Slice emittance measurements at the ELBE superconducting RF photoinjector

J. Rudolph, Helmholtz-Zentrum Berlin

EuCARD 2nd ANNUAL MEETING

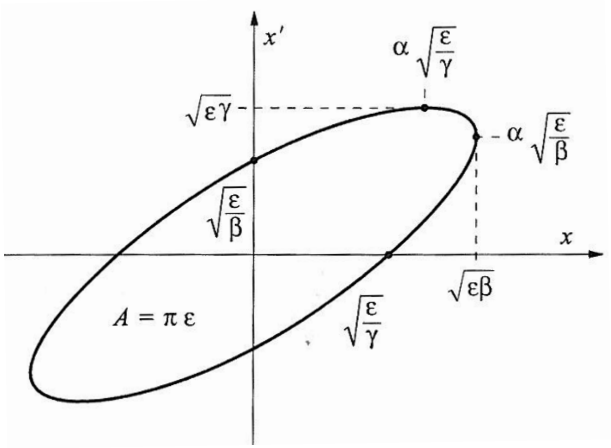
Overview

- **Emittance: Definition and Measurement**
- **Slice Emittance**
- **Slice Emittance Measurement:**
  - **Zero-Phasing at ELBE / SRF-Injector**
  - **Working Principle of Zero-Phasing Technique**
  - **First Measurement Results**
  - **Simulation Results**

Sigma Matrix for Particle Distribution Characterization

Emittance:

- Beam's ability to be focused → high intensity spot on sample
- Physical: (transverse) phase space volume
- Phase space ellipse may be described by Twiss-parameters or sigma matrix



- Characterize statistical particle distribution by first and second order moments (mean, variance, covariance): Mean and spread of particles

$$\sigma = \begin{bmatrix} \mathrm{var}(x) & \mathrm{cov}(x, x') \\ \mathrm{cov}(x', x) & \mathrm{var}(x') \end{bmatrix}$$

- Introduce covariance matrix for particle beam description → 'beam matrix', 'sigma matrix'
- rms-value (sigma) defined as square root of variance

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix}$$

- Emittance: square root of the determinant of the sigma matrix

$$\epsilon = \sqrt{\det(\sigma)} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

Emittance Measurement: Quadrupole Scan Technique

HZB Helmholtz Zentrum Berlin

- Quadrupole scan: vary beam transfer matrix M by changing quadrupole strength

- Transformation of sigma matrix through beamline

$$\sigma(s) = M \cdot \sigma(0) \cdot M^T$$

- Squared rms beam size

$$\sigma_{11}(s) = m_{11}^2 \sigma_{11}(0) + 2 m_{11} m_{12} \sigma_{12}(0) + m_{12}^2 \sigma_{22}(0)$$

- System of 3 equations with 3 unknowns

$$\begin{bmatrix} \sigma_{11}^{(a)}(s) \\ \sigma_{11}^{(b)}(s) \\ \sigma_{11}^{(c)}(s) \end{bmatrix} = \underbrace{\begin{bmatrix} m_{11}^{2\,(a)} & 2m_{11}^{(a)} m_{12}^{(a)} & m_{12}^{2\,(a)} \\ m_{11}^{2\,(b)} & 2m_{11}^{(b)} m_{12}^{(b)} & m_{12}^{2\,(b)} \\ m_{11}^{2\,(c)} & 2m_{11}^{(c)} m_{12}^{(c)} & m_{12}^{2\,(c)} \end{bmatrix}}_{A} \cdot \begin{bmatrix} \sigma_{11}(0) \\ \sigma_{12}(0) \\ \sigma_{22}(0) \end{bmatrix}$$

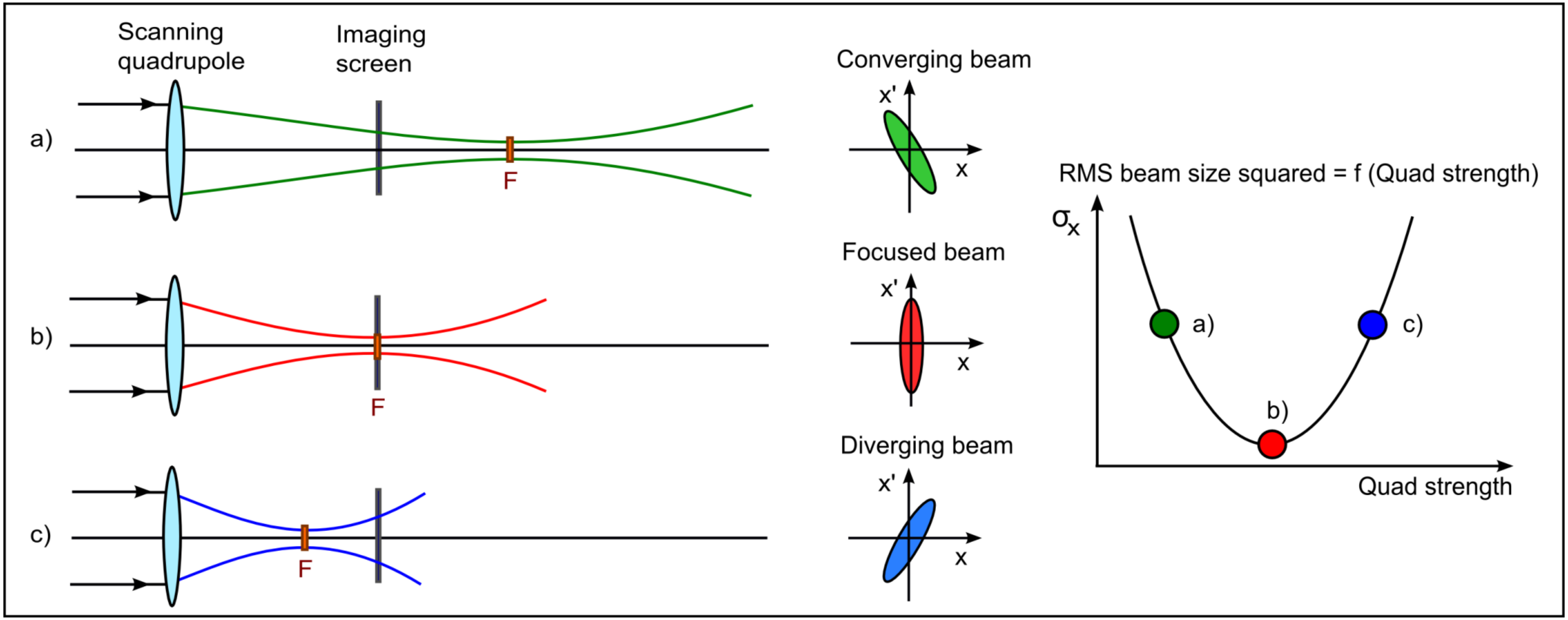
- Calculate sigma matrix elements and emittance

$$\begin{bmatrix} \sigma_{11}(0) \\ \sigma_{12}(0) \\ \sigma_{22}(0) \end{bmatrix} = A^{-1} \cdot \begin{bmatrix} \sigma_{11}^{(a)}(s) \\ \sigma_{11}^{(b)}(s) \\ \sigma_{11}^{(c)}(s) \end{bmatrix} \rightarrow \quad \epsilon = \sqrt{\det(\sigma)}$$

- What we need:
  - Beam size measurements and known transfer matrix elements

Emittance Measurement: Quadrupole Scan Technique

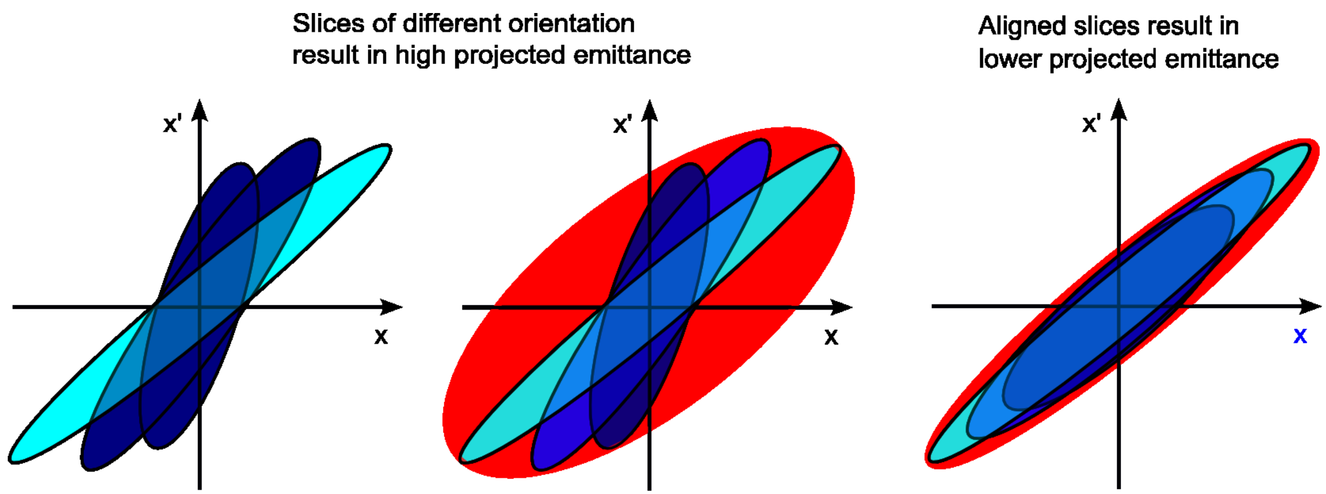
- Quadrupole scan technique: vary quadrupole strength and measure beam size on screen
- rms beam size on screen is a function of quadrupole strength
- Determine sigma matrix elements from fitting procedure → calculate emittance



From Projected Emittance to Slice Emittance

HZB Helmholtz Zentrum Berlin

- Normally: image beam on screen, measure projection of whole bunch
  - → 'Projected emittance'
- 'Slice Emittance': emittance varies as function of longitudinal position in bunch
  - Slices experience different focusing effects
  - Relevant for: emittance compensation schemes, FEL operation



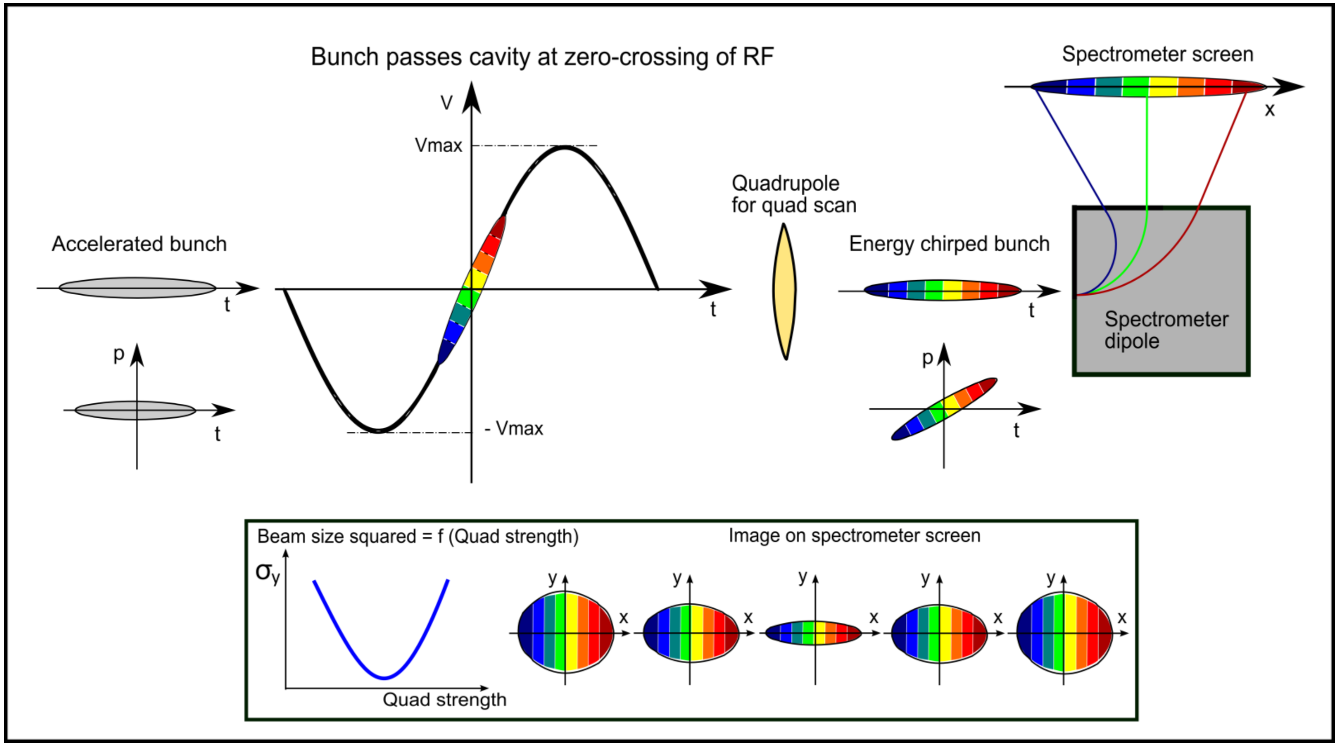
Blue: Slices of different emittance and orientation
Red: Resulting projected emittance

- Find a way to access slices and measure emittance
  → convert longitudinal distribution to transverse distribution
- How do we do that? → zero-phasing: Energy chirped beam + spectrometer dipole

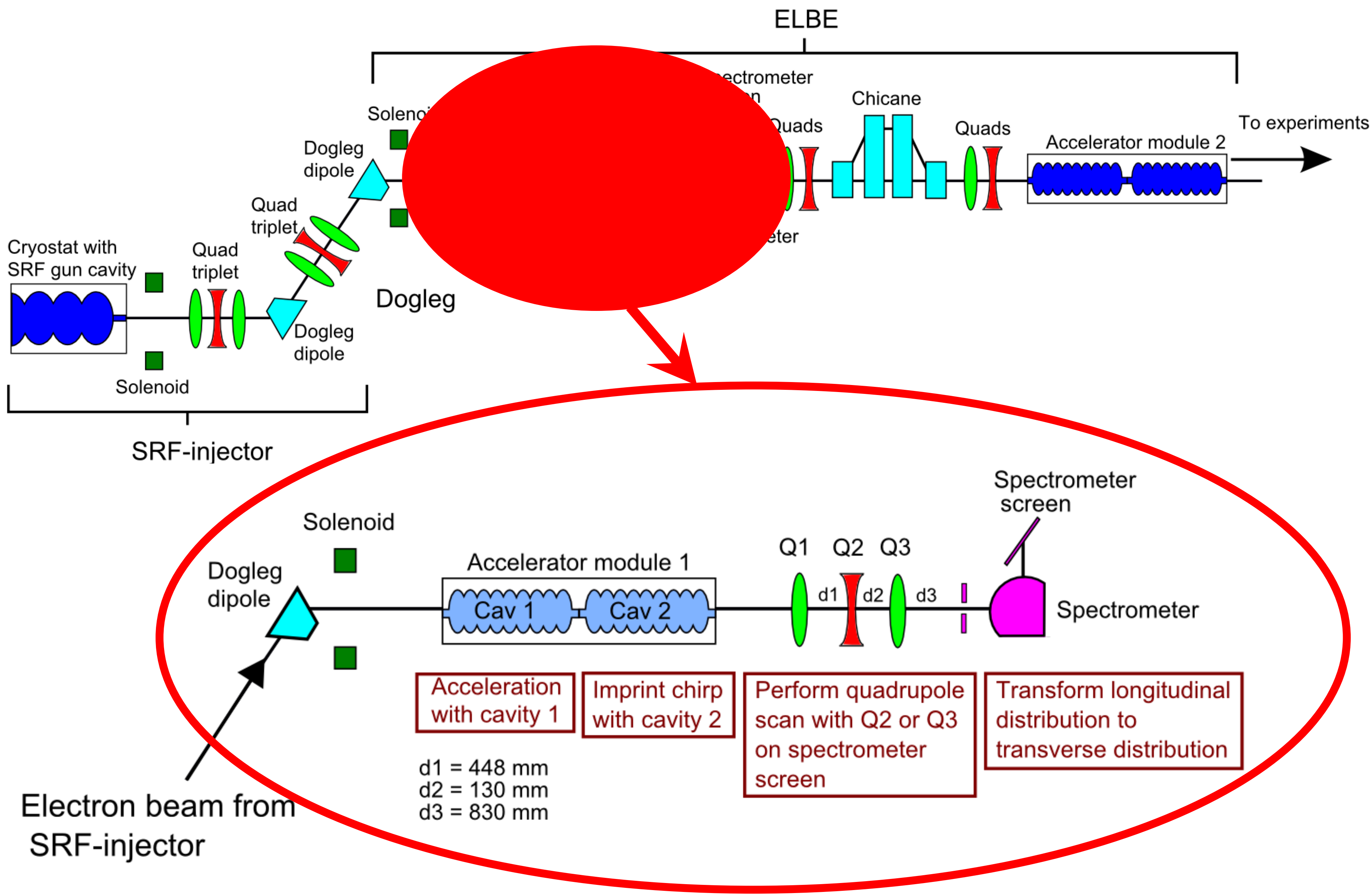
Principle of Zero-Phasing Technique for Slice Diagnostics

HZB Helmholtz Zentrum Berlin

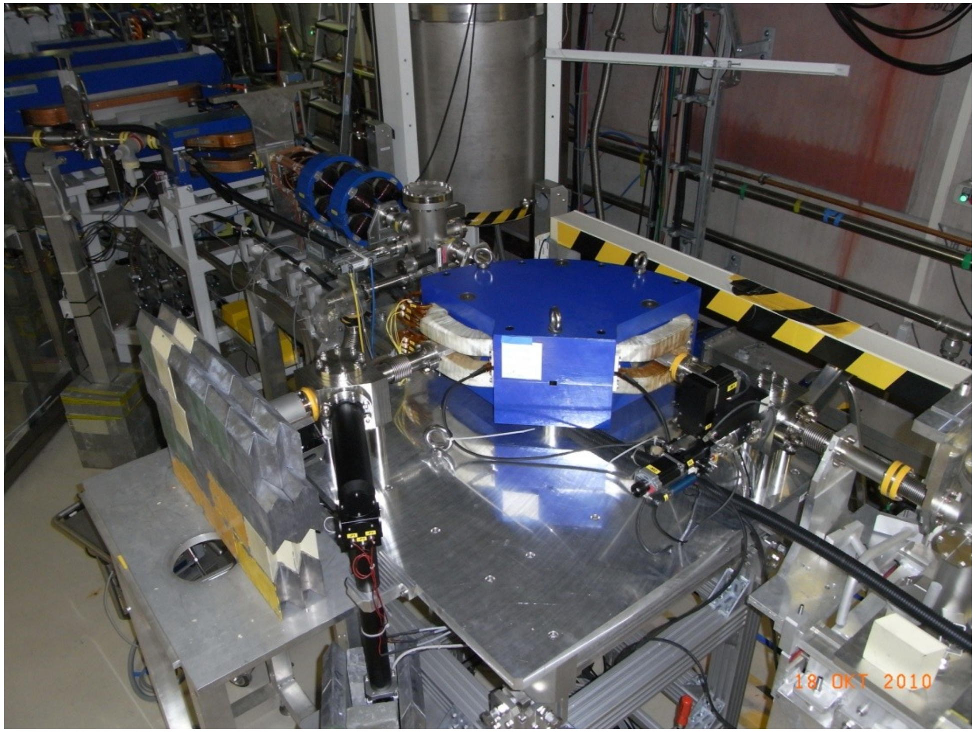
- Bunch passes cavity at zero-crossing of RF phase → correlation between energy and longitudinal bunch position
- Chirped beam send through spectrometer → longitudinal distribution transferred to transverse distribution → longitudinal slices accessible
- Beam size in **vertical** direction for each longitudinal slice measured
- Combination with quadrupole scan technique allows to reconstruct the vertical emittance for different slices

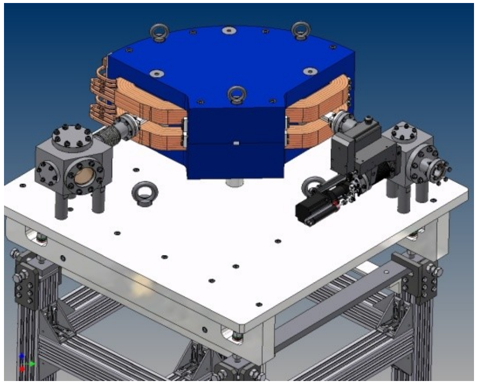


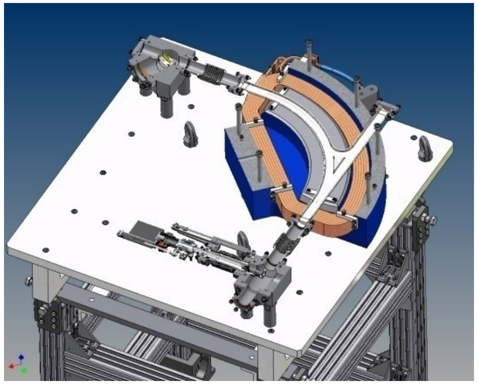
Optics Setup for Zero-Phasing at ELBE

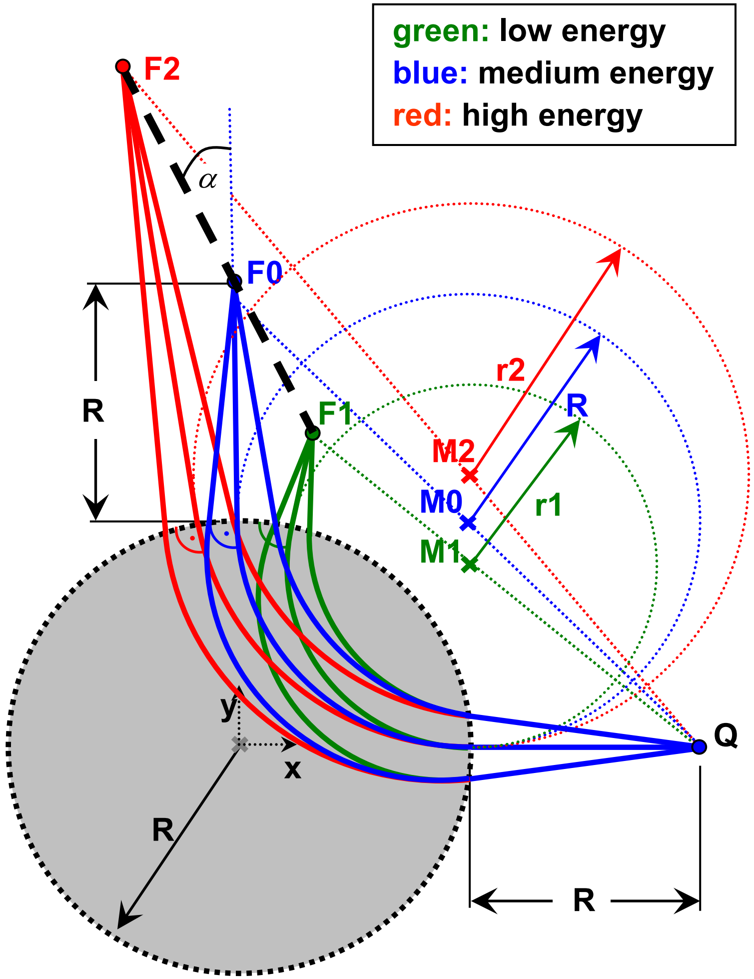


Browne-Buechner Spectrometer









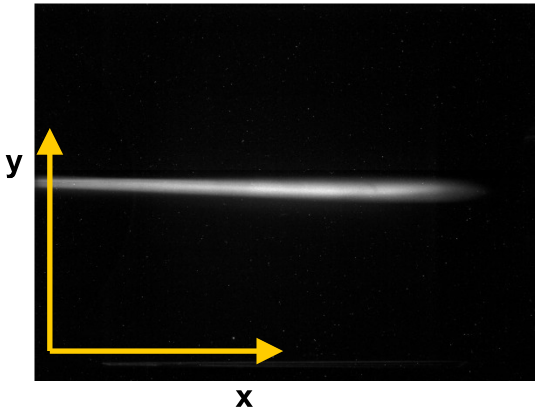
Overview: First Measurements and Analysis Procedure

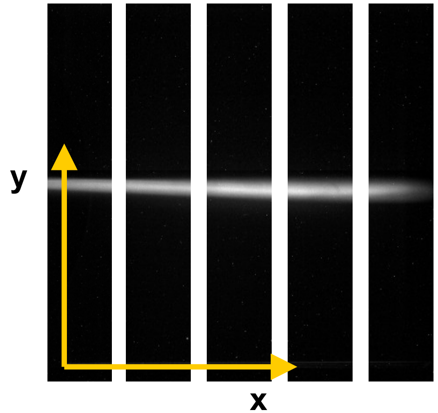
HZB Helmholtz Zentrum Berlin

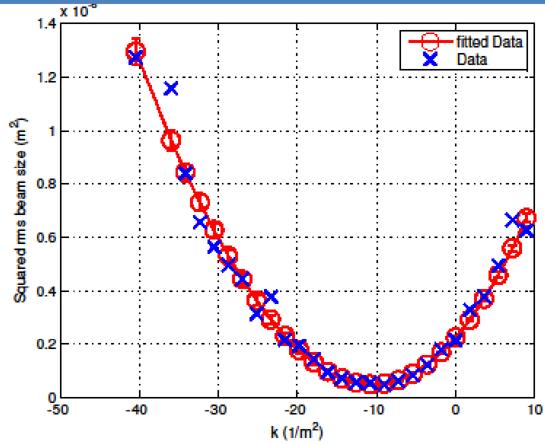
- Measurements performed at ~18 MeV and 10 pC for different phase settings of gun cavity and 2. linac cavity, spectrometer slit width 20 mm

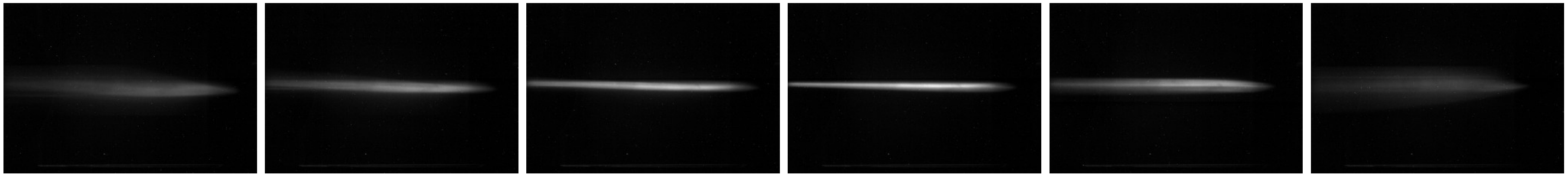
- Align and cut images, do projection over y for each slice, calculate vertical rms beam size
- Energy information used to start ‘elegant’ simulation to determine energy dependent transfer matrices (m33 and m34 needed)
- Calculate emittance from beam size and matrix elements using least-squares fit

- Position on screen → energy deviation → cav. phase → position in bunch → reconstruct longitudinal profile







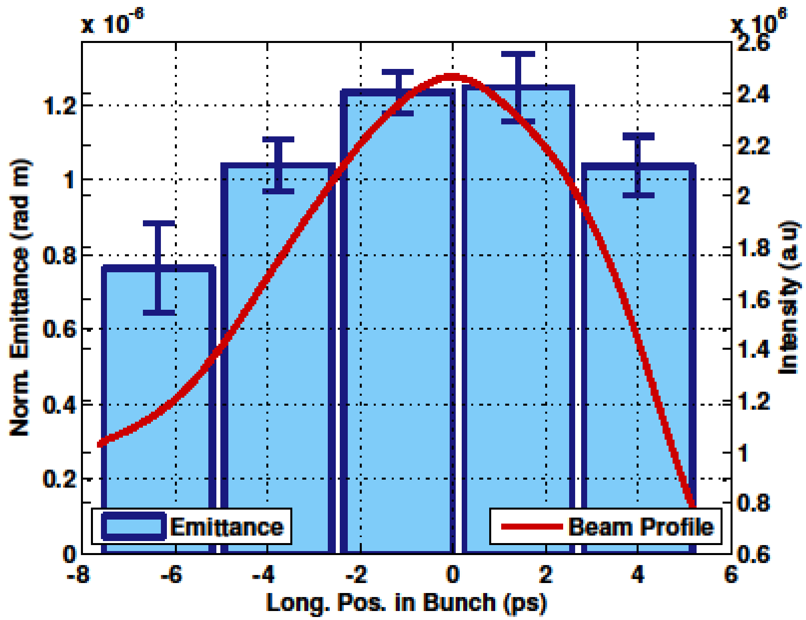


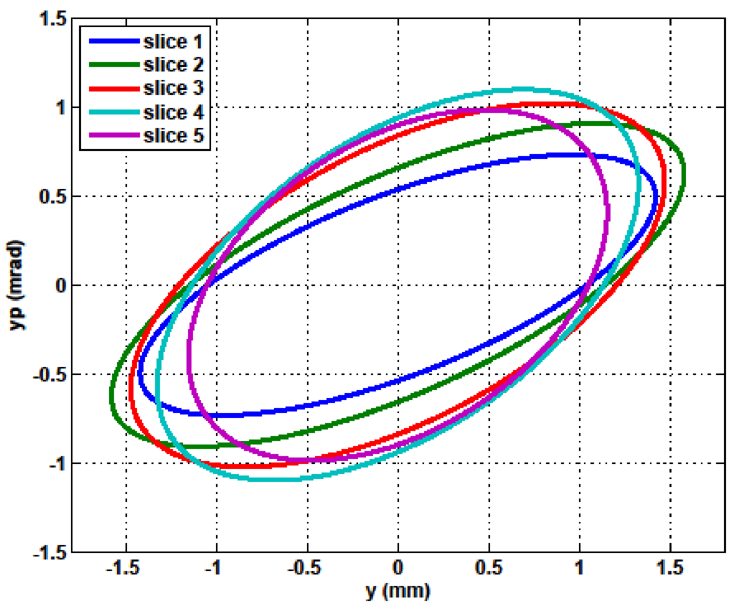
Slice Emittance: First Measurement Results (single meas. series)

HZB Helmholtz Zentrum Berlin

slice	emitt +/- emittErr	beta + /- betaErr (m)	alpha + /- alphaErr	gamma +/- gammaErr (1/m)
1	7.7e-7 +/- 1.2e-7	2.6 +/- 1.5e-1	-9.3e-001 +/- 1.0e-1	7.0e-001 +/- 6.7e-2
2	1.0e-6 +/- 6.9e-8	2.4 +/- 6.4e-2	-9.5e-001 +/- 4.4e-2	7.9e-001 +/- 3.3e-2
3	1.2e-6 +/- 5.6e-8	1.8 +/- 5.0e-2	-7.0e-001 +/- 3.6e-2	8.5e-001 +/- 3.3e-2
4	1.3e-6 +/- 9.0e-8	1.4 +/- 7.3e-2	-6.1e-001 +/- 6.0e-2	9.7e-001 +/- 5.6e-2
5	1.0e-6 +/- 8.0e-8	1.3 +/- 8.0e-2	-4.5e-001 +/- 6.8e-2	9.4e-001 +/- 6.5e-2

- Phase settings: -10 deg / 60 deg (gun / linac cavity)
- rms bunch length: 3.3 ps (excluding cut outer parts of beam)
- Emittance values follow longitudinal bunch profile

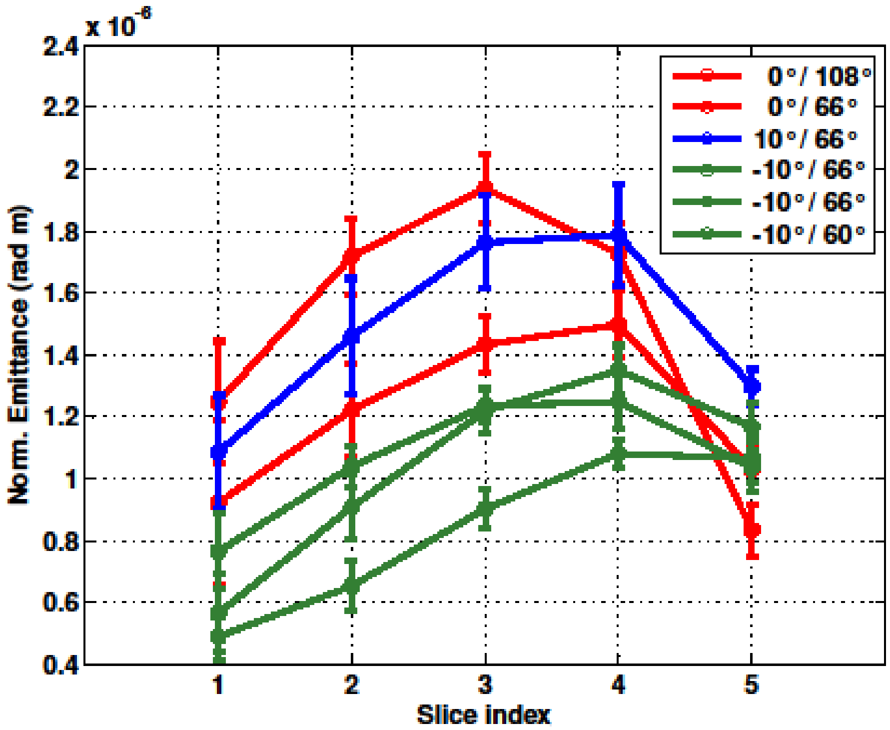




Slice Emittance: First Measurement Results (overall results)

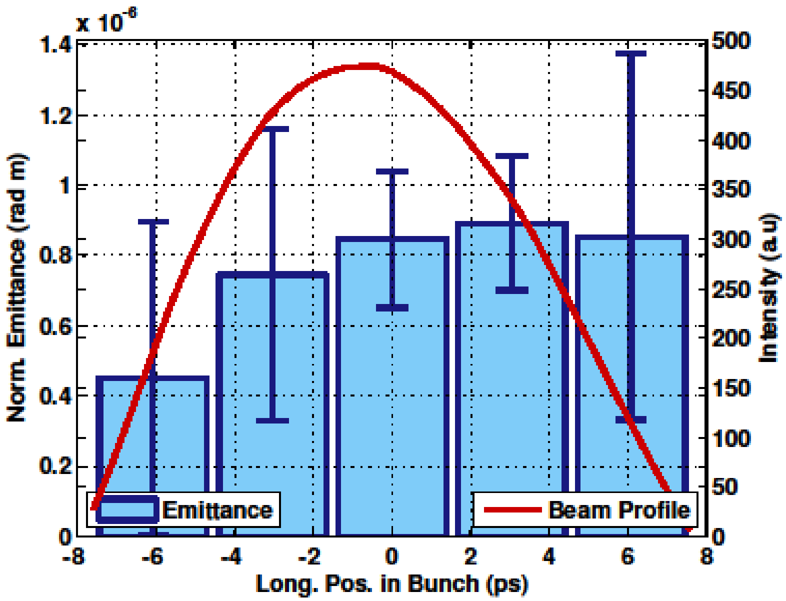
HZB Helmholtz Zentrum Berlin

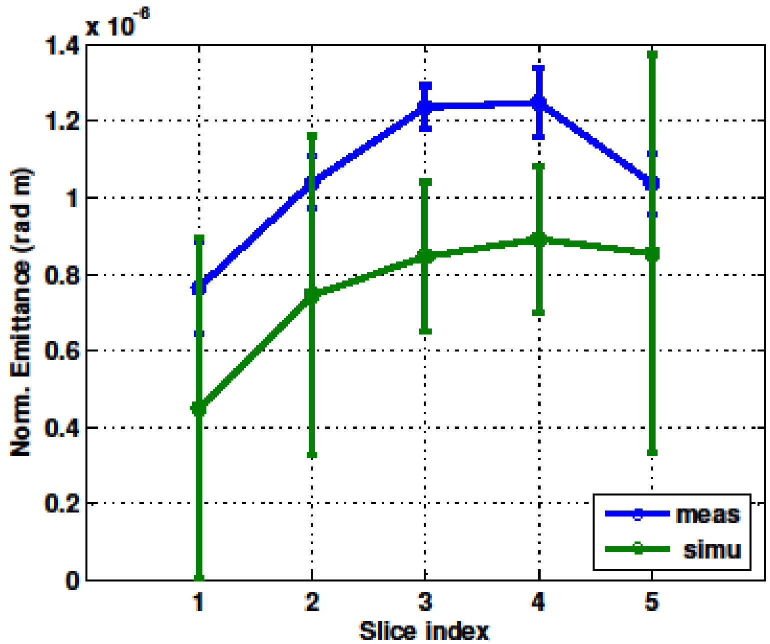
- Slice definition: left to right, slice 1 = head / slice 5 = tail of the bunch
- Phase definition: 0 deg is zero-crossing of the RF wave
- Slice emittance values between **0.5 mm mrad and 2 mm mrad**
- Emittance follows bunch profile, bunch length values around 4 ps
- Set similar phase settings to same colours
- Lowest emittances: -10 deg injection phase



Slice Emittance: Preliminary Simulation Results

- Simulations calculated using ‘ASTRA’ (electron gun) and ‘elegant’ (measurement procedure)
- Same analysis procedure as used for measurement
- Optics parameters as set in measurement → problematic





- Simulated values consistently lower than measured values (space charge excluded!)
- Slice emittance values between **0.5 mm mrad and 1 mm mrad**
- Simulation under investigation!

Summary and Outlook

HZB Helmholtz Zentrum Berlin

- Zero-Phasing Measurements successful
  - Slice emittance measurement: between 0.5 and 2 mm mrad
  - Similar values (projected emittance) determined by solenoid scan
  - Bunch length around 4 ps
  - Lowest emittance at -10 deg injection phase
- First simulations performed, but problematic
  - Lower slice emittance values: between 0.5 and 1 mm mrad
  - Similar characteristics as measurements
  - Further investigations needed
- Outlook: Second measurement period planned for summer 2011
  - Studies of phase dependency
  - Detailed studies for higher bunch charge
  - Resolution-optimised measurement
  - Optimisation of simulations, on-line simulation during measurements

Thank you for your attention!

HZB Helmholtz Zentrum Berlin

Thanks to

A. Arnold, M. Abo-Bakr, M. Justus, T. Kamps, U. Lehnert,

J. Teichert and R. Xiang, the ELBE crew and the Accelerator Physics group at HZB.