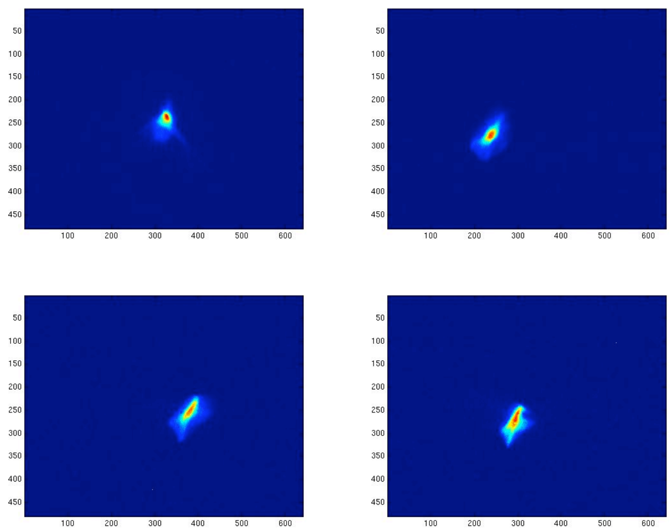
VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

Measurements of Transverse Emittance at the VUV-FEL at DESY

Katja Honkavaara (DESY / Univ. Hamburg)
for the VUV-FEL team

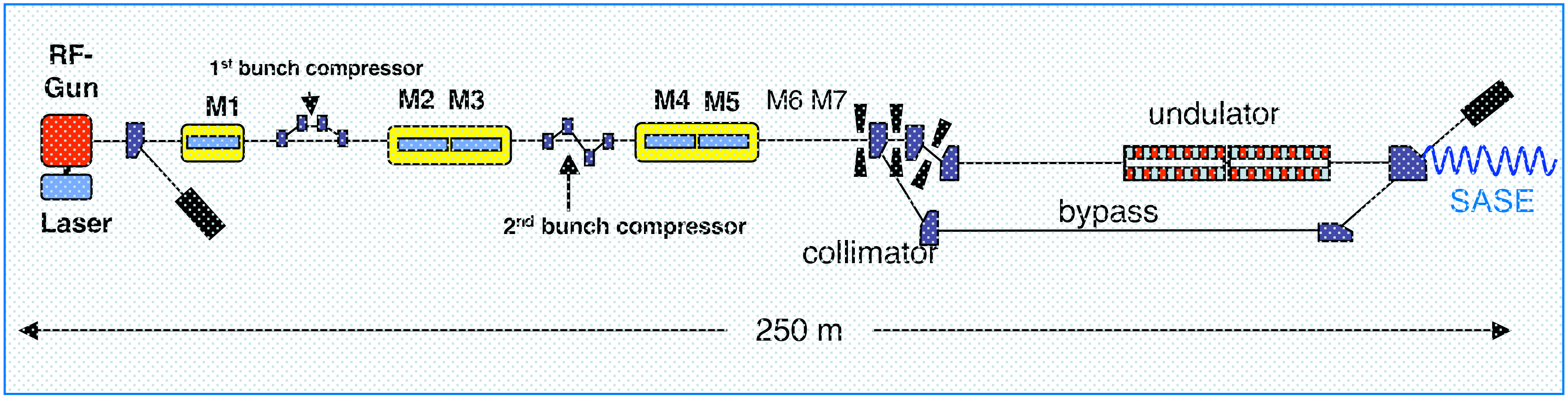


- VUV-FEL
- Measurements of projected emittance
- First measurements of slice emittance

The VUV-FEL at DESY, Hamburg

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

- SASE FEL user facility at DESY Hamburg in the wavelength range from vacuum ultraviolet to soft x-rays
- Commissioned in 2004 and beginning of 2005
- First lasing in January 2005 at 32 nm
- First user experiments started in June 2005
- A test bench for European XFEL and ILC



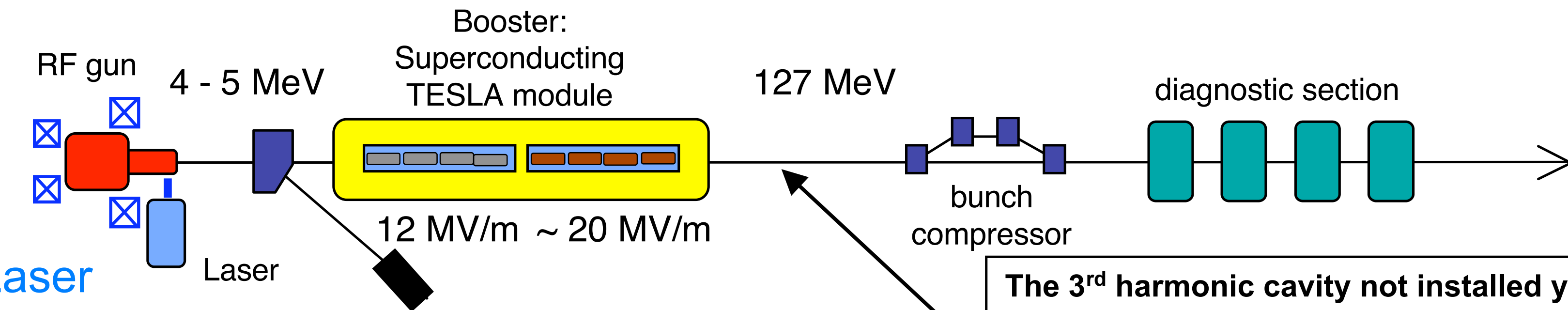
VUV-FEL Parameters

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

- Superconducting linac based on TESLA technology
- Energy up to 1 GeV
  - Present stage possible up to ~ 730 MeV
  - Presently operated at 445 MeV (lasing at 32 nm)
- Up to 7200 bunches per bunch train with 110 ns spacing; repetition rate up to 10 Hz
  - Presently: 1-30 bunches with 1 ms spacing (1 MHz), rep. rate 2 or 5 Hz
- Design electron beam parameters
  - Charge 1 nC / bunch
  - Normalized emittance 2 mm mrad
  - Peak current 2.5 kA
  - Energy spread 0.1%

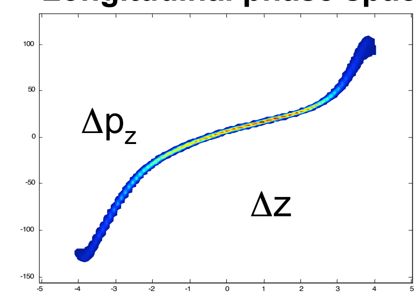
VUV-FEL Injector

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

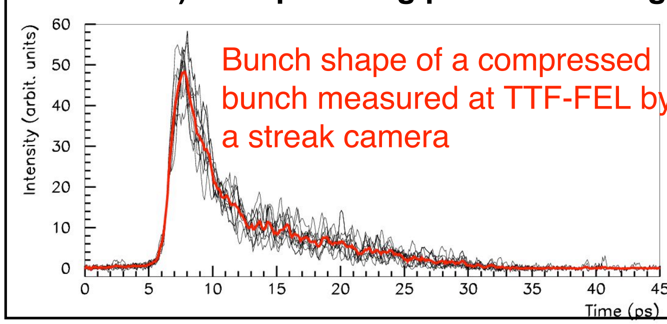


- Laser
  - Longitudinal gaussian shape (_ = 4.4 ps)
  - Transverse size Ø=3 mm
- RF gun
  - Commissioned and characterized at PITZ
  - Input power 3 MW (41 MV/m on the cathode)
  - Phase laser/gun RF 38 dg from zero crossing
- Solenoids
  - Main solenoid 277 A (0.163 T)
  - Bucking coil 20 A (to zero magnetic field on the cathode)
- Booster
  - 4 first cavities 12 MV/m, 4 last cavities ~ 20 MV/m
- Charge 0.5 – 1 nC; 1 – 30 bunches
- Beam energy 127 MeV

The 3rd harmonic cavity not installed yet.
Longitudinal phase space:

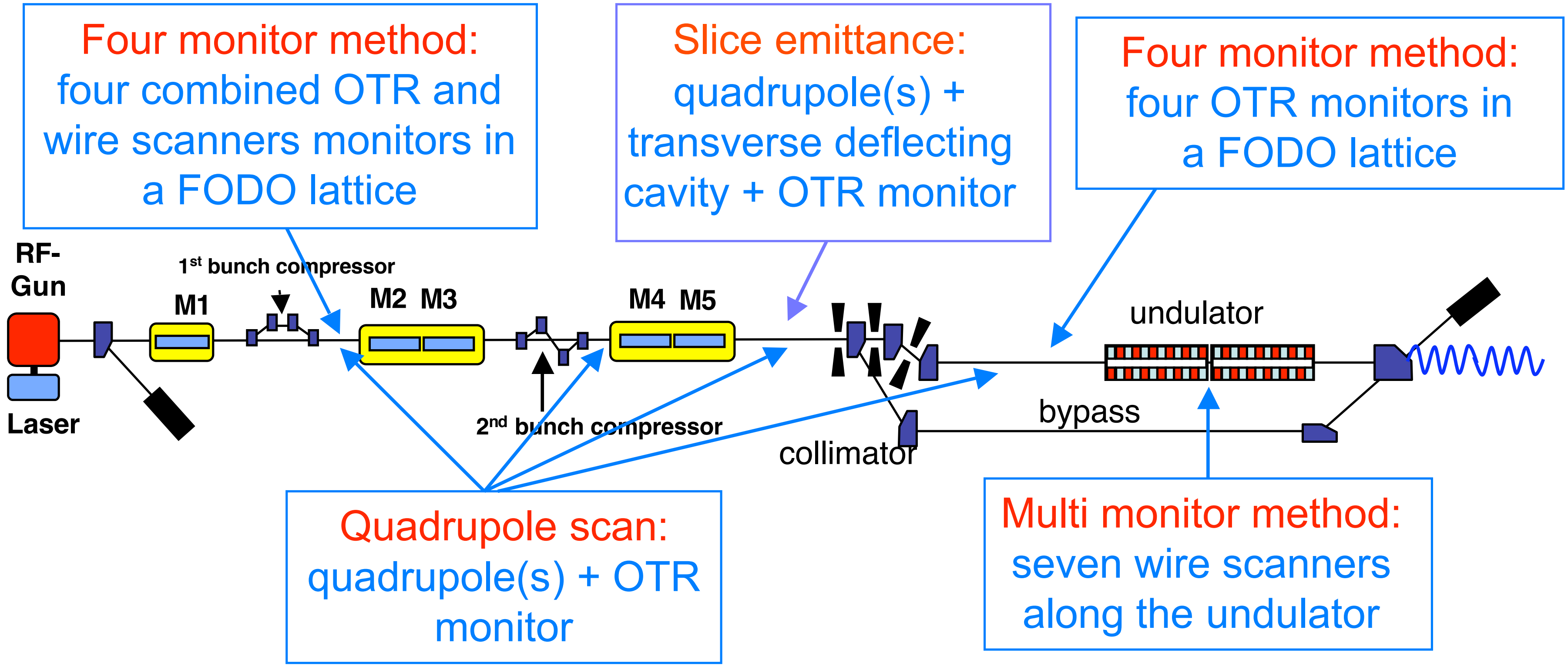


Longitudinal electron bunch shape after compression similar as at TTF-FEL (TTF 1, 1999-2002): sharp leading peak and a long tail



Emittance measurements

VUV-FEL
Vacuum-Ultraviolet Free-Electron Laser

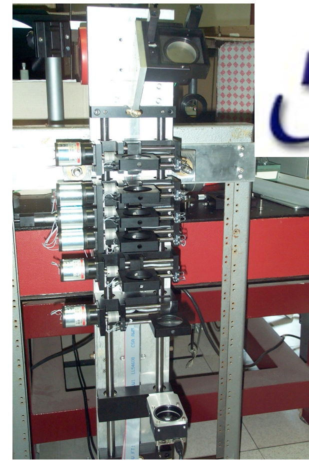


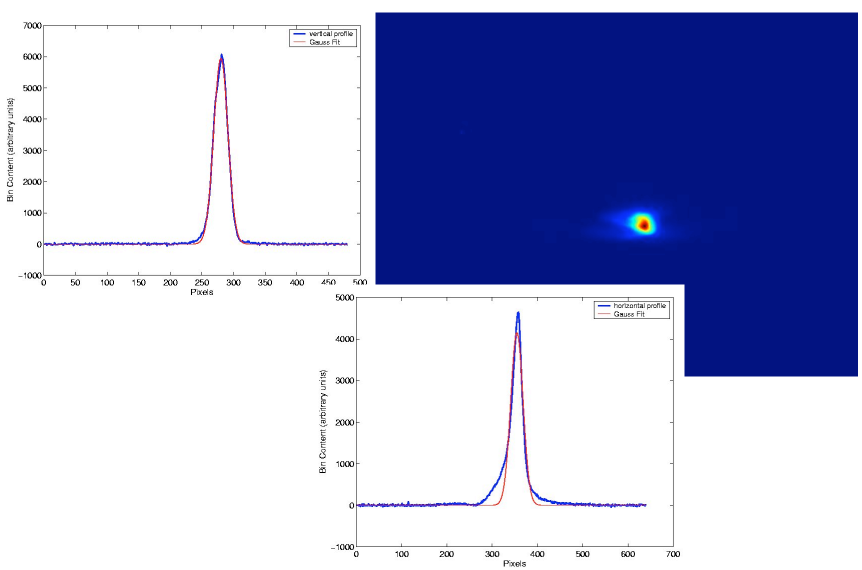
- Four (multi) monitor method
  - Beam size measured at several locations with fixed beam optics
- Quadrupole scan
  - Beam size measured at one location with different settings of one or several quadrupoles upstreams
  - Rarely used at the VUV-FEL (time consuming)

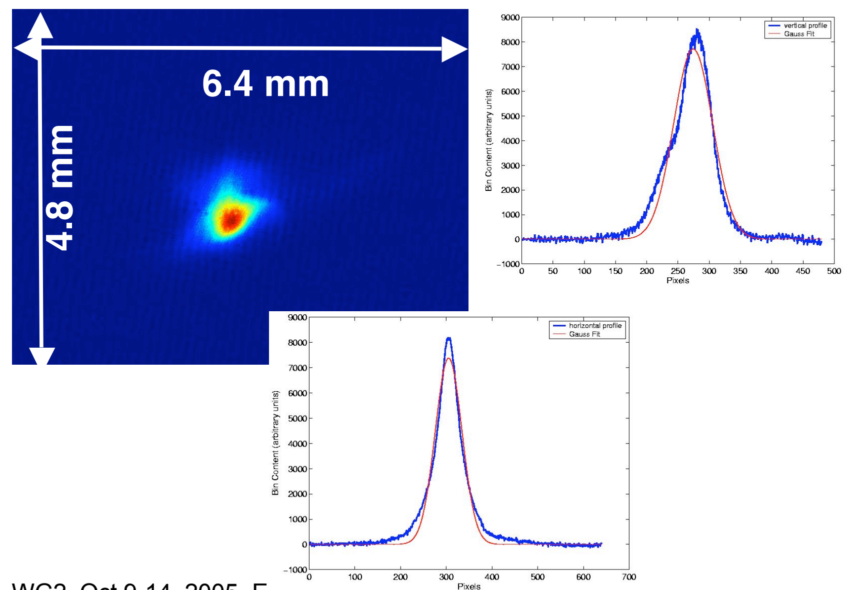
OTR monitors

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

- Use of optical transition radiation (OTR)
- OTR system designed and constructed by INFN-LNF and INFN-Roma2 in collaboration with DESY
- Based on digital cameras
- Remote controlled, 3 different magnifications
- Resolution down to ~ 10 um (rms)



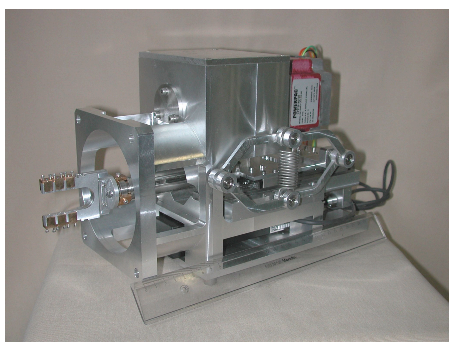




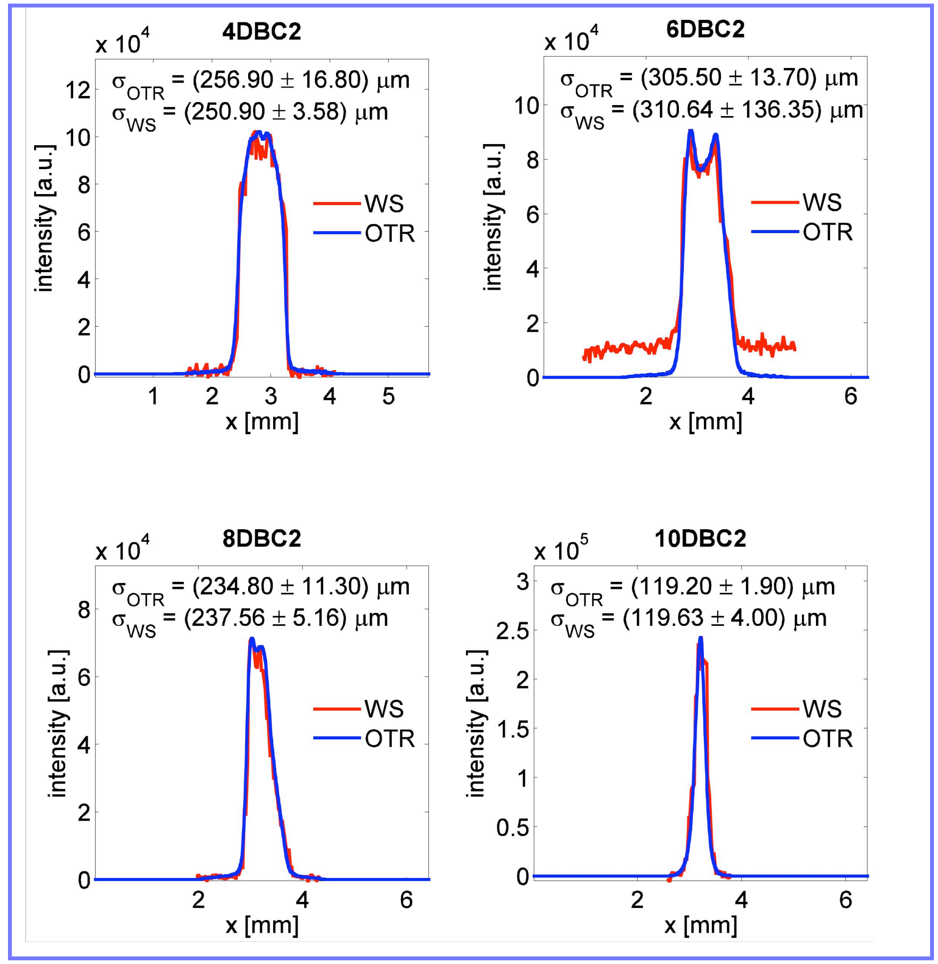
Wire scanners

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

- 8 wire scanners along the linac
  - modified CERN type
  - Mounted into a common vacuum chamber with an OTR screen
  - 45 dg movement with respect to the beam
- 7 wire scanner stations along the undulator
  - Design and construction by DESY (Zeuthen + Hasylab)
  - Separate horizontal and vertical scanners

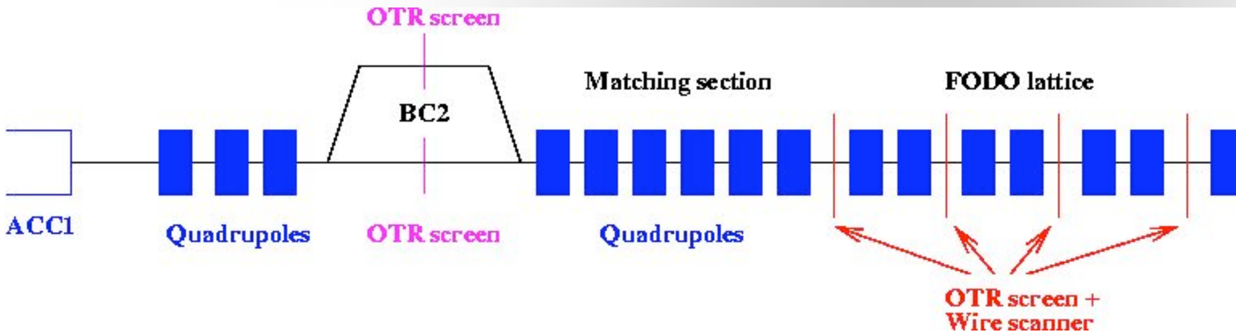


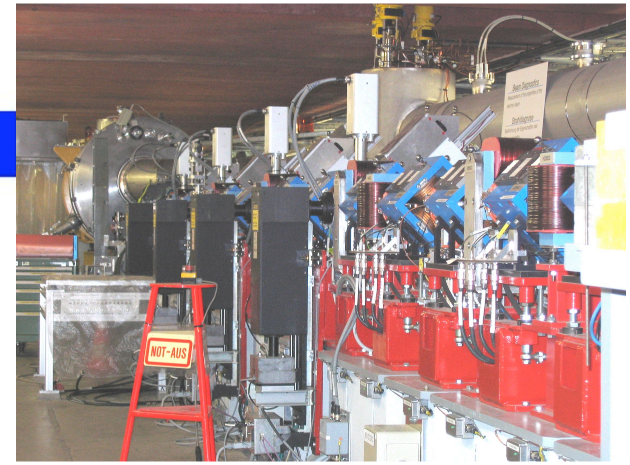
Comparison of beam profiles measured by OTR monitors and wire scanners in the injector FODO lattice



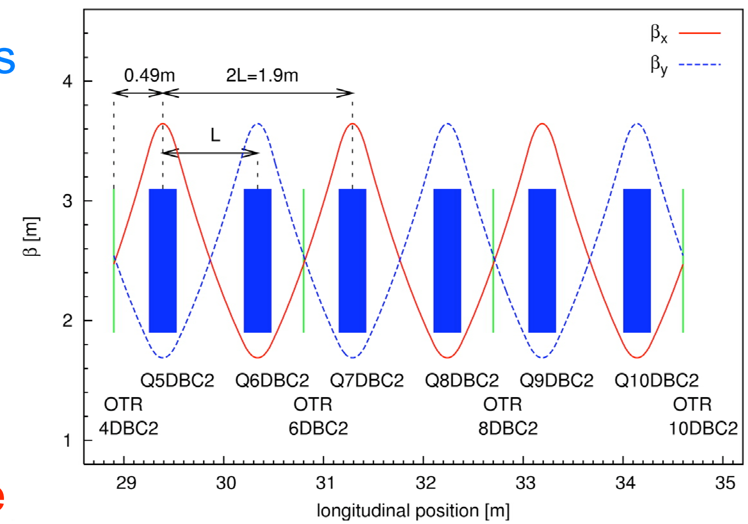
Emittance measurements at injector

VUV-FEL
Vacuum-Ultraviolet Free-Electron Laser





- FODO lattice of 6 quadrupoles with periodic beta function; 45 deg phase advance (design optics)
- Transverse beam distribution (shape and size) measured at four OTR monitors or wire scanners with fixed beam optics; presently only OTR monitors in routine use
- Emittance and Twiss parameters at the location of the first screen determined from beam distribution and known transport matrices by two methods:
  - Least square fitting of the emittance and Twiss parameters to the measured beam size
  - Tomographic reconstruction of the phase space



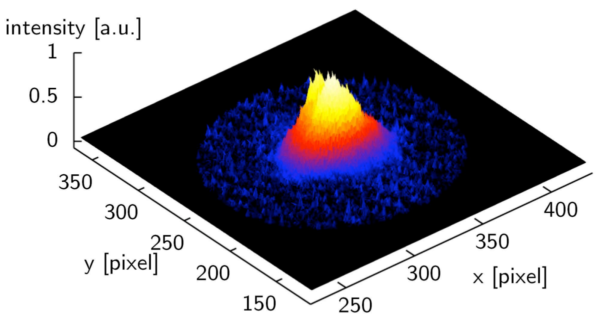
Data analysis (F.Löhl)

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

Image analysis

Sophisticated analysis procedure applied to beam images

- Subtraction of background
- Determination of region of interest
- Off-set corrections, filtering
- Determination of beam core containing 90% (an arbitrary choice) of the beam intensity
- Calculation of rms beam sizes



Emittance calculations

rms emittance of the entire beam and the core rms emittance containing 90% of the beam intensity are determined using two methods:

- Least square fitting
- Tomographic reconstruction of phase space

Error estimation

- Error estimation performed for the fitting method
- Statistical errors due to fluctuations of measured beam sizes: typically 2-4%
- Systematical errors taking into account errors in beam energy, quadupole gradients and calibration of OTR monitors estimated by Monte Carlo simulations: typically 5-6%
- Errors in following statistical errors only

Presentation of results

Normalized emittance
Beta
Alpha

Measured beam sizes

Mismatch parameters

$$\text{beta beating} = \max\left[\frac{\beta(s)-\beta_D(s)}{\beta_D(s)}\right]$$

$$B_{\text{mag}} = \frac{1}{2}(\beta\gamma_D - 2\alpha\alpha_D + \gamma\beta_D)$$

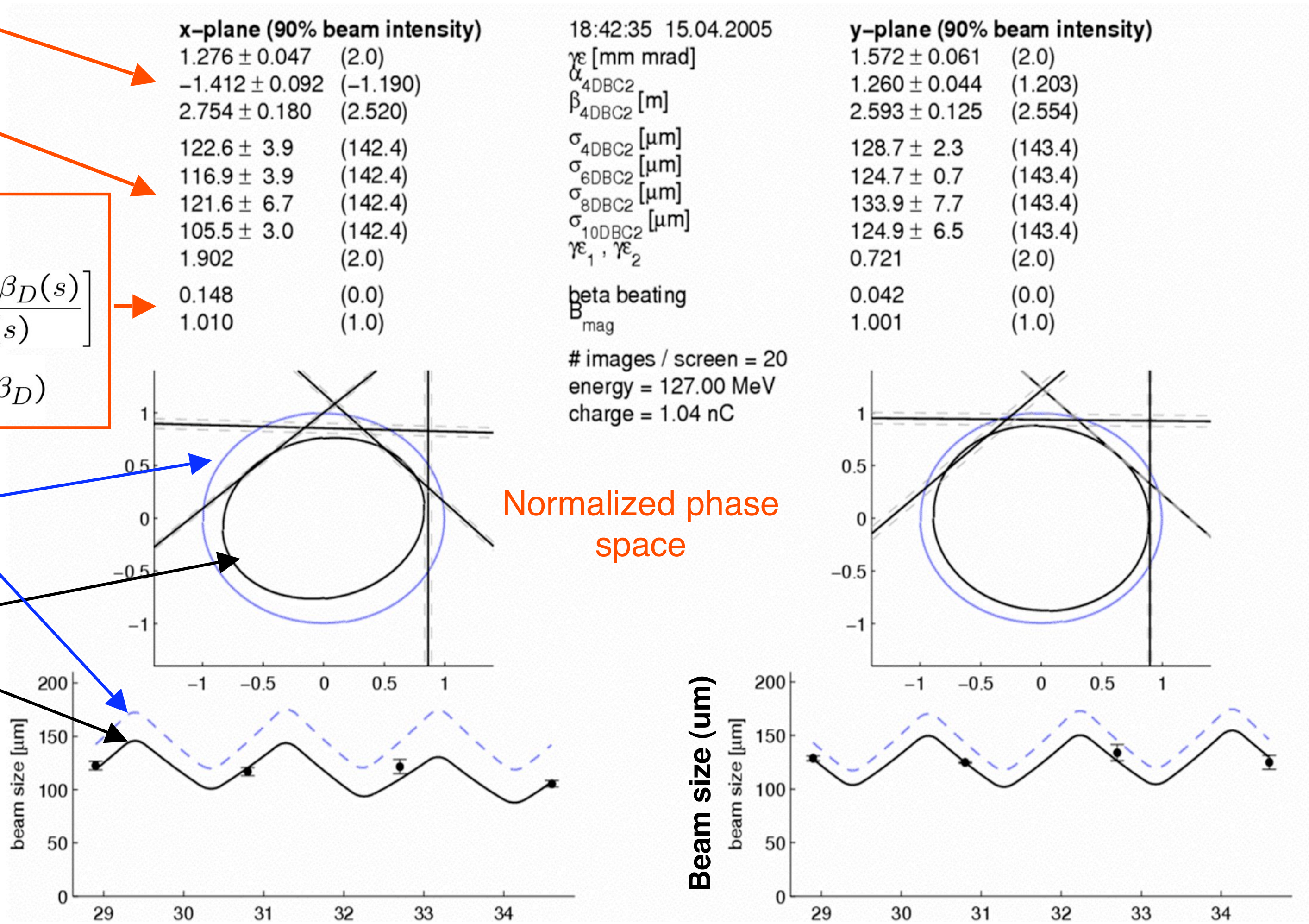
Design (matched; –N = 2 mm mrad)

Measured

Normalized phase space

Horizontal plane

Vertical plane



Example of 100% emittance (rms)

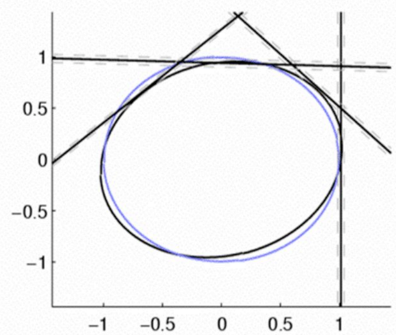
VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

Horizontal	1 nC	Vertical

2.0 mm mrad (horizontal) — 2.2 mm mrad (vertical)

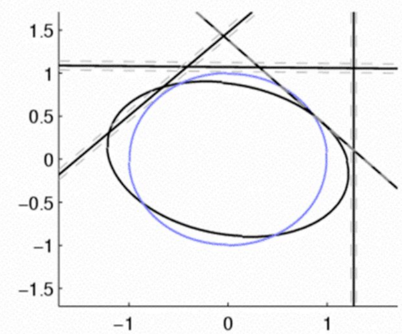
x-plane (100% beam intensity)		18:42:35 15.04.2005	y-plane (100% beam intensity)	
1.958 ± 0.060	(2.0)	$\gamma\varepsilon$ [mm mrad]	2.166 ± 0.086	(2.0)
−1.404 ± 0.071	(−1.190)	α_{4DBC2}	1.840 ± 0.097	(1.203)
2.713 ± 0.122	(2.520)	β_{4DBC2} [m]	3.513 ± 0.209	(2.554)
144.3 ± 3.9	(142.4)	σ_{4DBC2} [μm]	181.8 ± 3.8	(143.4)
152.9 ± 4.6	(142.4)	σ_{6DBC2} [μm]	139.8 ± 1.0	(143.4)
133.8 ± 5.5	(142.4)	σ_{8DBC2} [μm]	153.3 ± 7.5	(143.4)
133.6 ± 3.4	(142.4)	σ_{10DBC2} [μm]	151.9 ± 6.2	(143.4)
2.533	(2.0)	$\gamma\varepsilon_1$, $\gamma\varepsilon_2$	1.528	(2.0)
0.149	(0.0)	beta beating	0.427	(0.0)
1.010	(1.0)	B_{mag}	1.064	(1.0)

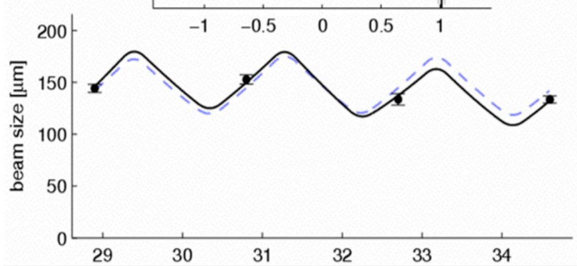
# images / screen = 20
energy = 127.00 MeV
charge = 1.04 nC

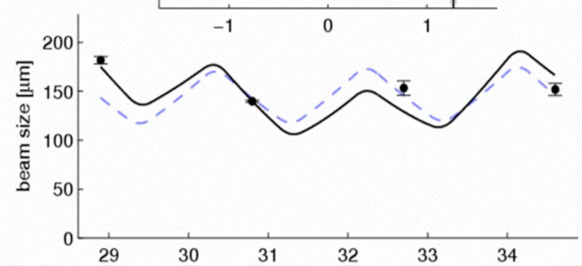


$$\varepsilon_{tr} = \sqrt{\varepsilon_x \cdot \varepsilon_y}$$

= 2.1 mm mrad







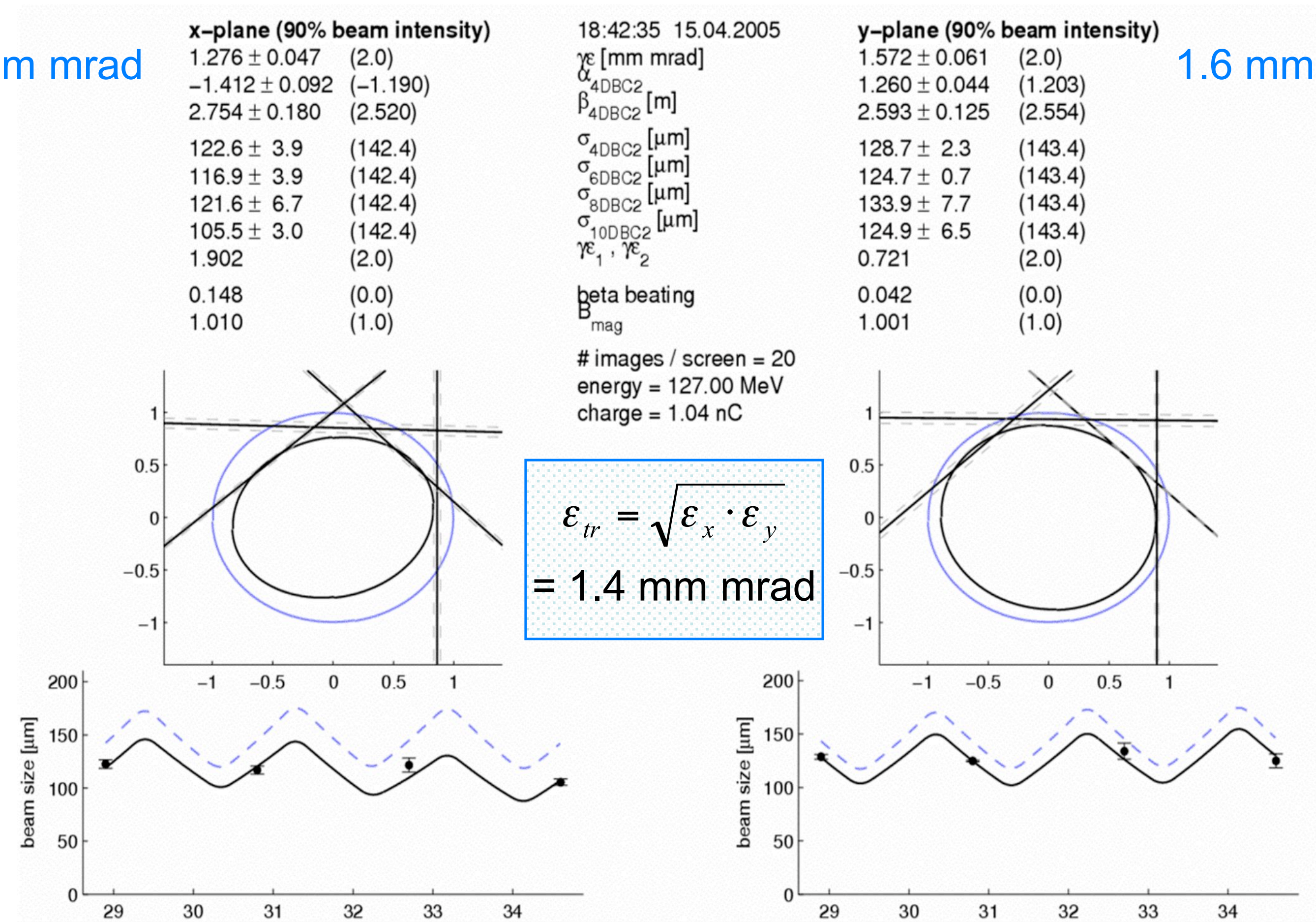
Example of 90% emittance (rms)

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

Horizontal 1 nC Vertical

1.3 mm mrad

1.6 mm mrad



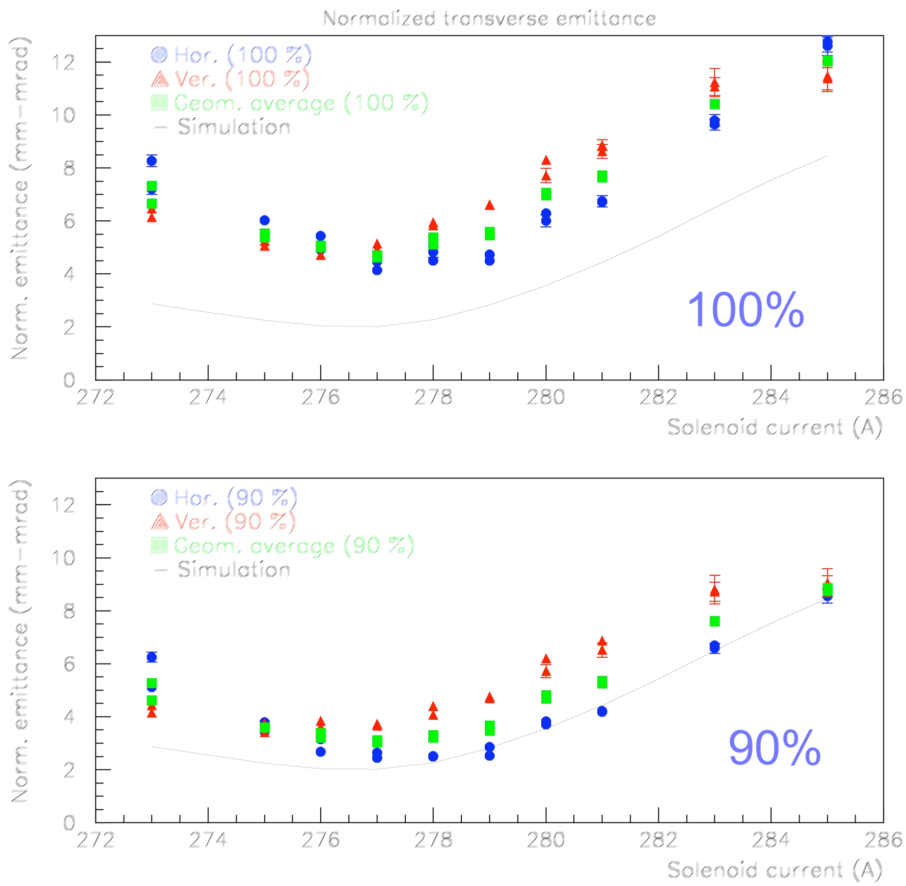
$$\varepsilon_{tr} = \sqrt{\varepsilon_x \cdot \varepsilon_y}$$

= 1.4 mm mrad

Emittance vs. solenoid current

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

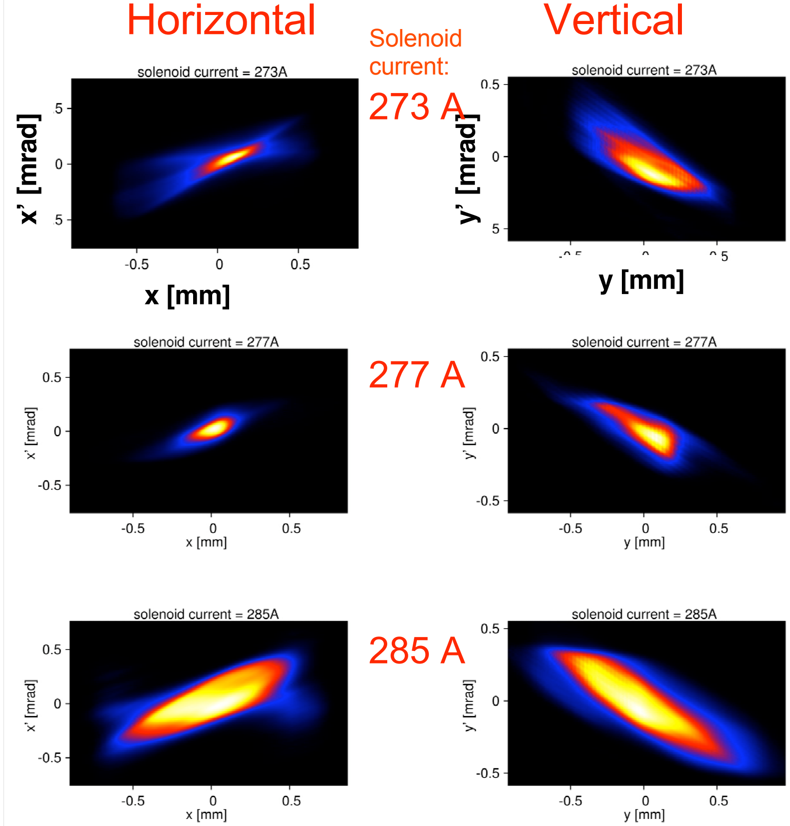
Normalized transverse rms emittance



Reconstructed transverse phase space

Horizontal

Vertical



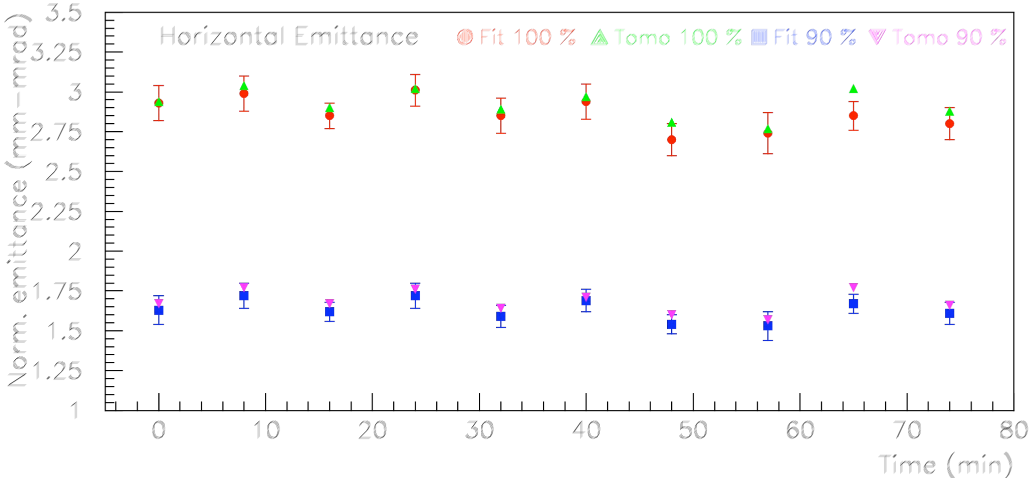
1 nC, 125 MeV

Beam through bunch compressor without compression (on-crest acceleration)
Injector with nominal parameters, but not tuned for minimum emittance

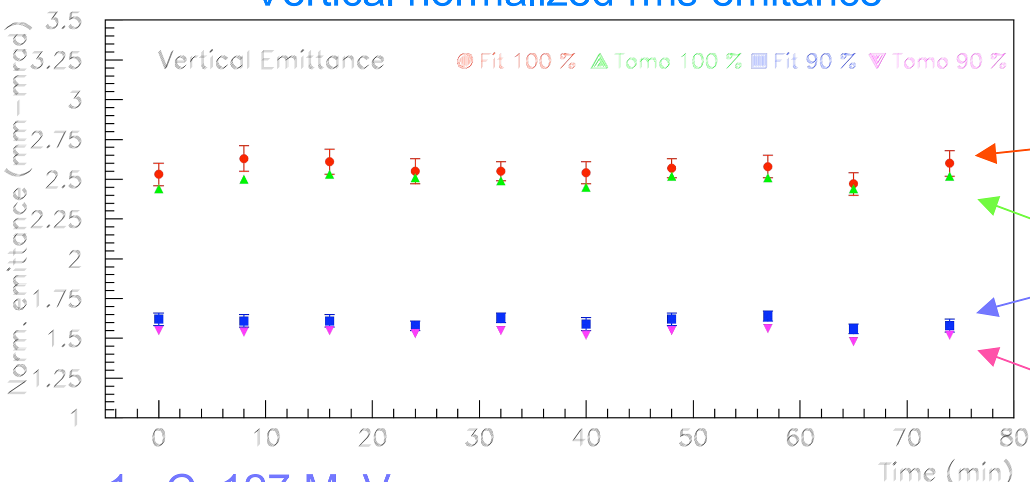
Reproducibility

Emittance measured 10 times during 75 minutes keeping same machine conditions

Horizontal normalized rms emittance



Vertical normalized rms emitance



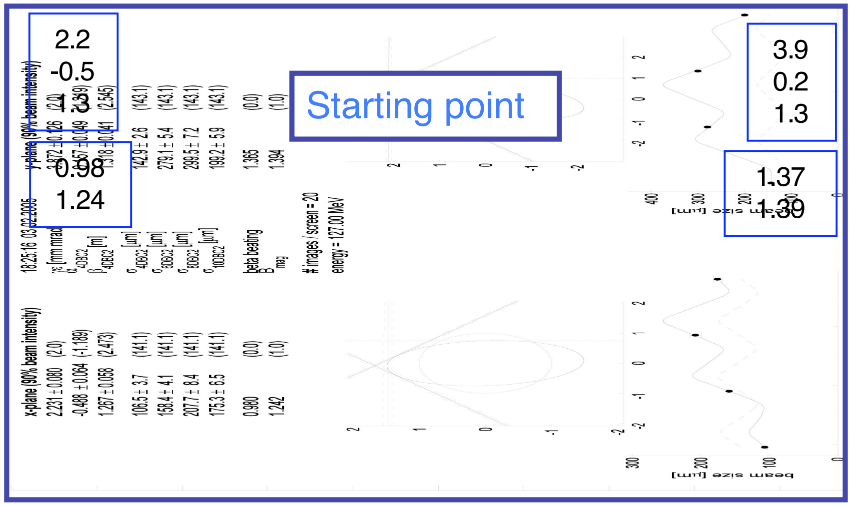
1 nC, 127 MeV

- Results by fitting and tomography agree well
- Jitter (rms) of the emittance
  - ~3.5% in horizontal plane
  - ~2% in vertical plane
  - in agreement with the estimated statistical errors

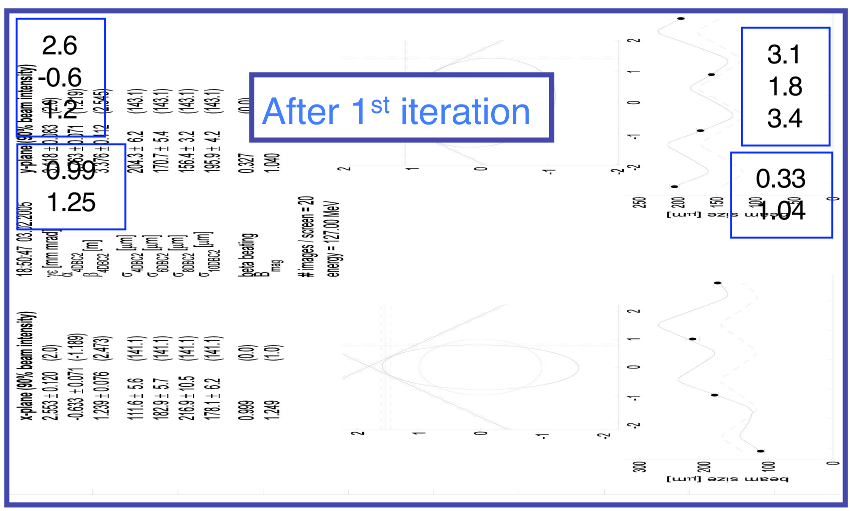
Fitting method, 100% beam intensity
Tomography, 100% beam intensity
Fitting method, 90% beam intensity
Tomography, 90% beam intensity

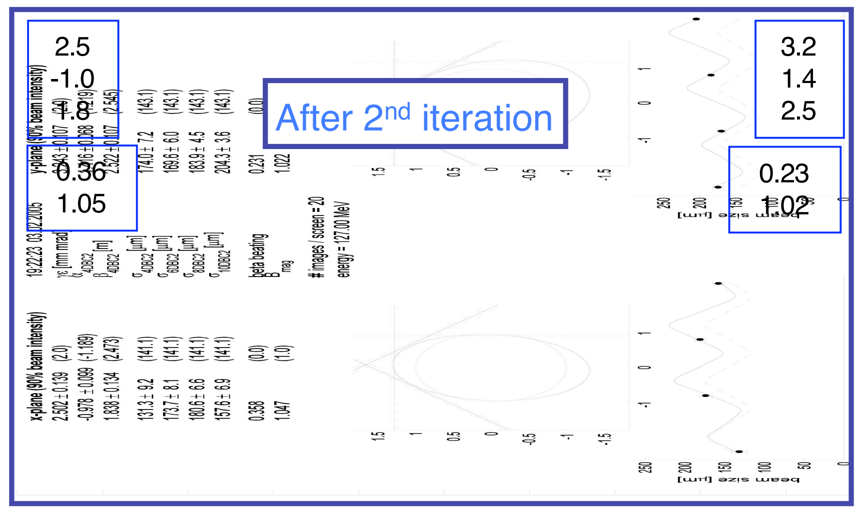
Example of matching

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser



1. Emittance and Twiss Parameters are measured
2. Based on this measurement, new currents in matching section quadrupoles are calculated to provide a better matching
3. Emittance and Twiss parameters are remeasured and matching repeated, if necessary

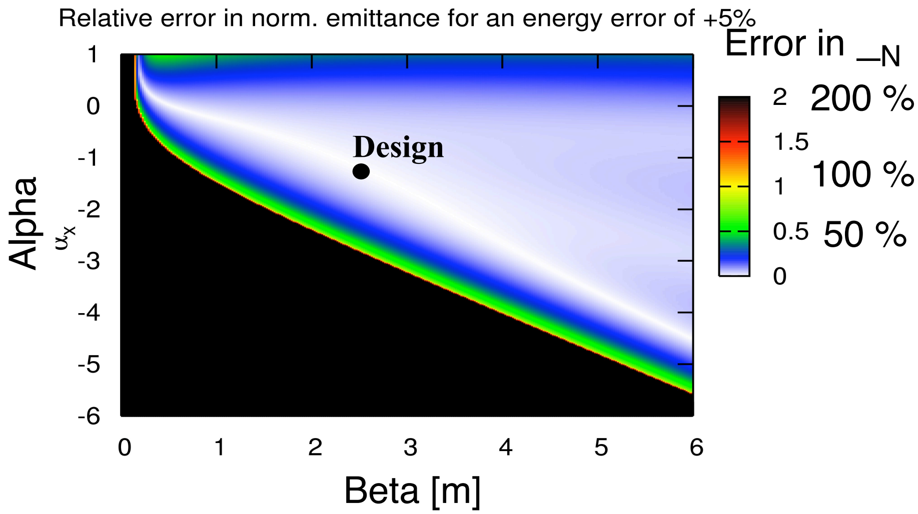




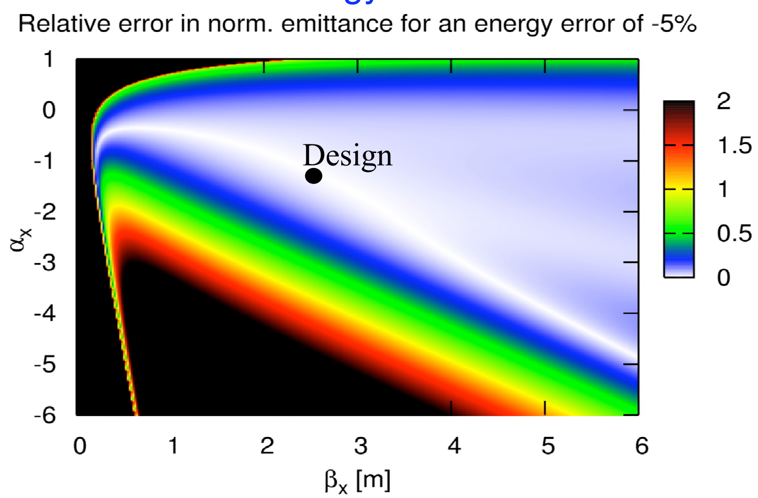
Dependence of error on matching

HELMHOLTZ GEMEINSCHAFT | DESY | VUV-FEL Vacuum-Ultraviolet Free-Electron Laser

Energy +5%



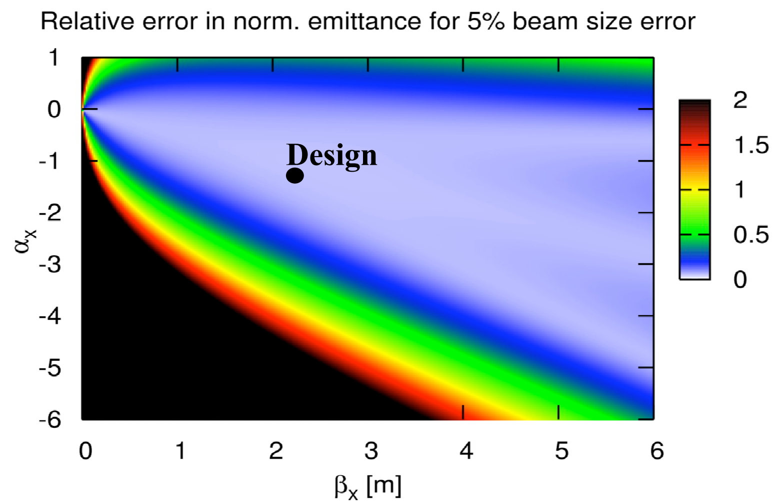
Energy -5%



Relative error in normalized emittance as a function of Twiss parameters:

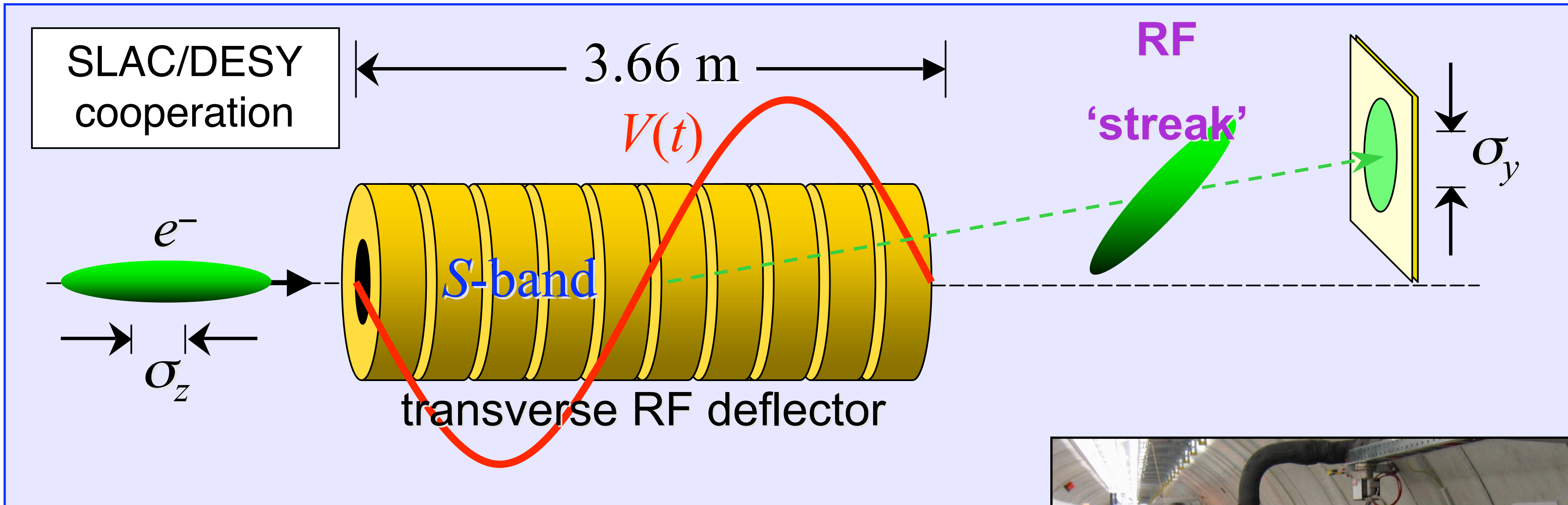
- for +5% and -5% error in the beam energy
- for 5% error in the beam sizes
- Design values (matched optics in the FODO lattice) are indicated

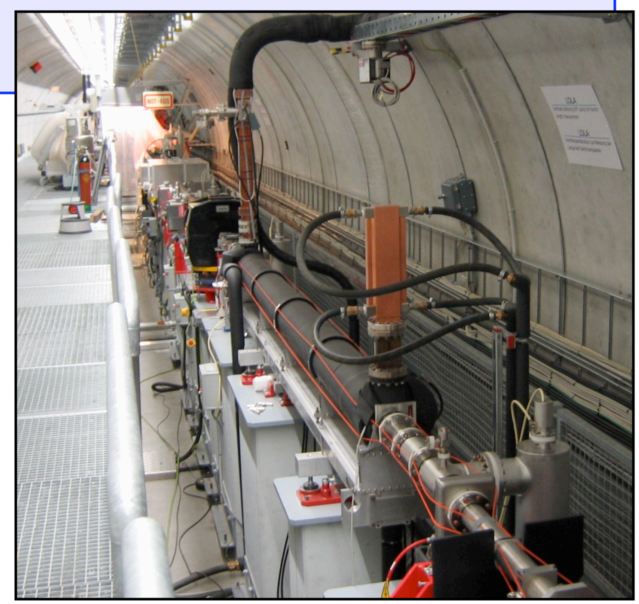
Beam size error 5%



Transverse deflecting cavity (LOLA)

VUV-FEL
Vacuum-Ultraviolet Free-Electron Laser





Disk loaded S-band wave guide structure mounted to VUV-FEL by collaboration between DESY and SLAC.

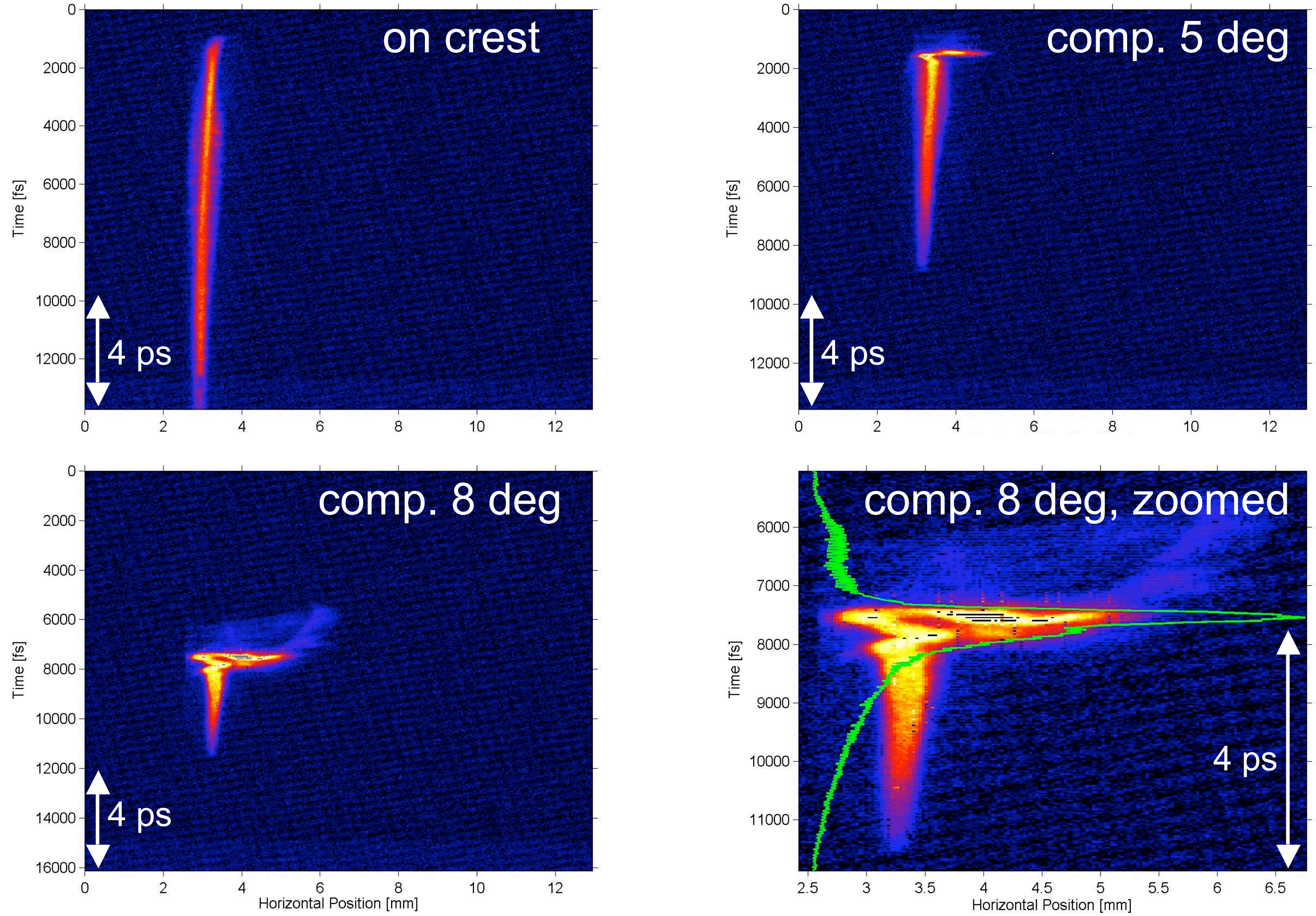
Time varying field deflects the electron beam transversally _ temporal distribution of the electron bunch is transformed into a spatial distribution

"Streaked" beam image is measured on an OTR monitor downstreams. Vertical direction of the image represents the temporal distribution of the bunch.

Examples of LOLA images

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

LOLA images (preliminary) taken with a different phase of the first accelerating module _ different compression by the bunch compressor

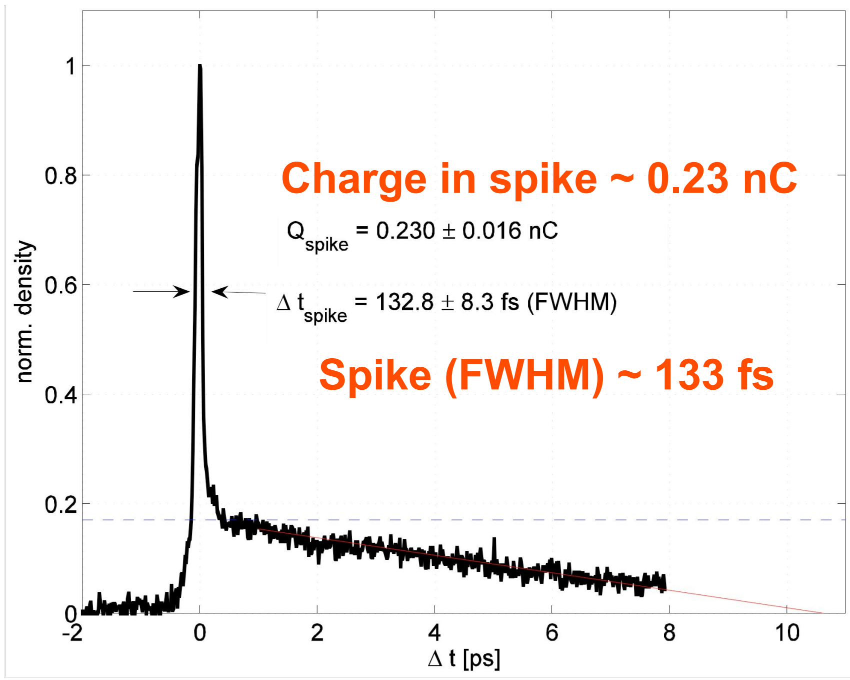


First slice-emittance measurements

VUV-FEL Vacuum-Ultraviolet Free-Electron Laser

- Electron beam streaked by the LOLA cavity and beam image measured at OTR monitor _ vertical direction represents the temporal distribution
- Streak strength of such that the entire beam image is on the OTR screen (not maximum streak _ time resolution limited)
- Quadrupole scan used to determine the emittance
- Off-crest acceleration in the first accelerating module (6.5 deg) _ compressed bunch
- Other accelerating modules with on-crest acceleration

Longitudinal charge distribution

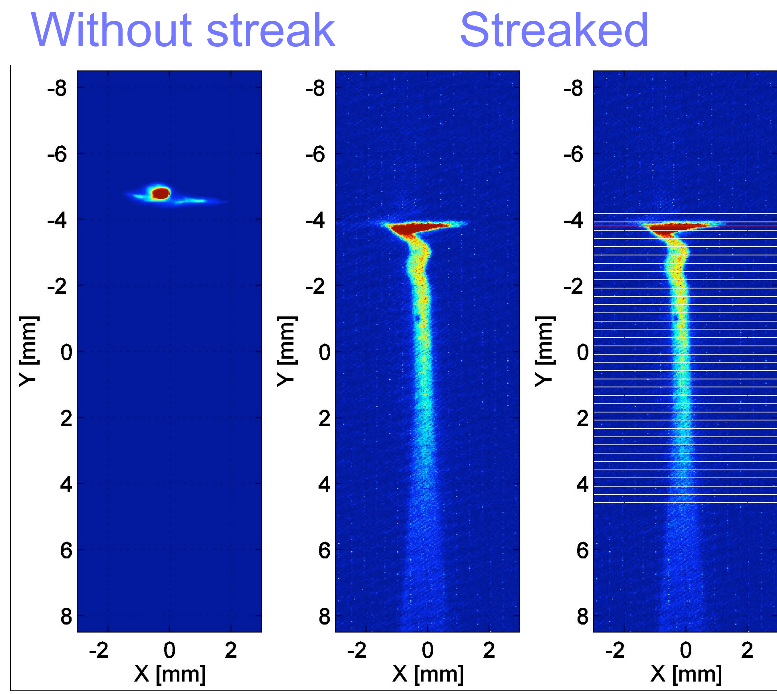


- Beam energy 445 MeV
- Bunch charge 1 nC

Preliminary data analysis (M.Röhrs)

VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

- Beam image divided into horizontal slices with width of 250 um (154 fs)
- Quadrupole scan to determine horizontal emittance and twiss parameters of the entire bunch and a single slice (least square fitting method)
- Scanning quadrupole ~ 40 m upstream of the screen; between an accelerator module and 6 quadrupoles



Reference point: peak of the vertical profile

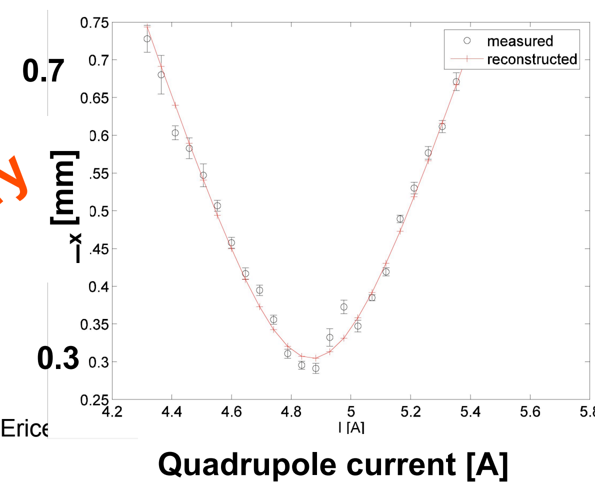
Beam image divided to horzontal slices of 154 fs

Quadrupole scan (entire bunch):

_N ~ 8 mm mrad (100% rms)

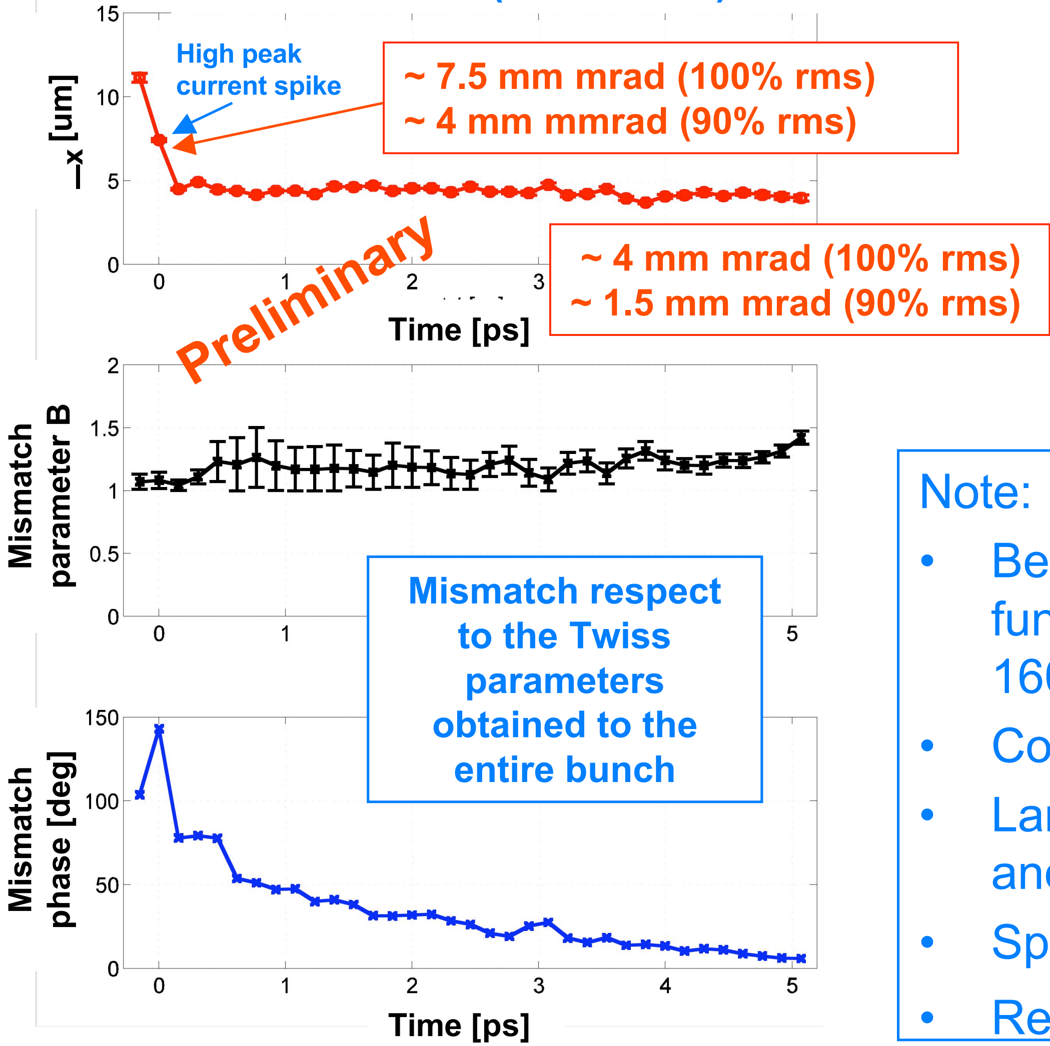
_N ~ 4 mm mrad (90% rms)

Note: compressed bunch



Preliminary results

Normalized horizontal slice emittance (100 % rms)



Systematical error estimated using Monte Carlo simulations taking into account errors in quadrupole gradients and beam energy:

- Systematical error in absolute values of emittance: ~35%
- Systematical error for slice emittance ratios is negligible compared to the statistical errors

Note:

- Beam optics not optimized (large beta function; vertical beam size between 160 um and 340 um)
- Compressed bunch
- Large difference between 100% rms and 90% rms emittances
- Space charge effects not included
- Resolution limitations?

Summary and Outlook

- Measurements of projected emittance at the VUV-FEL
  - routinely at the injector using four-monitor method with OTR monitors; wire scanners available soon
  - before undulator using multi-monitor method with OTR monitors
    - measurements conditions not yet optimized
  - in the undulator using multi-monitor method with wire scanners
  - along the linac at several locations using quadrupole scan
    - time consuming, rarely used
- First measurements and preliminary data-analysis of slice-emittance using transverse deflecting cavity and quadrupole scan done. Next steps:
  - measurements with an uncompressed bunch
  - better optimized beam optics
  - quadrupole scan using two or more quads (tomography)
  - improvements of data-analysis