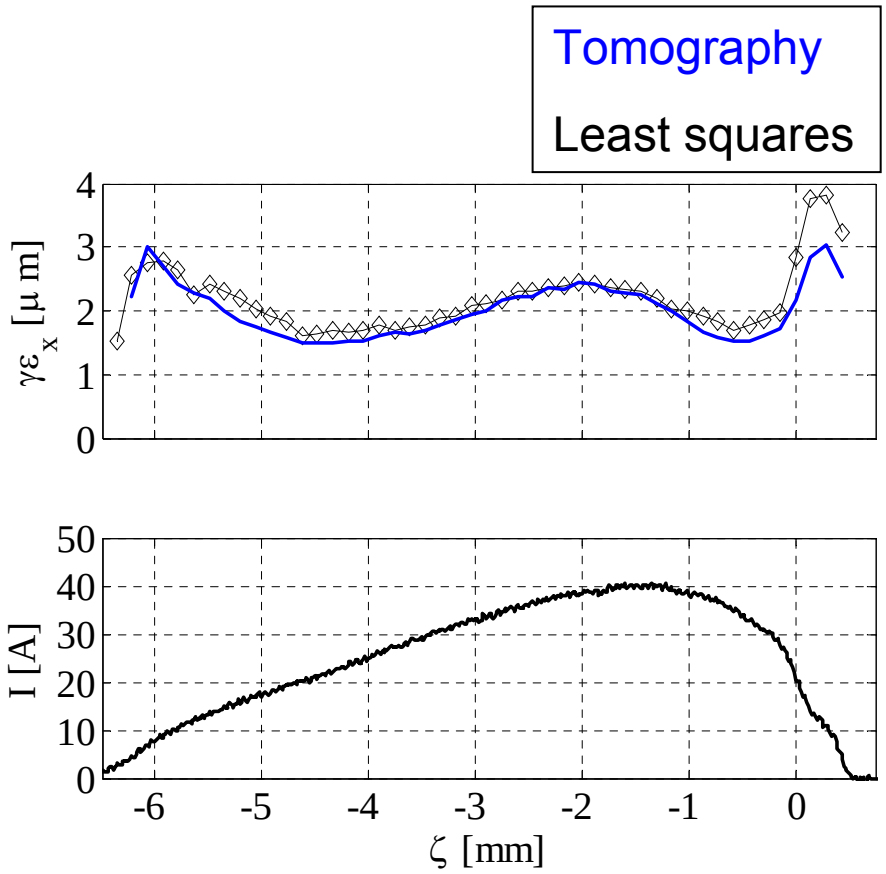
y-correlated and time-correlated contributions:



Tomographic reconstruction of phase space distributions







490 MeV, 0.6 nC, on-crest operation

Outline

- Setup at FLASH
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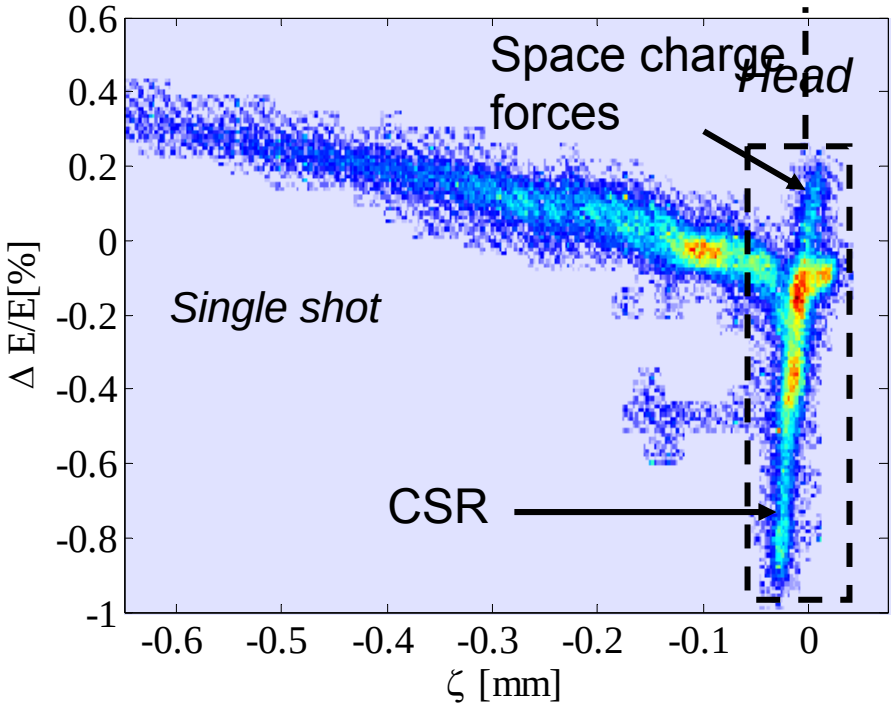
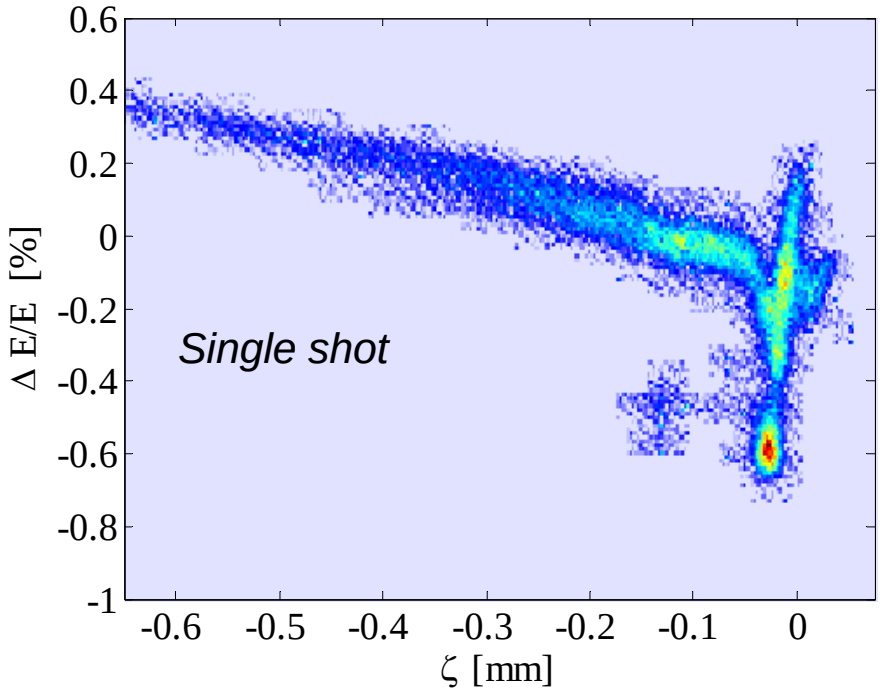
Measurement conditions

- Measurements performed at
  - 494 MeV (27 nm)
  - 677 MeV (13.7 nm)
  - 964 MeV (6.8 nm)
- Average pulse energy:
  - 0.5 µJ (964 MeV)
  - 5 µJ (677 MeV)
  - 10 µJ (494 MeV)

  → not saturated!
- Optics and beam orbit changed downstream of the compressor chicanes → no FEL-radiation during the measurements, but: longitudinal phase space and emittance not changed!

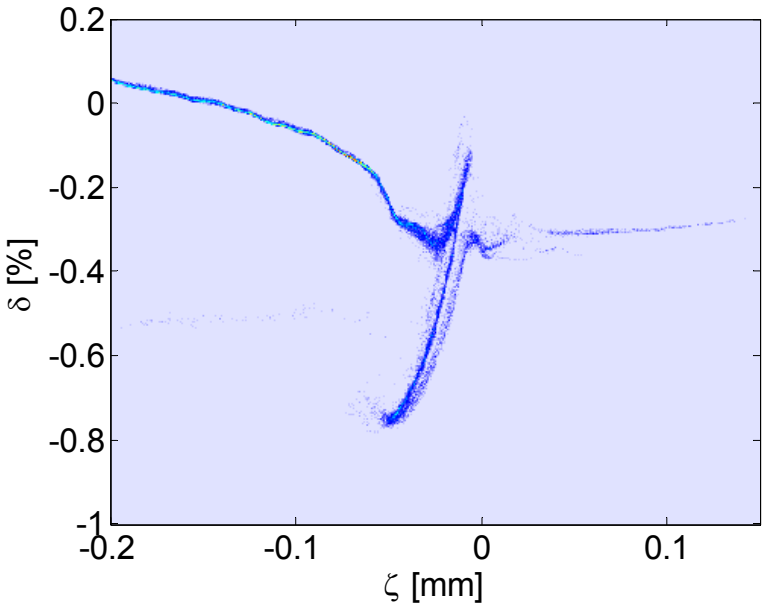
Longitudinal phase space measured under FEL-operating conditions





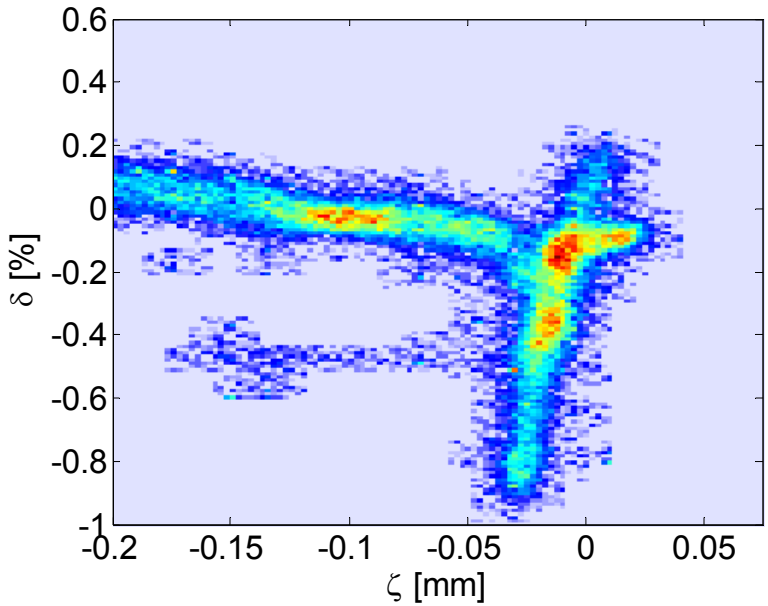
Comparison to simulations: longitudinal phase space under FEL operating conditions

Simulation* :



494 MeV, 0.7nC

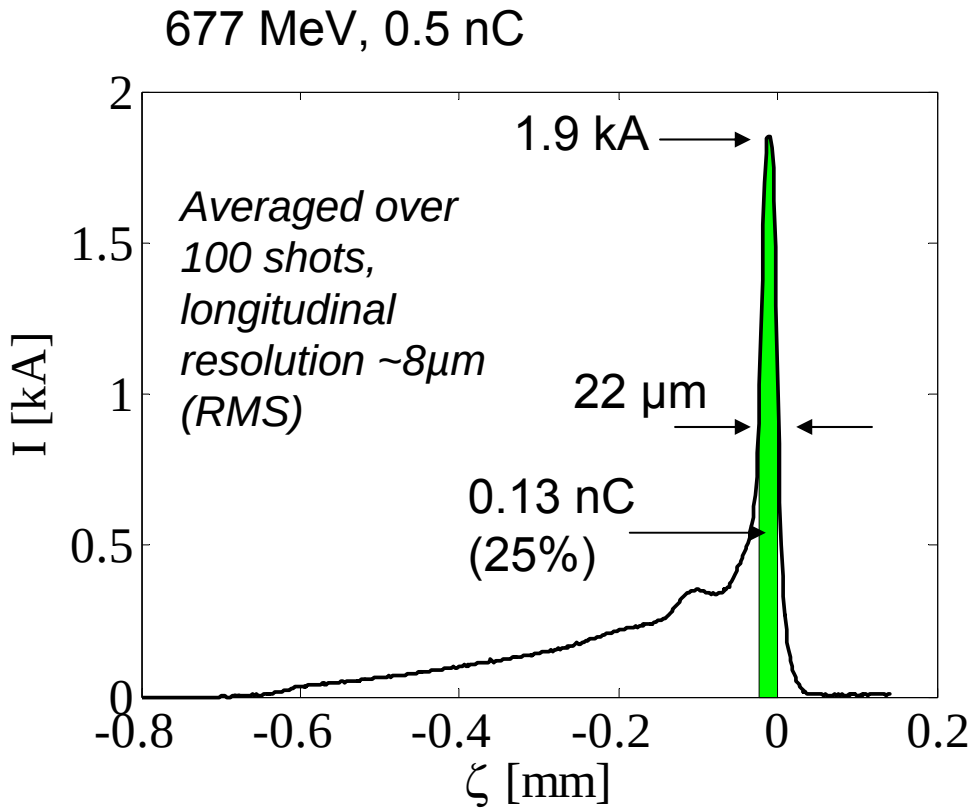
Measurement



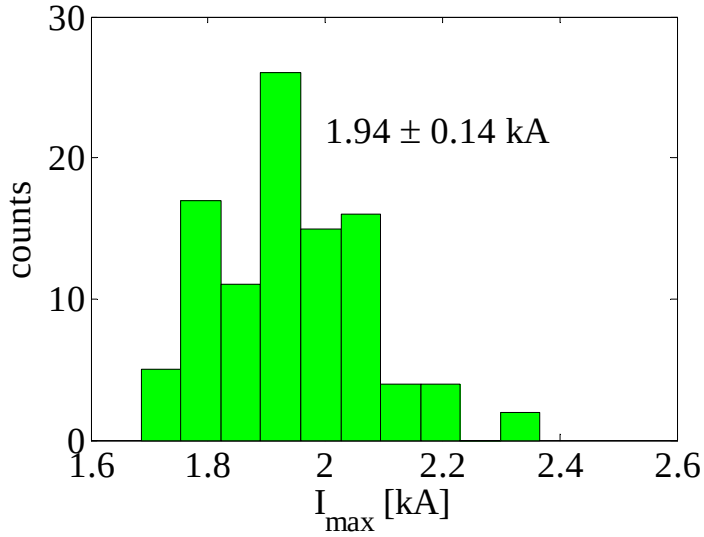
677 MeV, 0.5 nC

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

Measured current profile under FEL-operating conditions

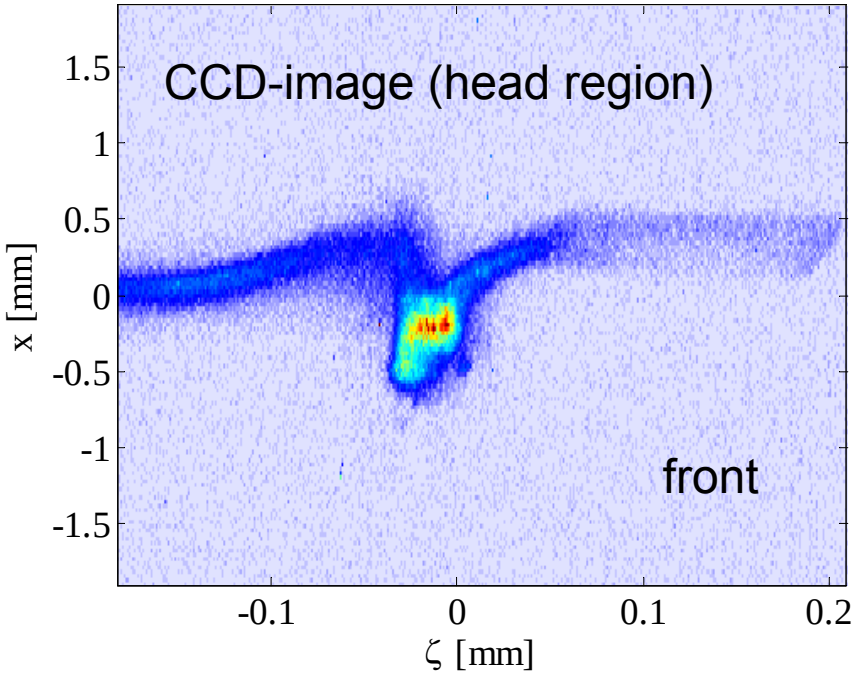


Fluctuations from shot to shot: peak current I_{max}

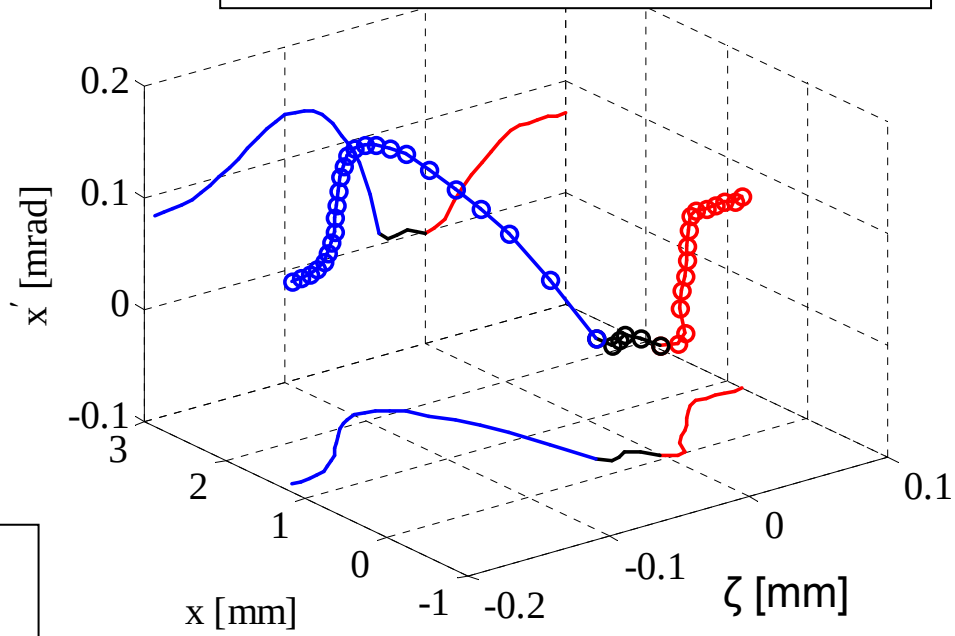


FEL-operating conditions: centroid offsets

494 MeV, 0.7 nC



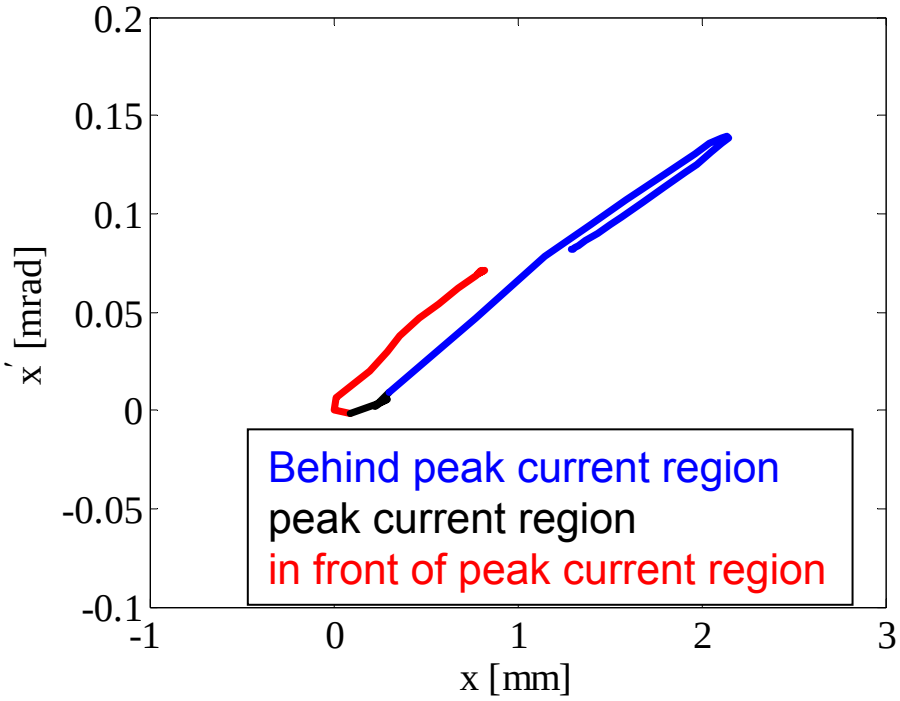
behind peak current region
peak current region
in front of peak current region



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

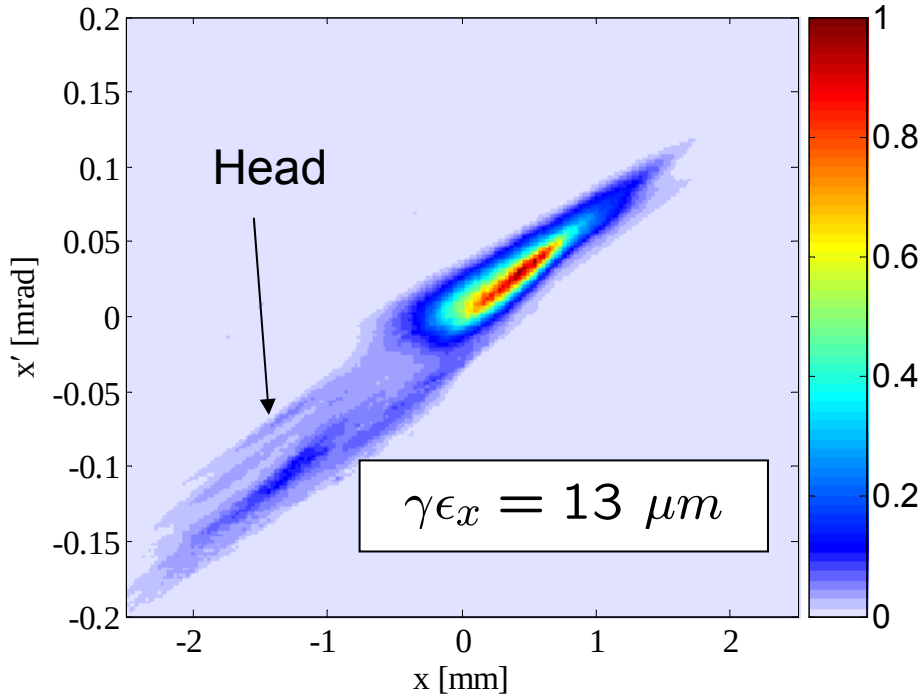
Horizontal phase space

Centroid curve:

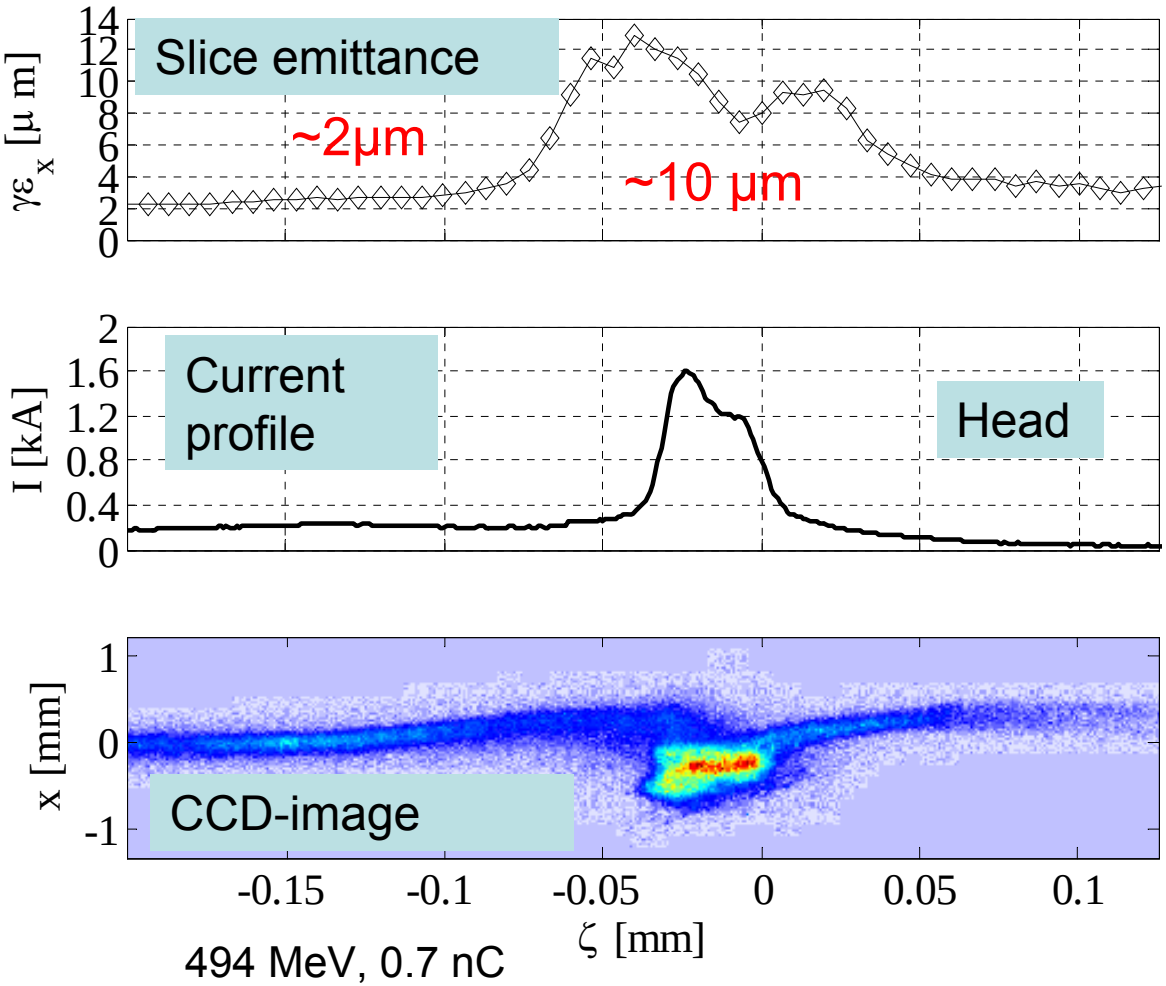


494 MeV, 0.7 nC

Projected distribution in horizontal phase space:



FEL-operating conditions: slice emittance



Longitudinal resolution ~ 8 µm (RMS)

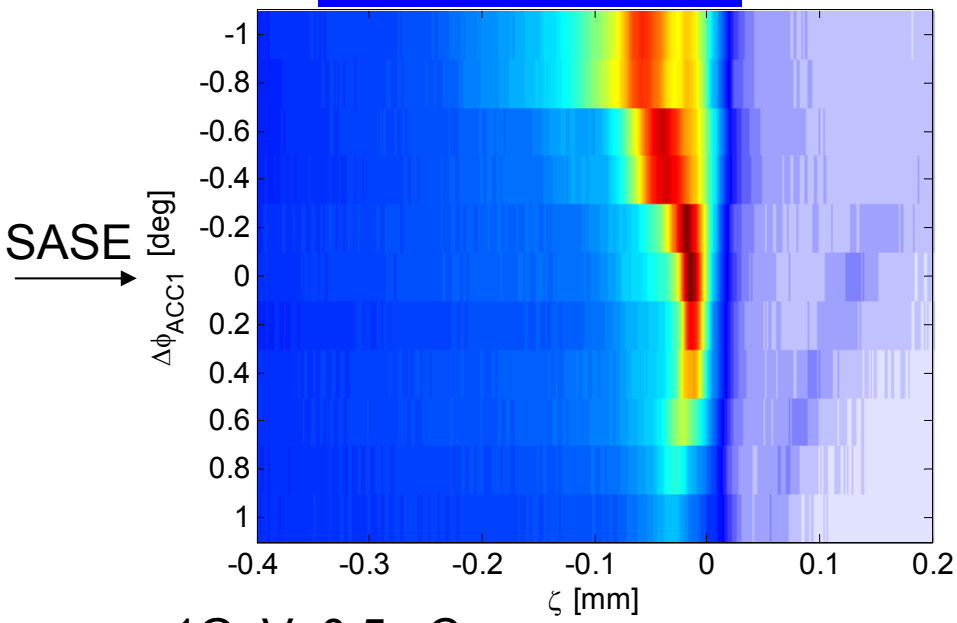
Increase in slice emittance in the peak current region:

- Cause?
- FEL-criterion?

Dependence on the RF-phase of module ACC1

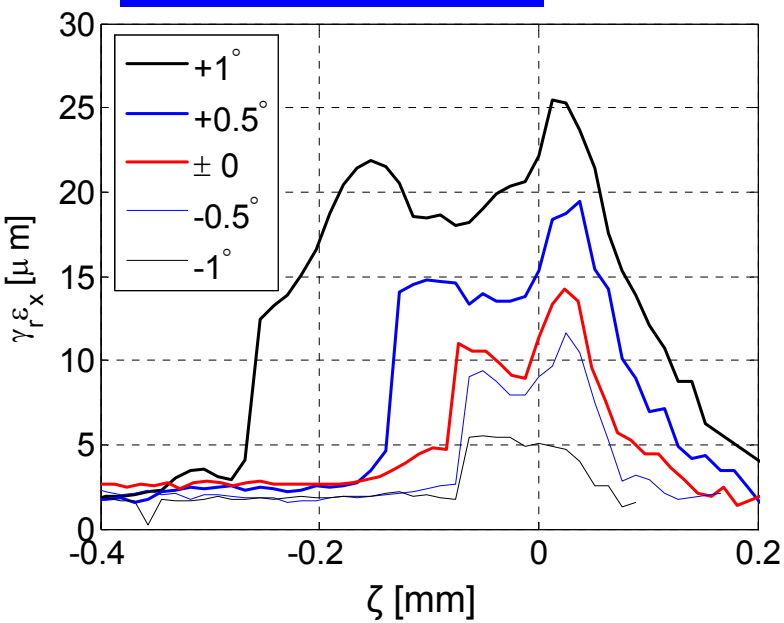
Comparison of experimental results and simulations: important parameters not known with sufficient accuracy, in particular the RF-phase of the first accelerating module (accuracy:~1˚, needed: ~0.1˚)

Current profiles



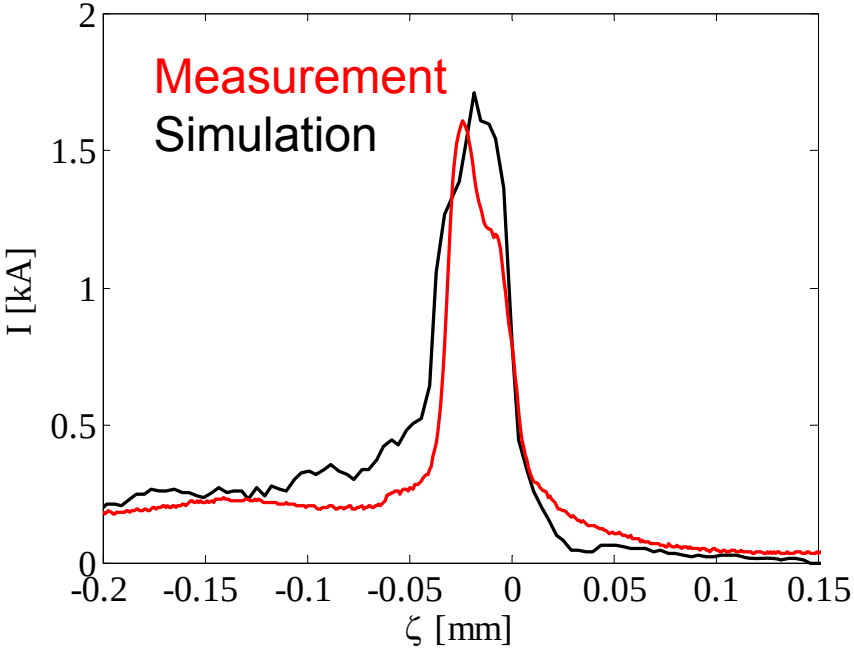
1GeV, 0.5 nC

Slice emittance

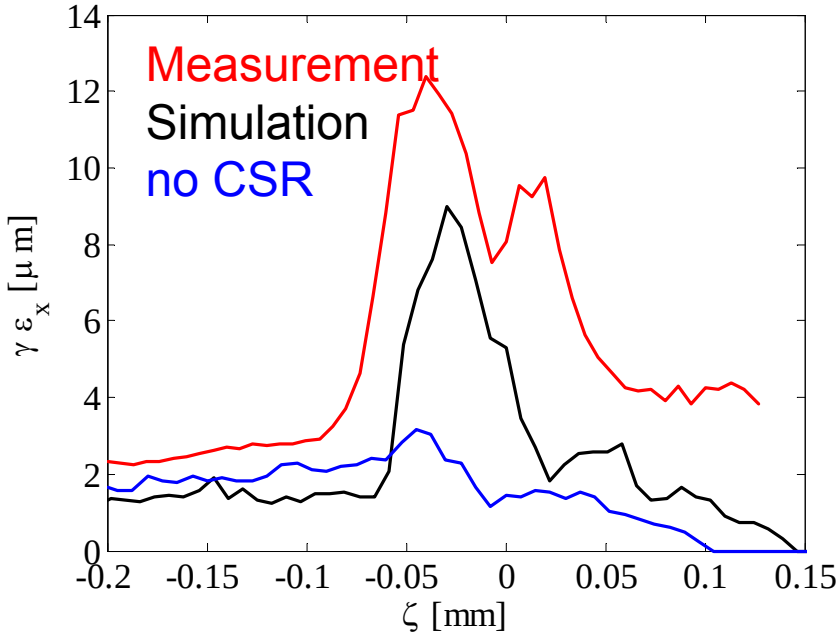


Comparison to numerical simulations

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



Slice emittance

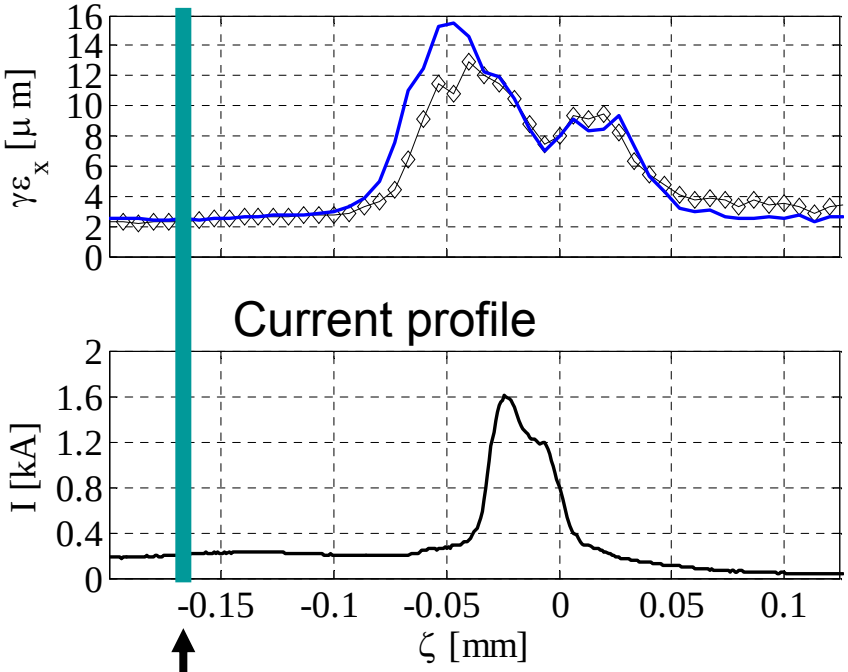


Simulations with ASTRA (K. Flöttmann) and CSRTrack (M. Dohlus)

Reconstructed phase space

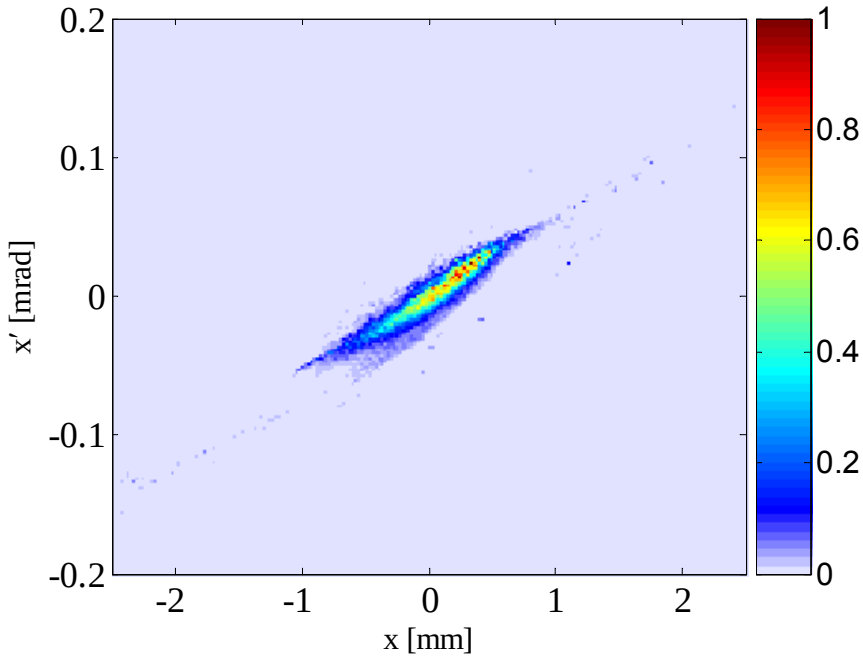
Slice emittance

Tomography
Least squares

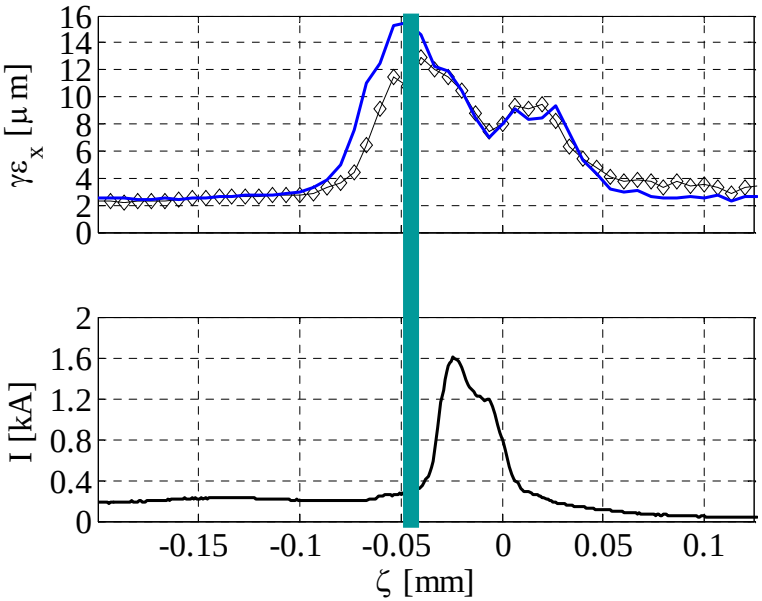


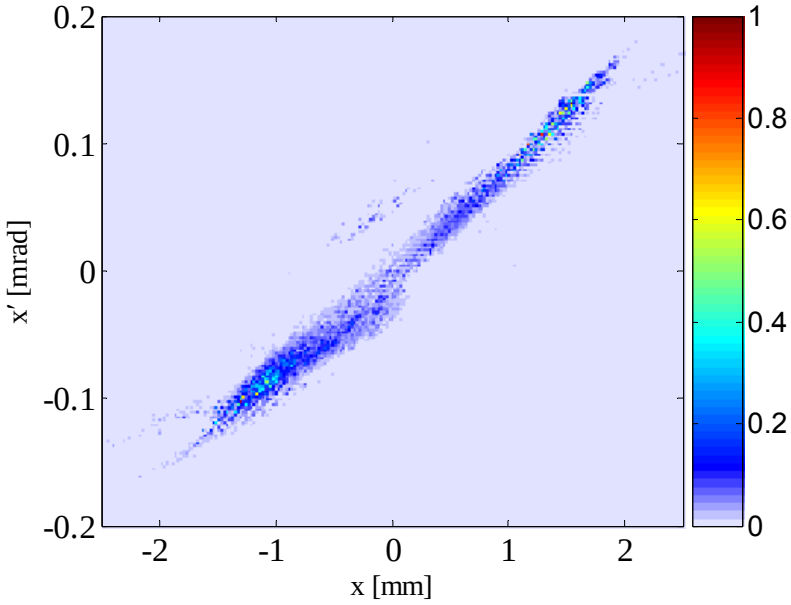
longitudinal slice position,
thickness Δζ = 8 μm

Reconstructed phase space:

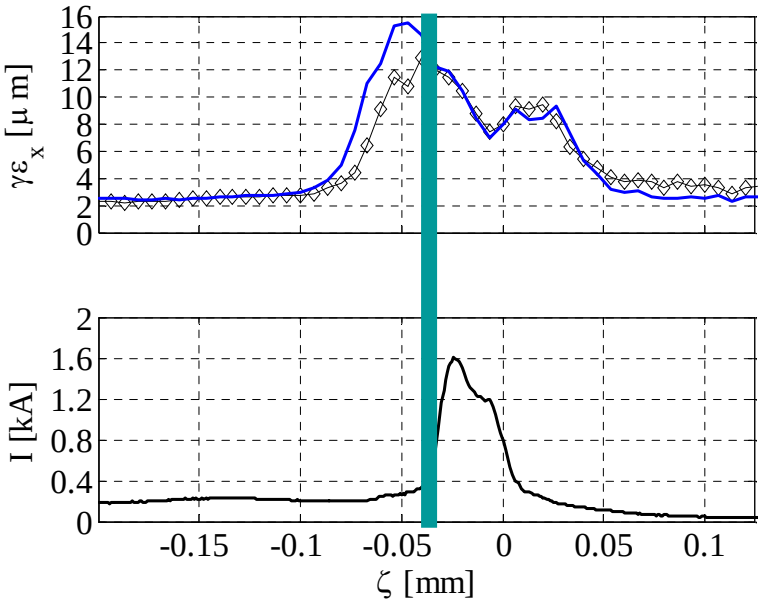


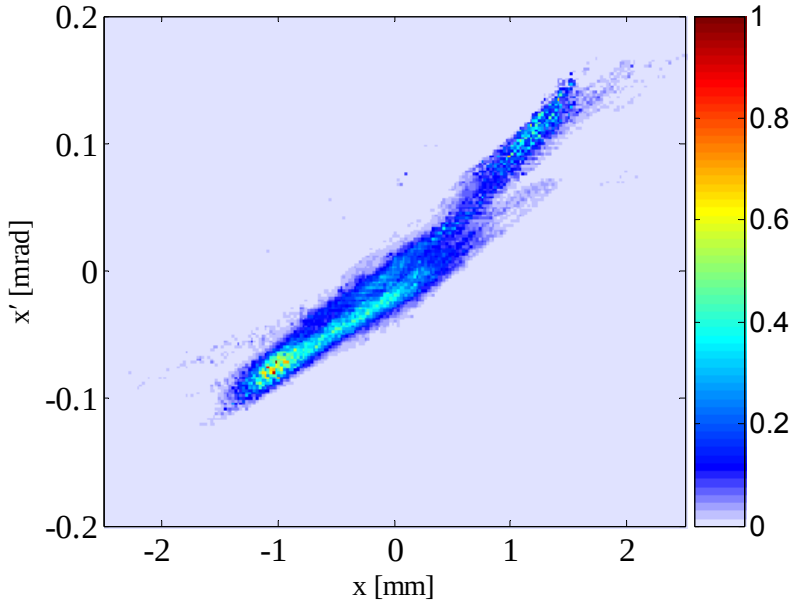
Reconstructed phase space



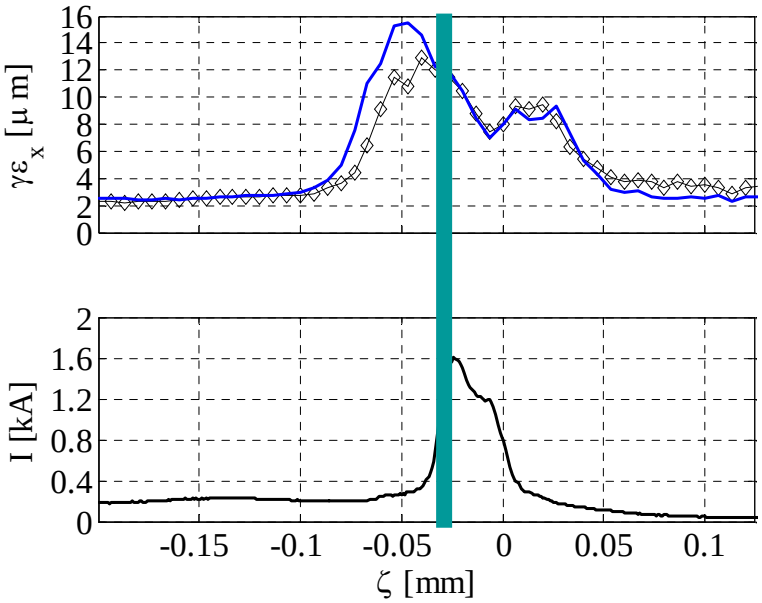


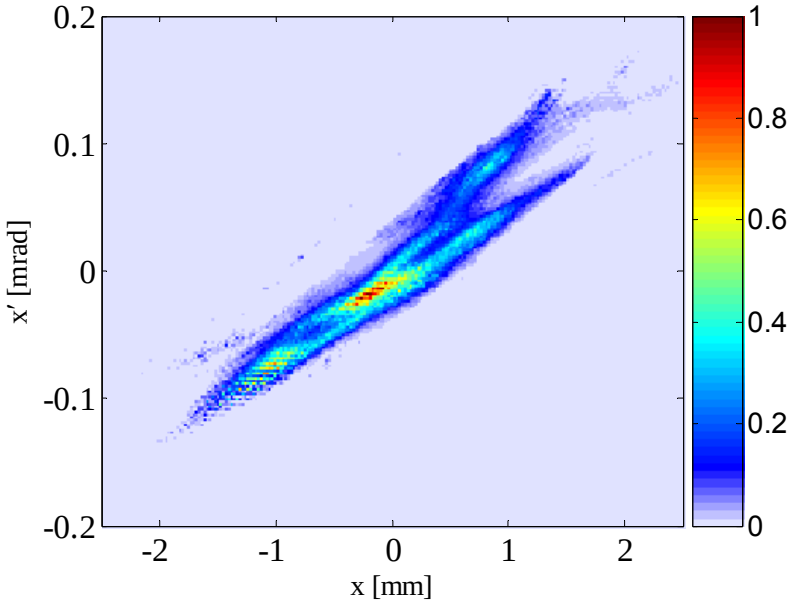
Reconstructed phase space



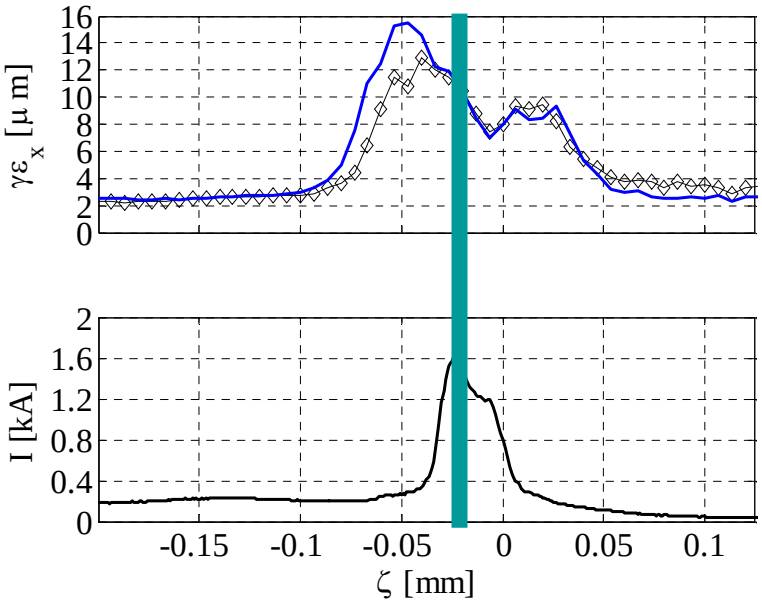


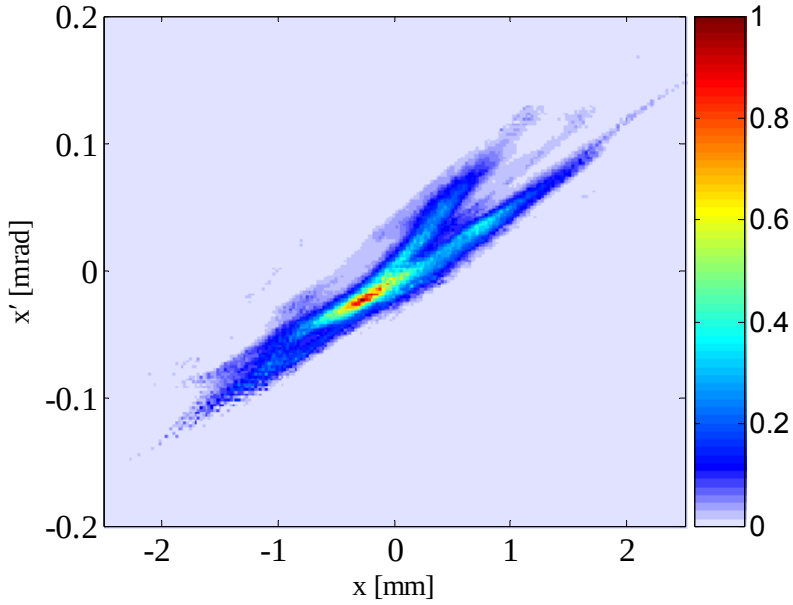
Reconstructed phase space



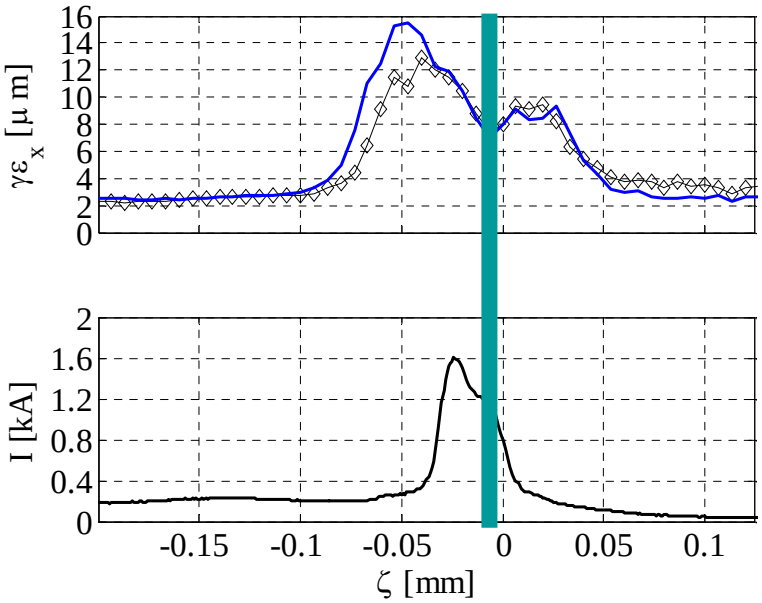


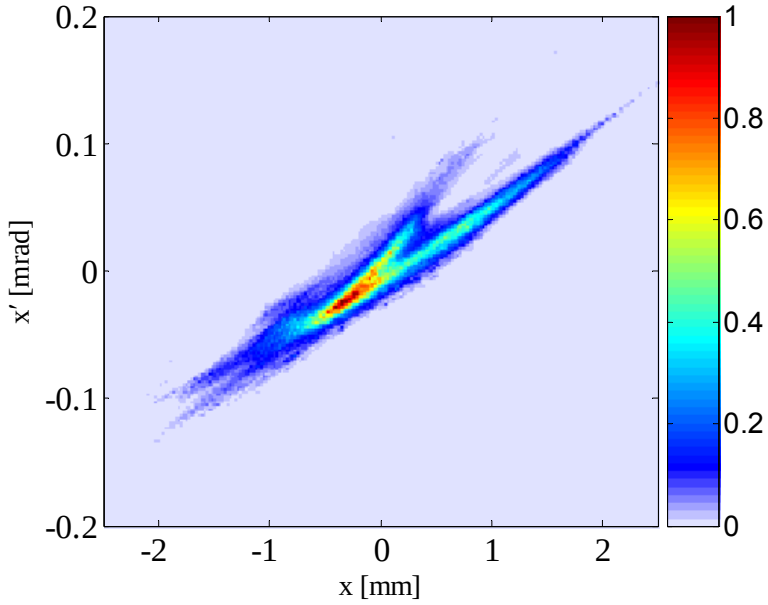
Reconstructed phase space



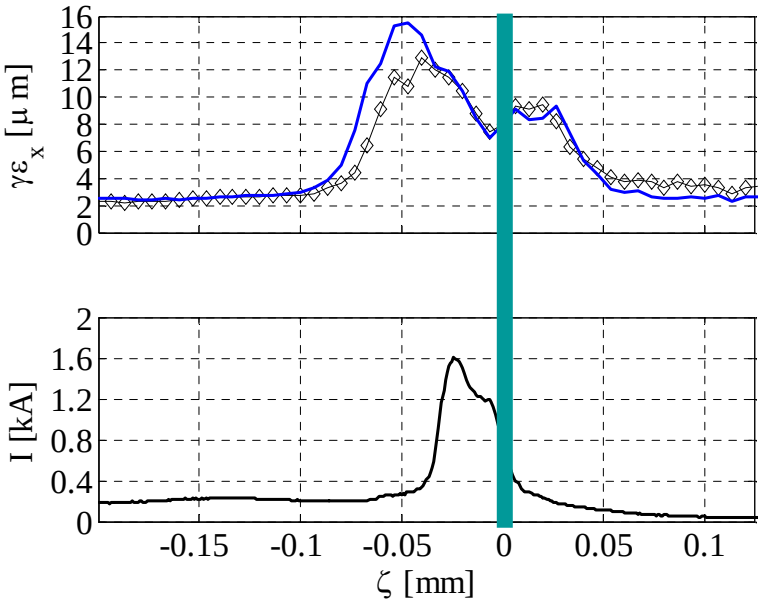


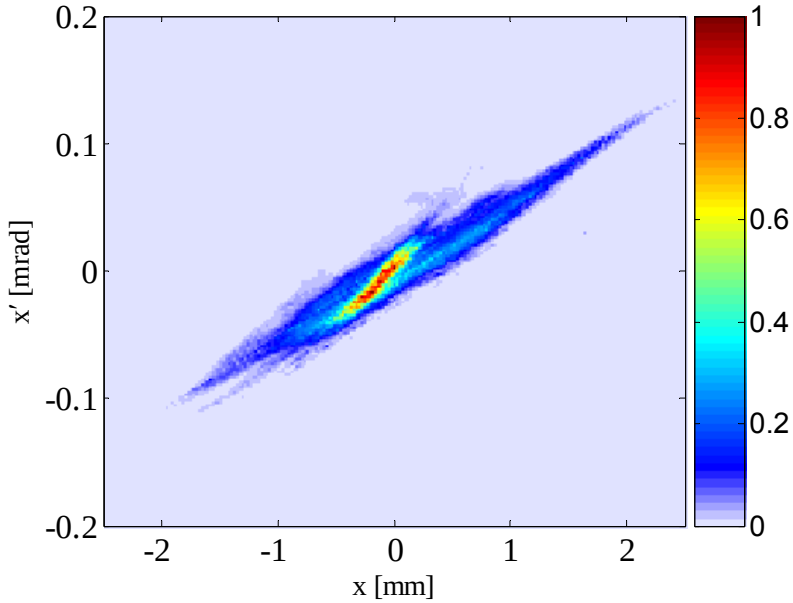
Reconstructed phase space





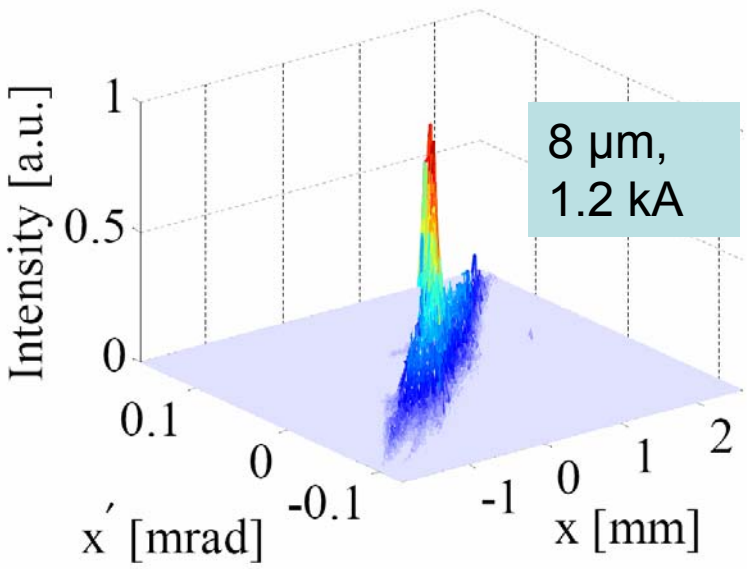
Reconstructed phase space



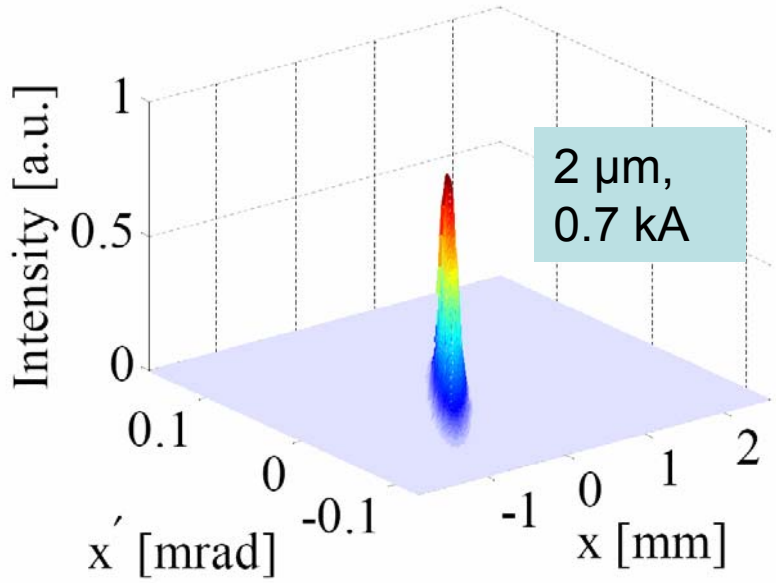


Emittance analysis

Measured distribution in the peak current region



2-dimensional Gaussian fit to the peak



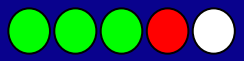
typical: 2-4 µm normalized emittance, 0.5 – 1.0 kA peak current

→ FEL radiation not saturated

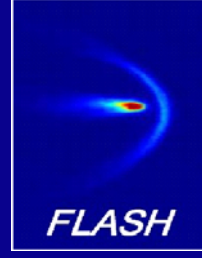
→ peak current may change downstream of the TDS

Outline

- Setup at FLASH
- Measurement methods
- Results under FEL operating conditions
- Error sources
- Summary



Error sources: Horizontal slice emittance



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

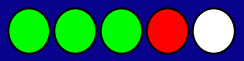
→ Upper bound for emittance, lower bound for peak current

- 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

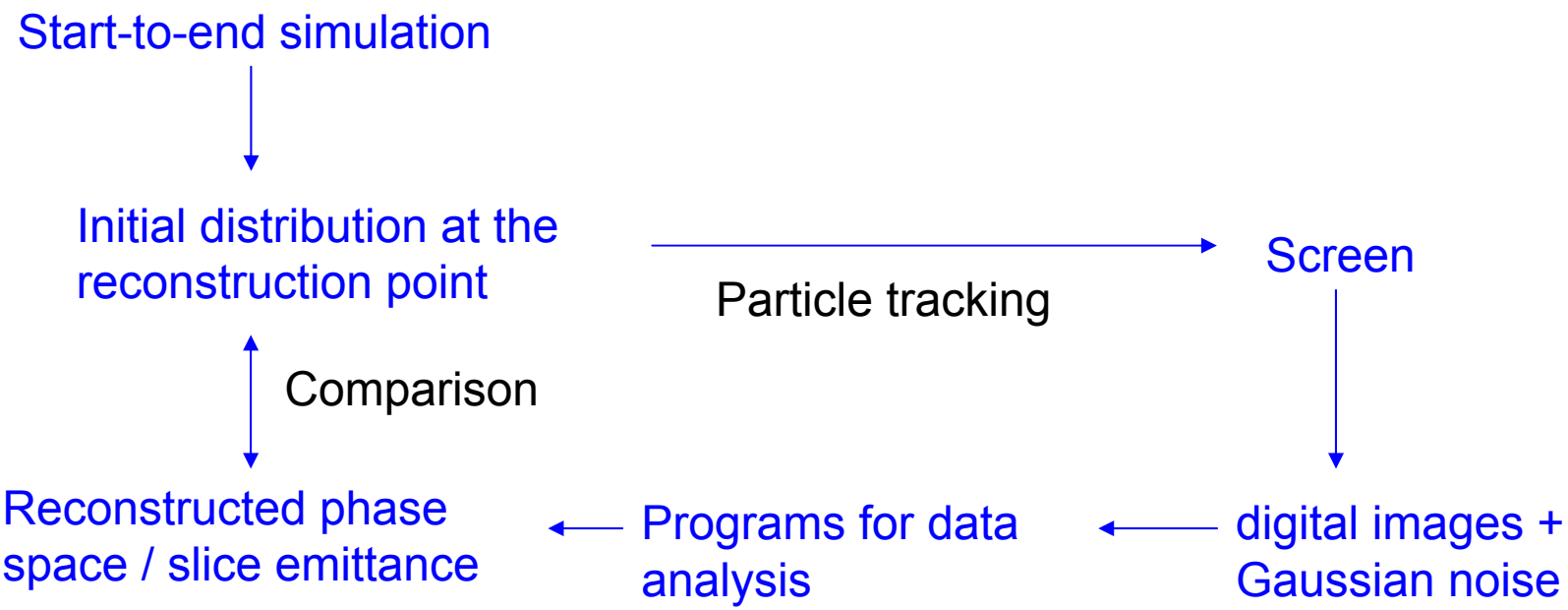
→ Emittance error < 20 % (RMS) for typical conditions

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

→ Simulation of a measurement using ASTRA

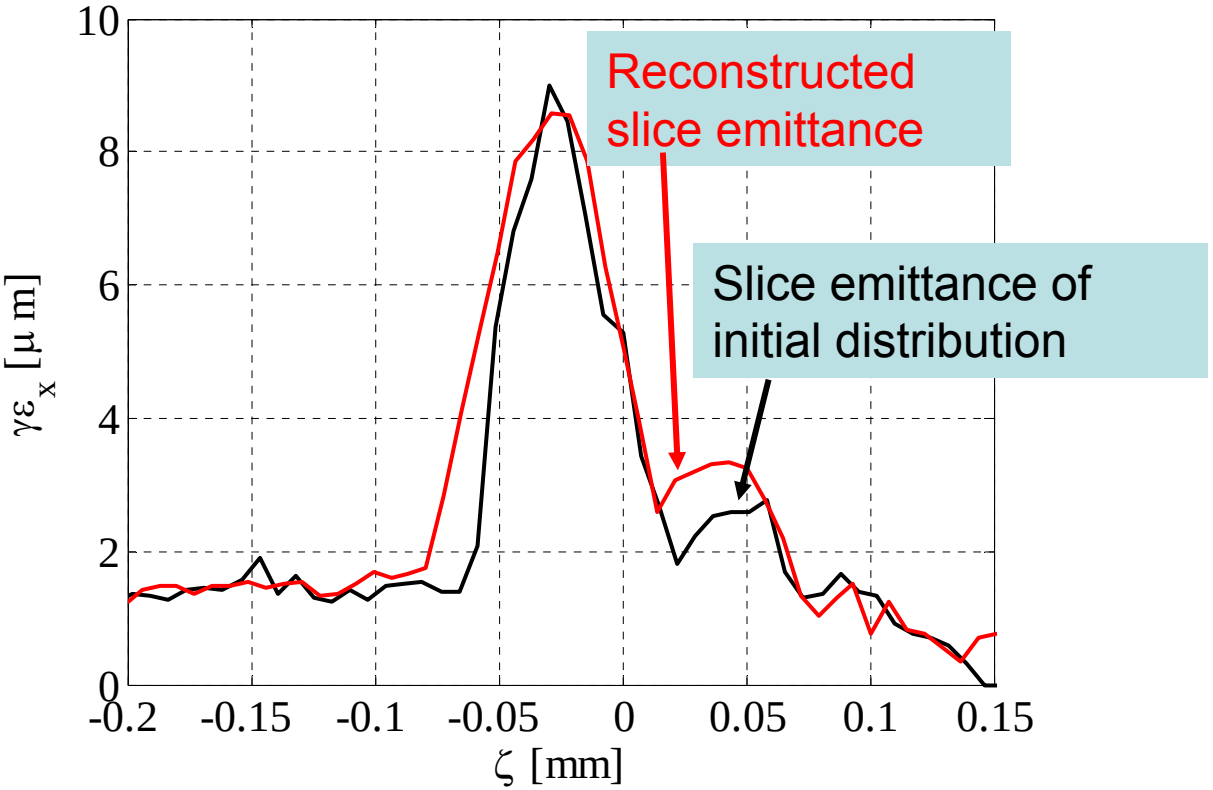


Simulation of an emittance measurement / a tomographic reconstruction

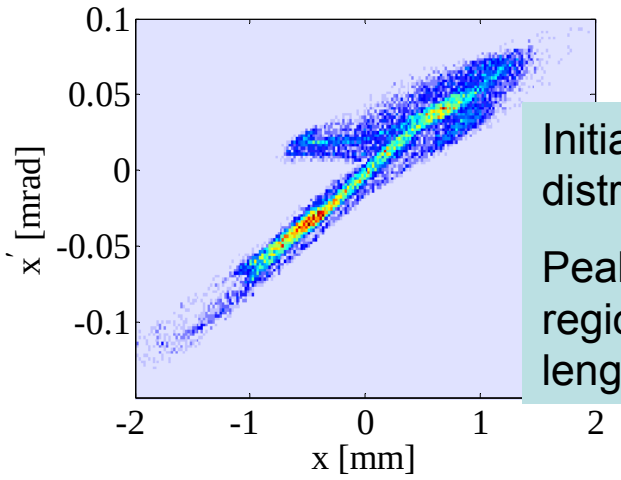


Simulation of a slice emittance measurement

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

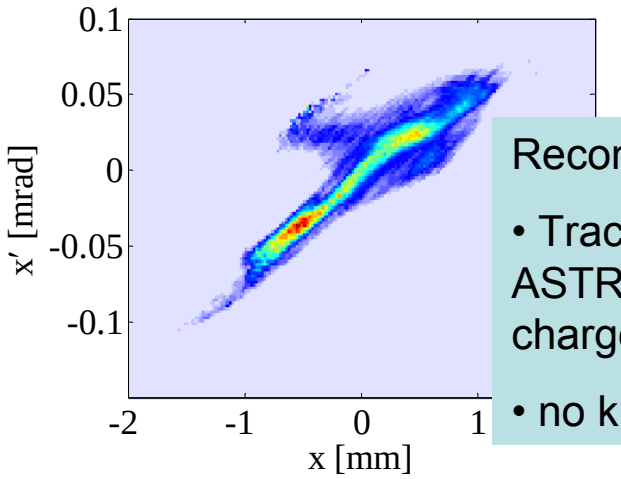


Simulation of a tomographic reconstruction: peak current region



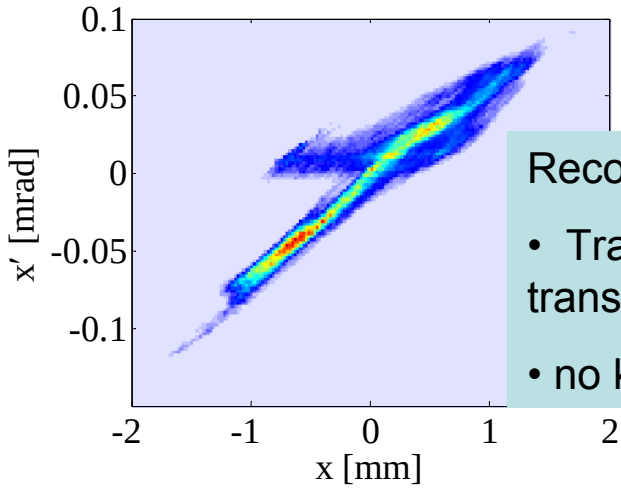
Initial distribution:

Peak current region (25 µm length)



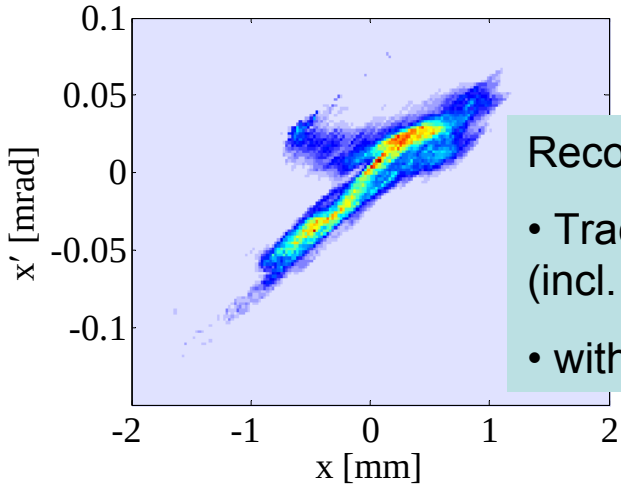
Reconstruction:

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



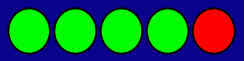
Reconstruction:

- Tracking: linear transfer matrices
- no kicker



Reconstruction:

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



Summary

- TDS successfully used to measure the current profile, longitudinal phase space and horizontal slice emittance with a longitudinal resolution of ~10 μm (30 fs)
- 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 very much for your attention!