ERL2005 Jefferson Lab
WG4

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Measurements of Transverse Emittance at the TTF VUV-FEL

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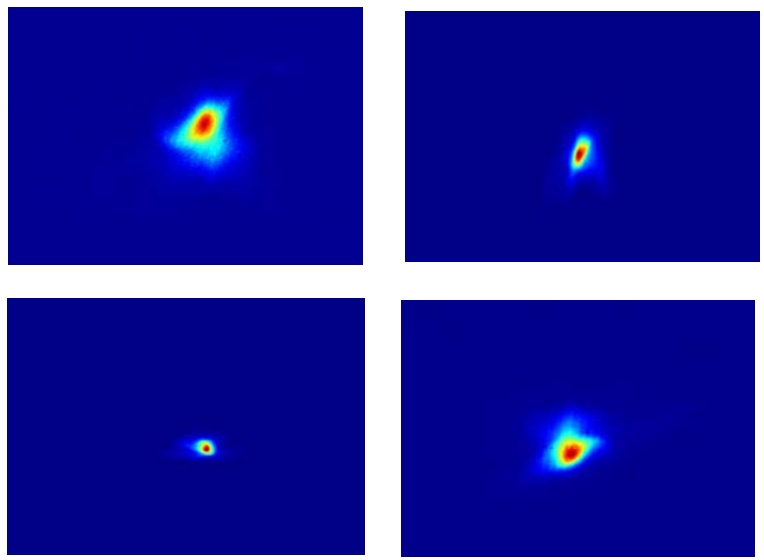
- Methods and devices
- Measurements
- Analysis and results



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Definition of Emittance

The transverse rms emittance is defined in terms of x and x' as

$$\epsilon = \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

Twiss parameters are related to the second moments of the beam distribution as

$$\boxed{\begin{aligned} < x^2 >_s &= \beta(s)\epsilon \\ < xx' >_s &= -\alpha(s)\epsilon \\ < x'^2 >_s &= \gamma(s)\epsilon \end{aligned}}$$

Emittance can be written as

$$\boxed{\epsilon = \sqrt{(\beta\epsilon)(\gamma\epsilon) - (\alpha\epsilon)^2}}$$

Normalized emittance:

$$\boxed{\varepsilon_N = \gamma_{rel}\varepsilon}$$

Methods and Devices

- Methods to measure the emittance
  - Four or multi monitor method:
    Measure beam size at several locations with fixed beam optics
  - Quadrupole scan:
    Measure beam size at one location with different settings of one or several quadrupole upstreams
- What we do at TTF:
  we have two sections with four screens embedded in a FODO lattice
  - We use optical transistion radiation (OTR) to measure the beam size
  - Wirescanners are mounted together with the screens, however, the commissioning has not been finished yet
  - We usually do not do quadrupole scans anymore (too time consuming)

4 screen method: Calculation Principle

Beam size

Transport matrix elements from point 0 to point i

$$r_i^2 = m_{11,i}^2(\beta_0\epsilon) - 2m_{11,i}m_{12,i}(\alpha_0\epsilon) + m_{12,i}^2(\gamma_0\epsilon)$$

In Matrix form:

$$\begin{pmatrix} r_1^2 \\ r_2^2 \\ \dots \\ r_n^2 \end{pmatrix} = \begin{pmatrix} m_{11,1}^2 & -2m_{11,1}m_{12,1} & m_{12,1}^2 \\ m_{11,2}^2 & -2m_{11,2}m_{12,2} & m_{12,2}^2 \\ \dots & & \\ m_{11,n}^2 & -2m_{11,n}m_{12,n} & m_{12,n}^2 \end{pmatrix} \begin{pmatrix} \beta\epsilon \\ \alpha\epsilon \\ \gamma\epsilon \end{pmatrix}$$

3 unknown parameters

Emittance $\epsilon = \sqrt{(\beta\epsilon)(\gamma\epsilon) - (\alpha\epsilon)^2}$

We have more than 3 measurements -> a fit to determine (βε), (γε), and (αε)

Chi-Square Fit

The chi-square method provides a way to determine a parameter set, which 'most-likely' fits the data to a given function.

Let's have n measurements of variable y_i at point x_i with an error of σ_i. We want to fit a function f to the data; a_j are the m unknown parameters, n > m. The chi-square method states that the best values of a_js are those which minimize the sum

$$\chi^2 = \sum_{i=1}^{n} \left[\frac{y_i - f(x_i; a_j)}{\sigma_i} \right]^2$$

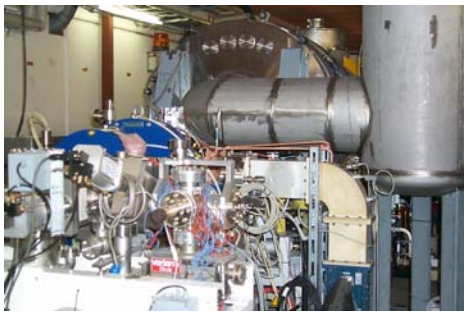
In our case the function f is the square of the beam size :

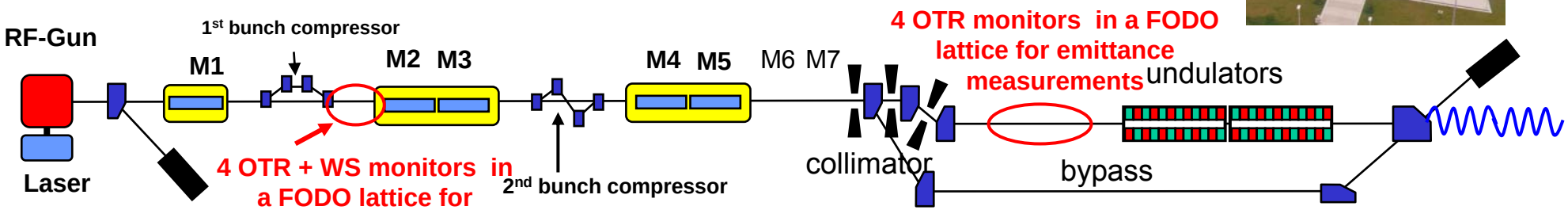
$$f(x_i; a_j) = r^2 = m_{11}^2(\epsilon\beta) - 2m_{11}m_{12}(\epsilon\alpha) + m_{12}^2(\epsilon\gamma)$$

Parameters to fit: a_1 a_2 a_3

Problem: we have only 4 measurement points to determine 3 parameters. Method sensitive to the beam size errors (weight in the fit), especially when the errors differ from point to point.

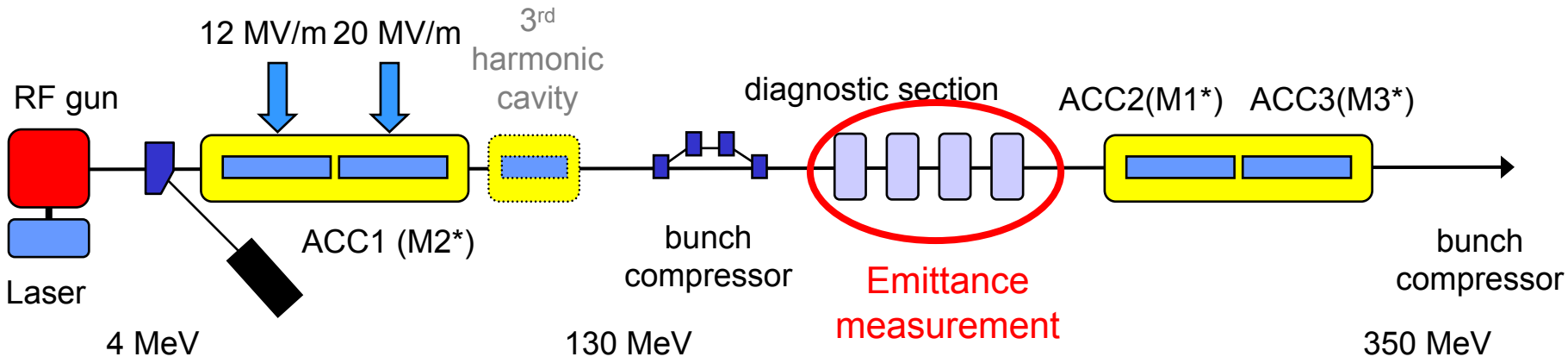
TTF Linac





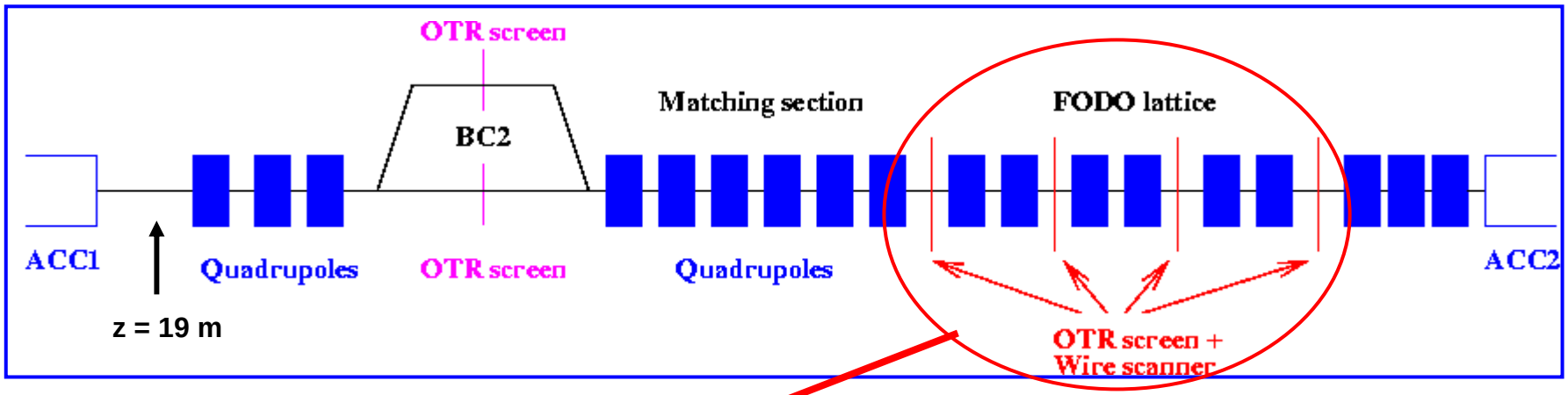
250 m

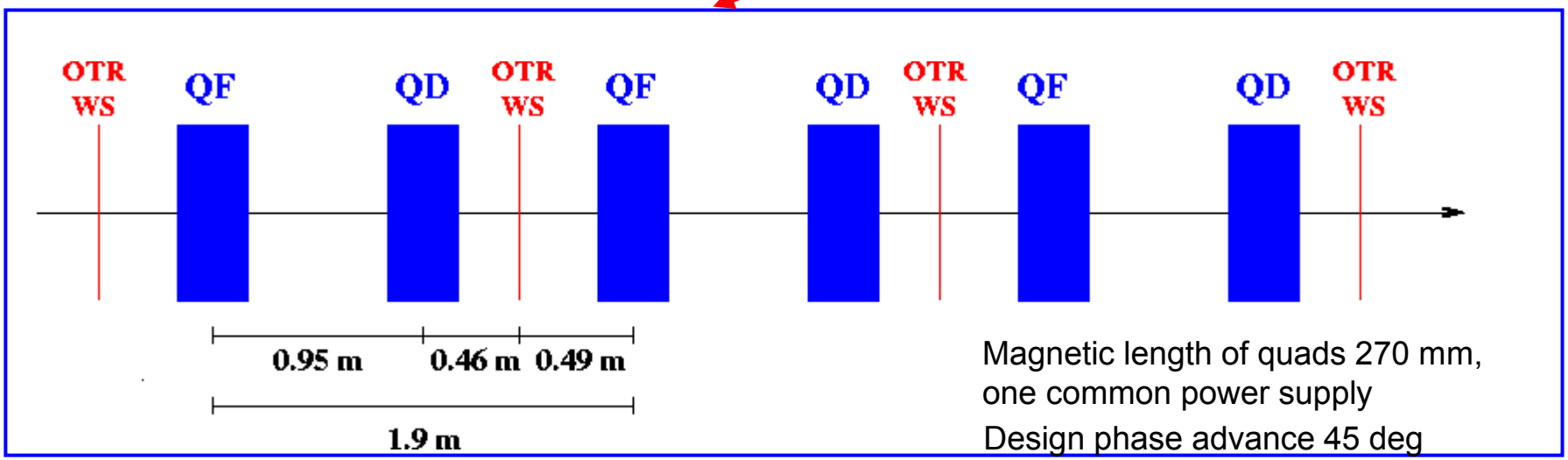
Injector Layout



- Standards TESLA superconducting accelerating modules (eight 9-cell 1.3 GHz structures)
  - Booster: first 4 cavities operated with 12 MV/m (reduce space charge)
  - further acceleration to an energy of 127 MeV for first bunch compression, to 350 MeV for 2nd compression
- Laser is an upgrade of the TTF1 laser
- Cathodes: Cs_2Te, load lock system from TTF1
- 3rd harmonic cavity not yet installed, required for lasing with short wavelength

Schematic of the Diagnostics Section



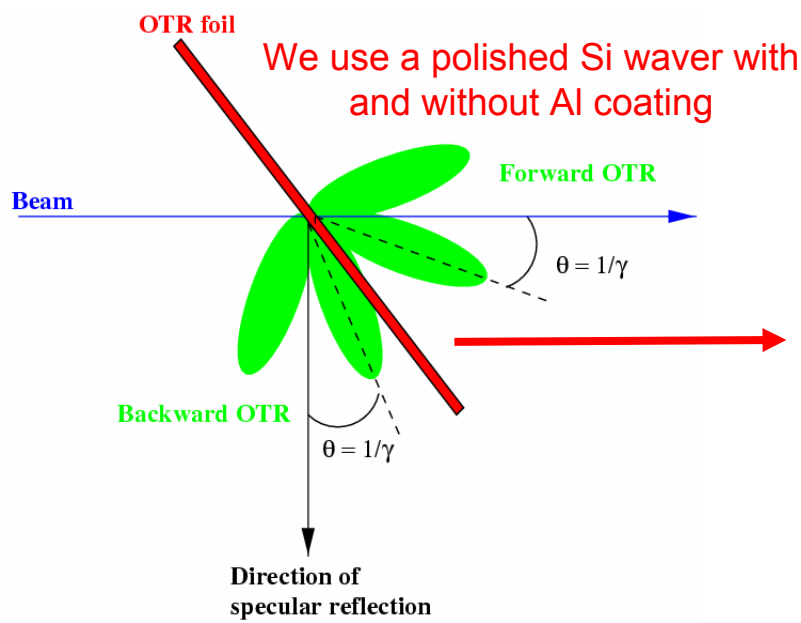


Magnetic length of quads 270 mm, one common power supply

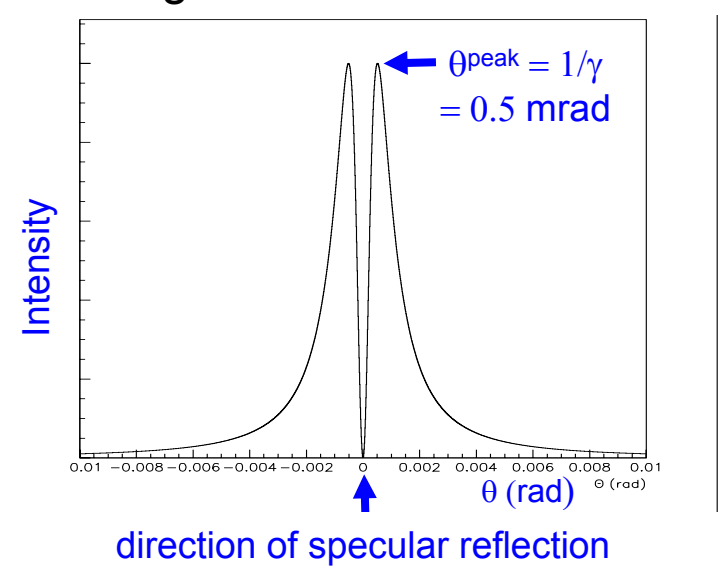
Design phase advance 45 deg

Optical Transition Radiation (OTR)

- Transition radiation is electromagnetic radiation emitted when a charged particle crosses a boundary between two media with different optical properties
- Visible part of the radiation is called Optical Transition Radiation (OTR)
- Backward OTR, produced by a mirror like surface, is usually used to image the beam with an optical system
- Fast single shot measurement of beam shape, linear response
- However, high charge densities may destroy the radiator



OTR angular distribution at E = 1 GeV

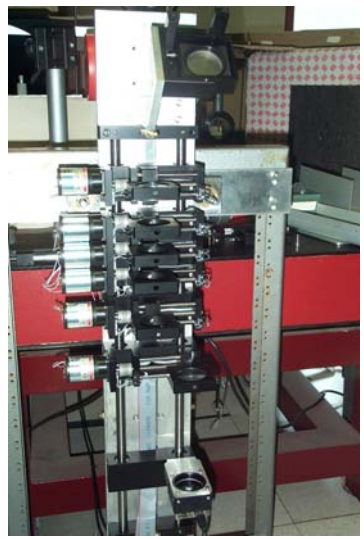


Standard OTR Monitor at TTF

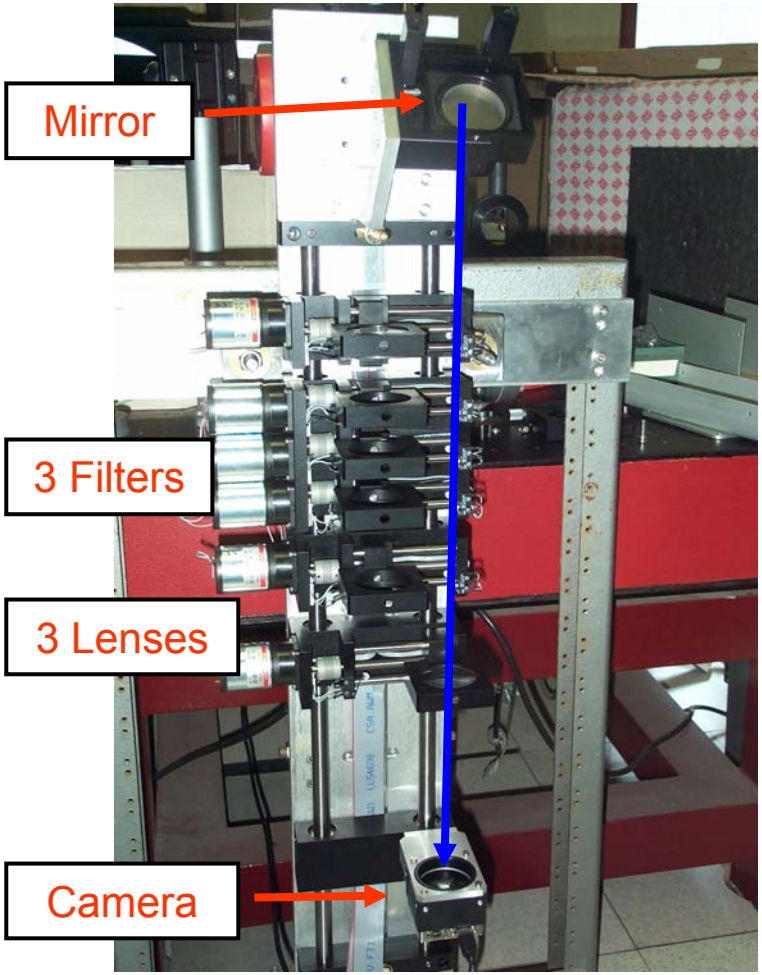
The TTF OTR system has been designed and constructed in collaboration between DESY, INFN-LNF, and INFN-Roma2

We have:

- Special designed vacuum chamber
- Stepper motor mover + motor driver
- Screen + screen holder
- Optical set-up to image the beam
- Support structures for vacuum chambers and optical set-ups
- Read-out electronics + software
- Control and acquisition software
- User interface
- 7 of the 18 standard OTR monitors are combined with a wirescanner

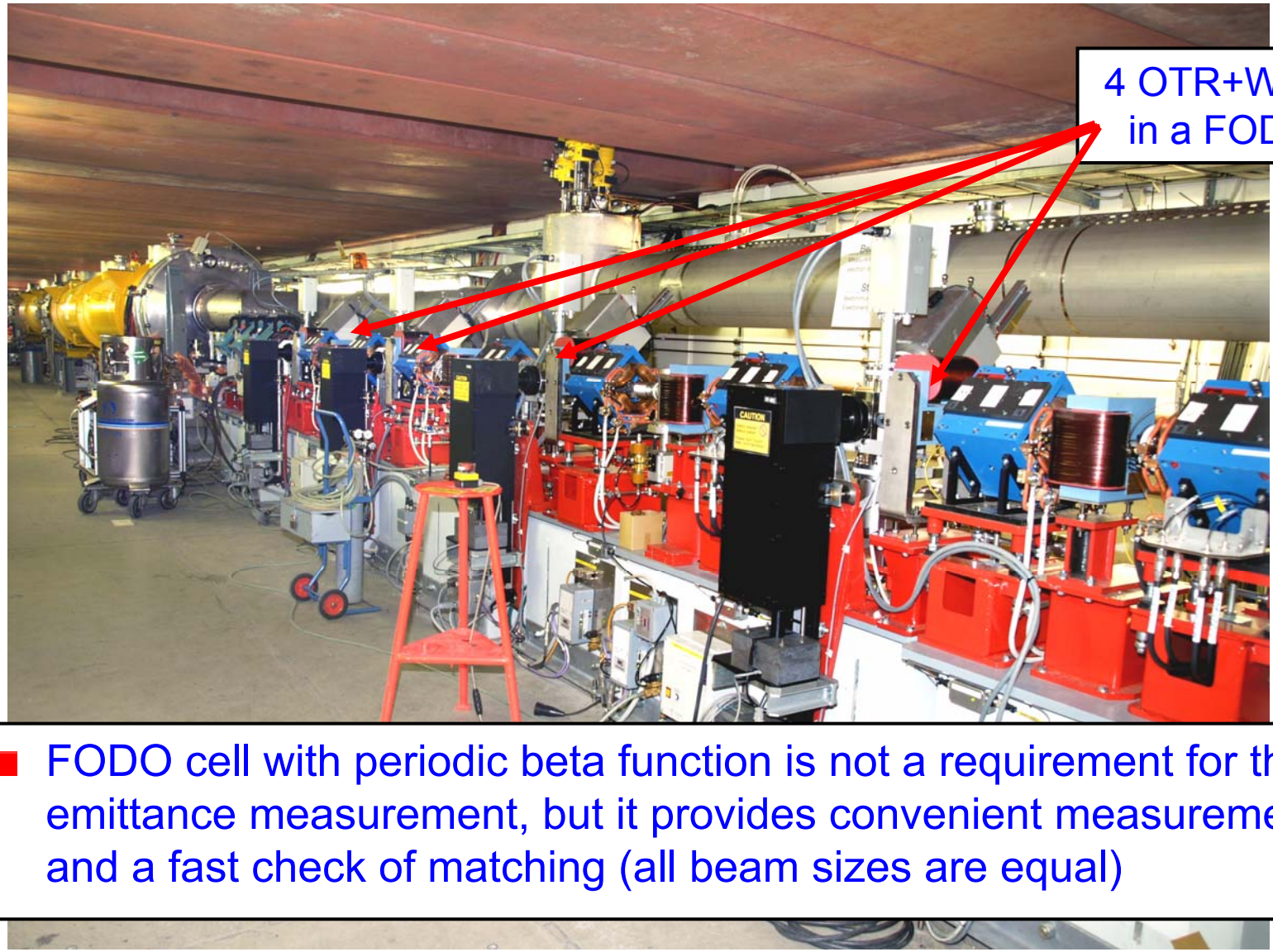


Standard Optical Set-Up



- Lenses and filters are remotely controlled
- 3 achromat doublets providing nominal magnifications of 1.0, 0.39, and 0.25
- 3 neutral density filters
- Basler A301f digital camera with firewire (IEEE1394) interface
- Small industrial PC computers in the tunnel, an ‘image server’ PC in the control room
- Resolution of the system ~10 µm (with magnification of 1.0)

Emittance Measurement Setup Injector

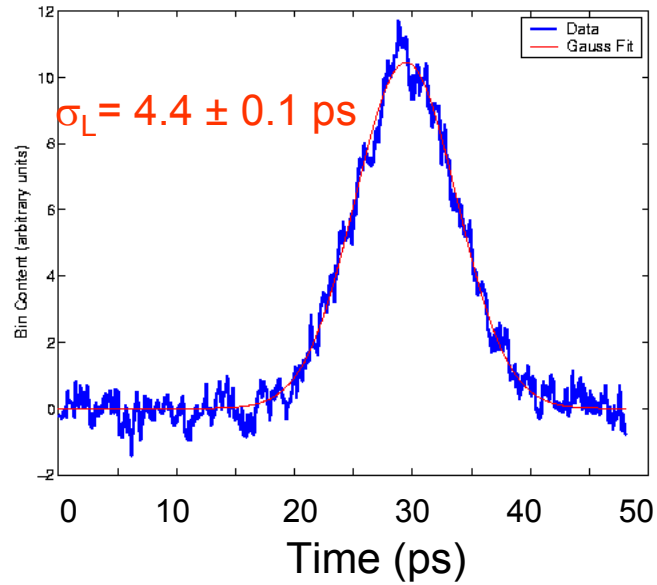


- FODO cell with periodic beta function is not a requirement for the emittance measurement, but it provides convenient measurements and a fast check of matching (all beam sizes are equal)

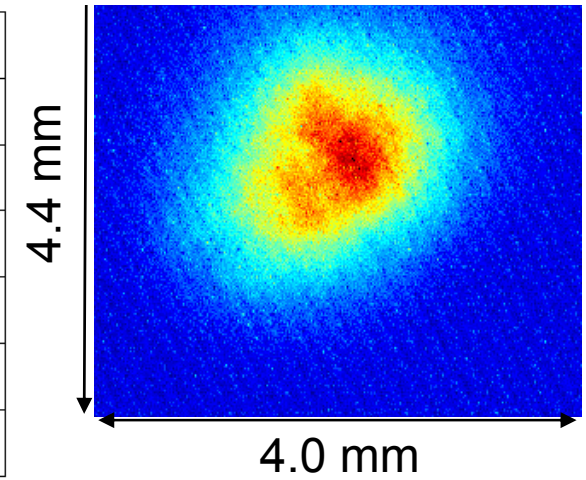
Standard Injector Settings

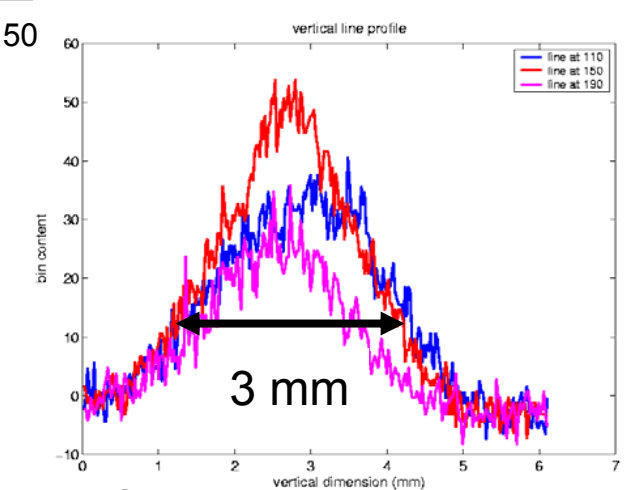
- Charge 1 nC, 1 bunch
- Phase laser/gun RF 38 dg from zero crossing
- RF power 3.2 MW
- Solenoid 273 to 285 A
- Bucking coil 20 A (zero magnetic field on cathode)
- Beam energy 127 MeV
- Laser transverse size Ø=3 mm
- Laser with longitudinal gaussian shape σ_L = 4 ps

Laser longitudinal profile



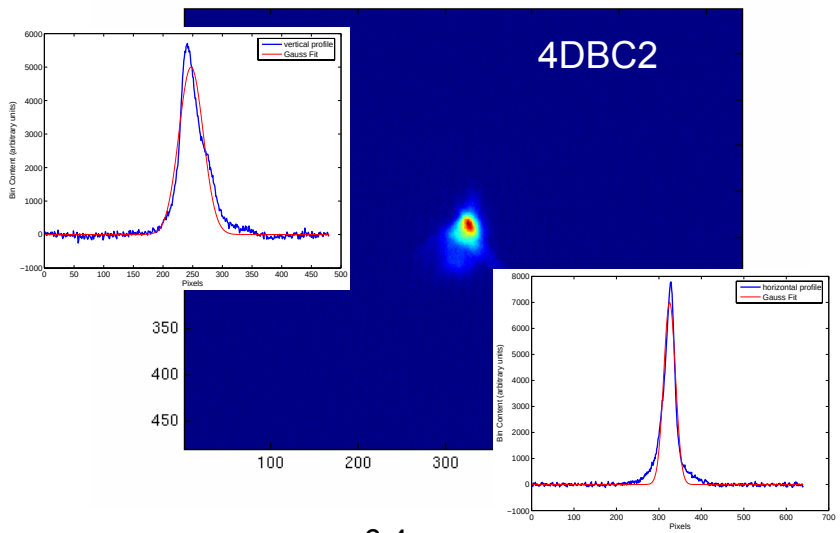
Laser transverse profile

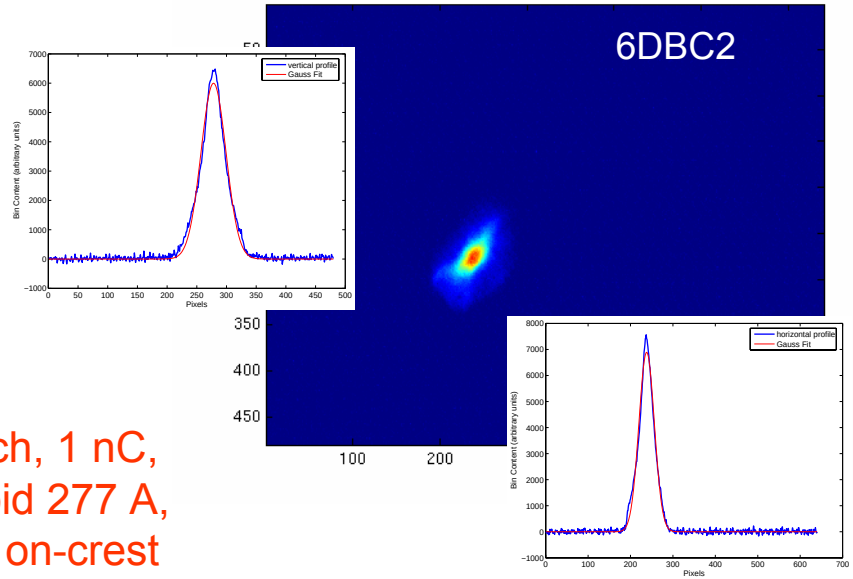




Shown are single pixel slices

Example of beam images (matched)

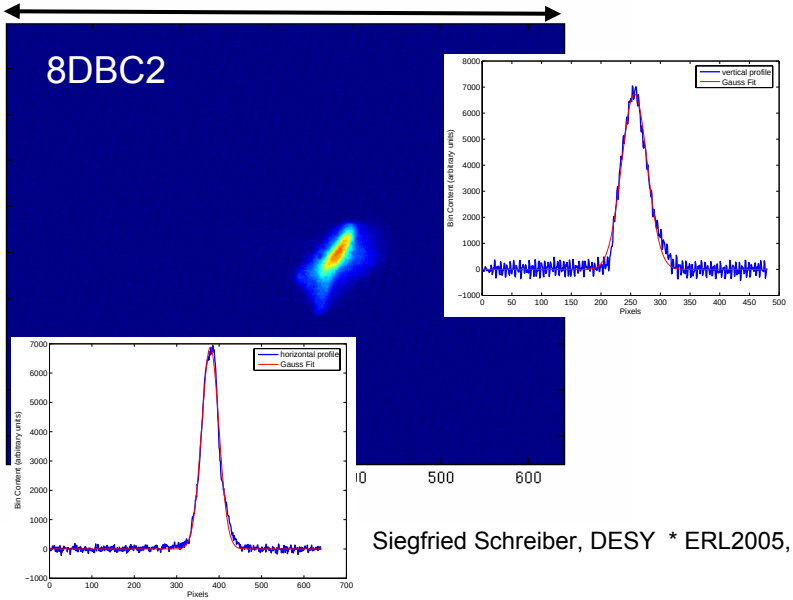


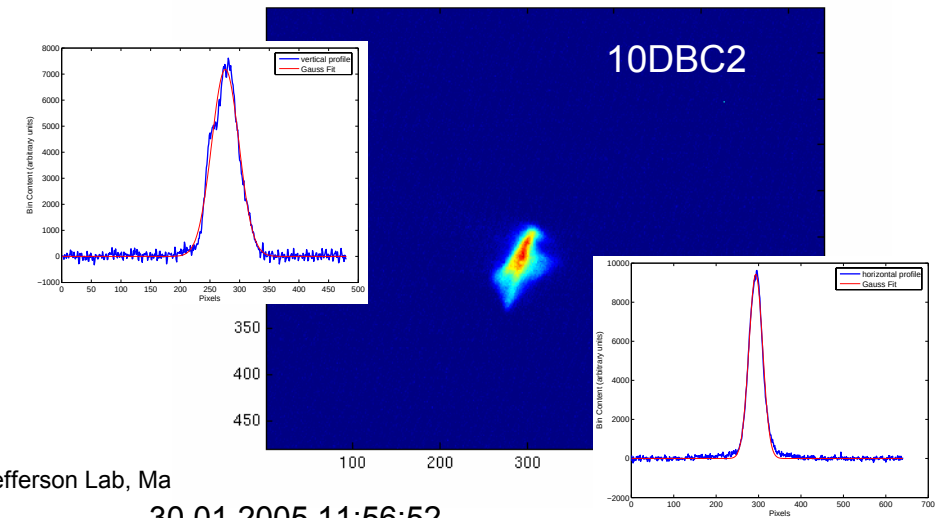


1 bunch, 1 nC,
Solenoid 277 A,
ACC1 on-crest

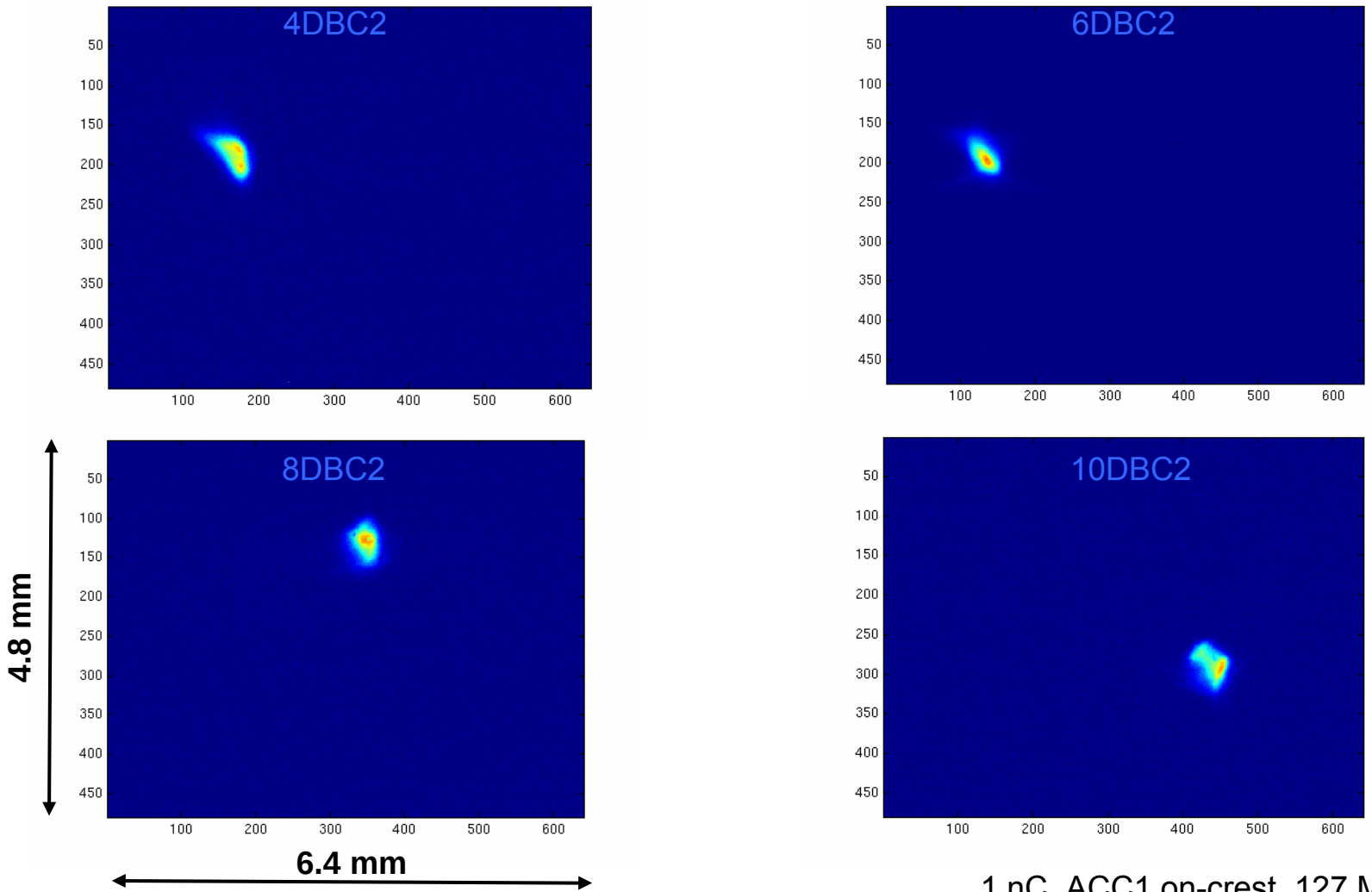
6.4 mm

4.8 mm





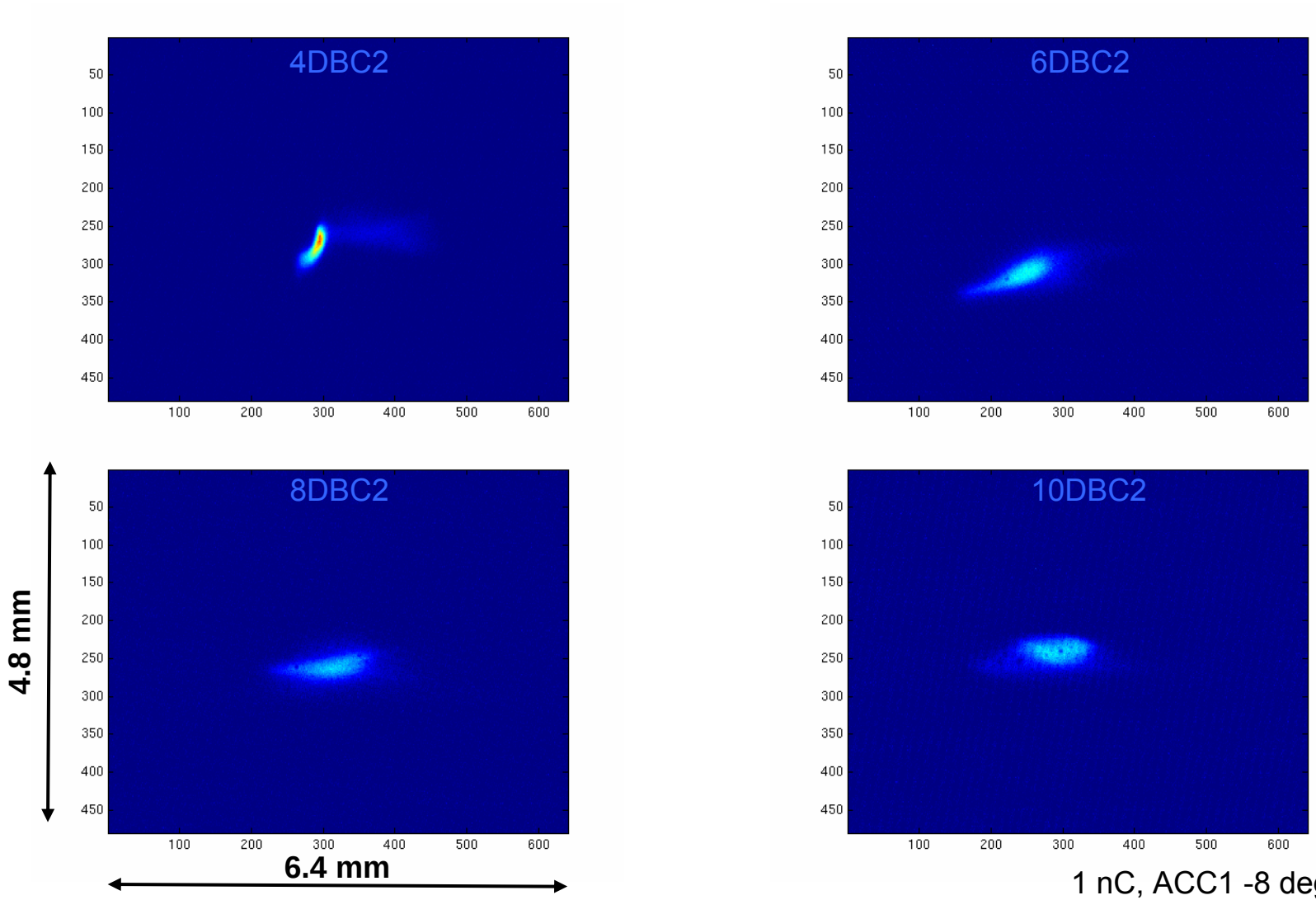
Example of beam images, ACC1 on-crest



1 nC, ACC1 on-crest, 127 MeV

06.02.2005 11:09:18

Example of beam images: ACC1 off-crest



1 nC, ACC1 -8 deg off-crest

06.02.2005 14:51:16

Image Analysis

- Simulations usually use the true rms value of the projected beam distribution – this is easy in the simulation, but difficult for measured images
- We need to estimate the rms beam size as good as possible
- The 2D distribution is projected onto the horizontal and vertical axis
- For a gaussian shaped beam without halo or other disturbing effects, a gaussian fit to the profiles gives a good estimate of the rms beam size
- However, typically the beam has an irregular shape, there is no reason why it should be gaussian in the first place
- A true rms calculation is very sensitive to offset errors, and a halo leads to unrealistic large rms values: the rms must be calculated for the ‘core’ of the beam
- The ‘core’ is usually defined using a cut on the intensity, 90% is commonly used

Image Analysis

For each of the four screens:

1. 20 to 50 beam images and background images are recorded
2. Average background is calculated and substracted
3. Wavelet filter (from Matlab package) used to remove noise from images
4. Region of interest (ROI) automatically searched
    1. Starting point from maximum intensity of profiles
    2. Calculate rms beam size and center of mass
    3. New ROI selected as 5 x calculated rms beam size
    4. Calculate new rms size and center of mass -> new ROI
    5. Repeat until converges -> final ROI
5. 90 % of total intensity determined (by cutting away the low intensity part of the image)
6. Horizontal and vertical projections made for 100 % and 90 % intensity cut
7. rms beam sizes of the projections is calculated

Preliminary Data Analysis

- In the preliminary on-line data analysis, we use the rms values (both, the 100 % and 90 % intensitiy cut)
- Measurement errors include only the standard deviation of the beam sizes of all images taken
- No systematic errors taken into account for the on-line analysis (eg. errors in energy, calibration, magnet quadrupole fields)
  - !! Especially if the beam has not been matched to the FODO lattice, the error in energy may lead to significant errors in emittance (% range)
  - !! Therefore, in case of scans, the beam has been rematched for each data point

Example of emittance measurement

90 % cut

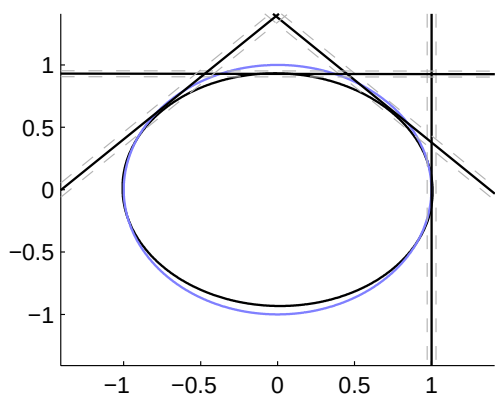
Preliminary

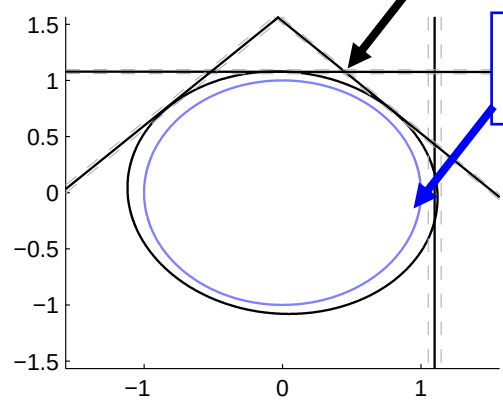
x−plane (90% beam intensity)		11:09:18 06.02.2005	y−plane (90% beam intensity)	
1.880 ± 0.060	(2.0)	$\gamma\varepsilon$ [mm mrad]	2.418 ± 0.055	(2.0)
−1.270 ± 0.075	(−1.189)	α_{4DBC2}	1.305 ± 0.056	(1.219)
2.673 ± 0.101	(2.473)	β_{4DBC2} [m]	2.641 ± 0.091	(2.546)
141.2 ± 4.0	(141.1)	σ_{4DBC2} [μm]	157.3 ± 6.7	(143.1)
137.6 ± 5.4	(141.1)	σ_{6DBC2} [μm]	154.7 ± 2.4	(143.1)
130.9 ± 3.4	(141.1)	σ_{8DBC2} [μm]	154.2 ± 2.5	(143.1)
140.0 ± 5.7	(141.1)	σ_{10DBC2} [μm]	161.5 ± 3.6	(143.1)
2.994	(2.0)	$\gamma\varepsilon_1$, $\gamma\varepsilon_2$	0.987	(2.0)
0.081	(0.0)	beta beating	0.042	(0.0)
1.003	(1.0)	B_{mag}	1.001	(1.0)

# images / screen = 20
energy = 127.00 MeV
charge = 1.01 nC

measured

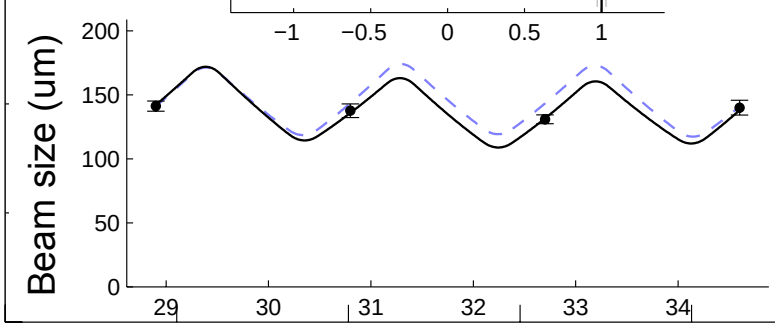
Expected if matched

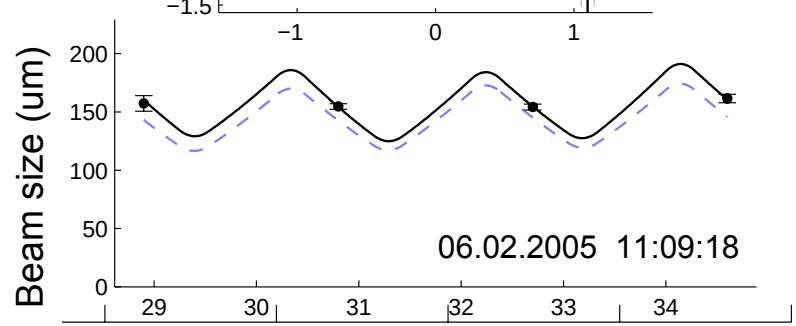




ACC1 on-crest, 127 MeV, 1 nC

Well matched beam in FODO lattice

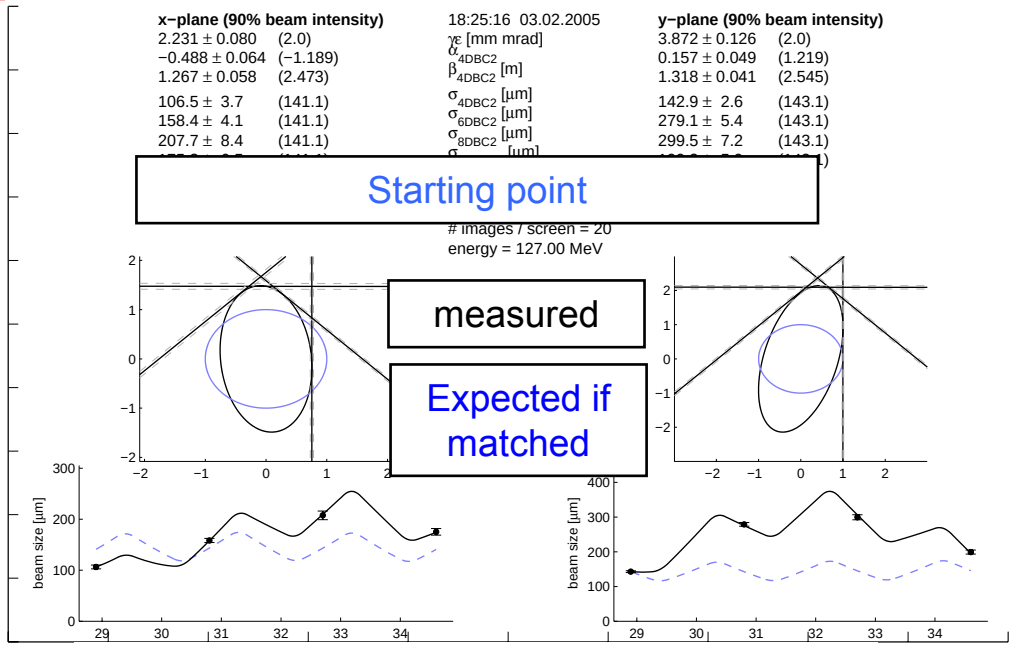


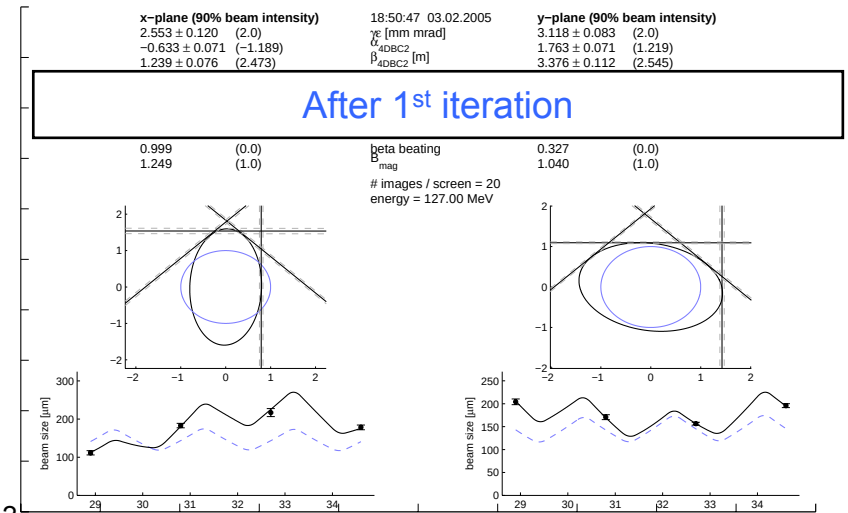


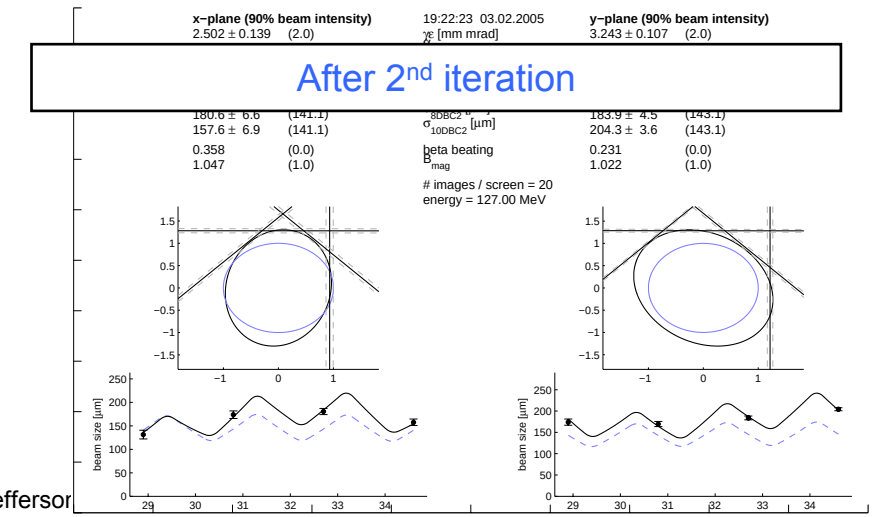
Example of Matching Proceedure

Poceedure:

1. Emittance and Twiss parameters measured
2. Based this measurement, new quadrupole currents are calculated providing better matching
3. Emittance and Twiss parameters remeasured and matching repeated, if necessary

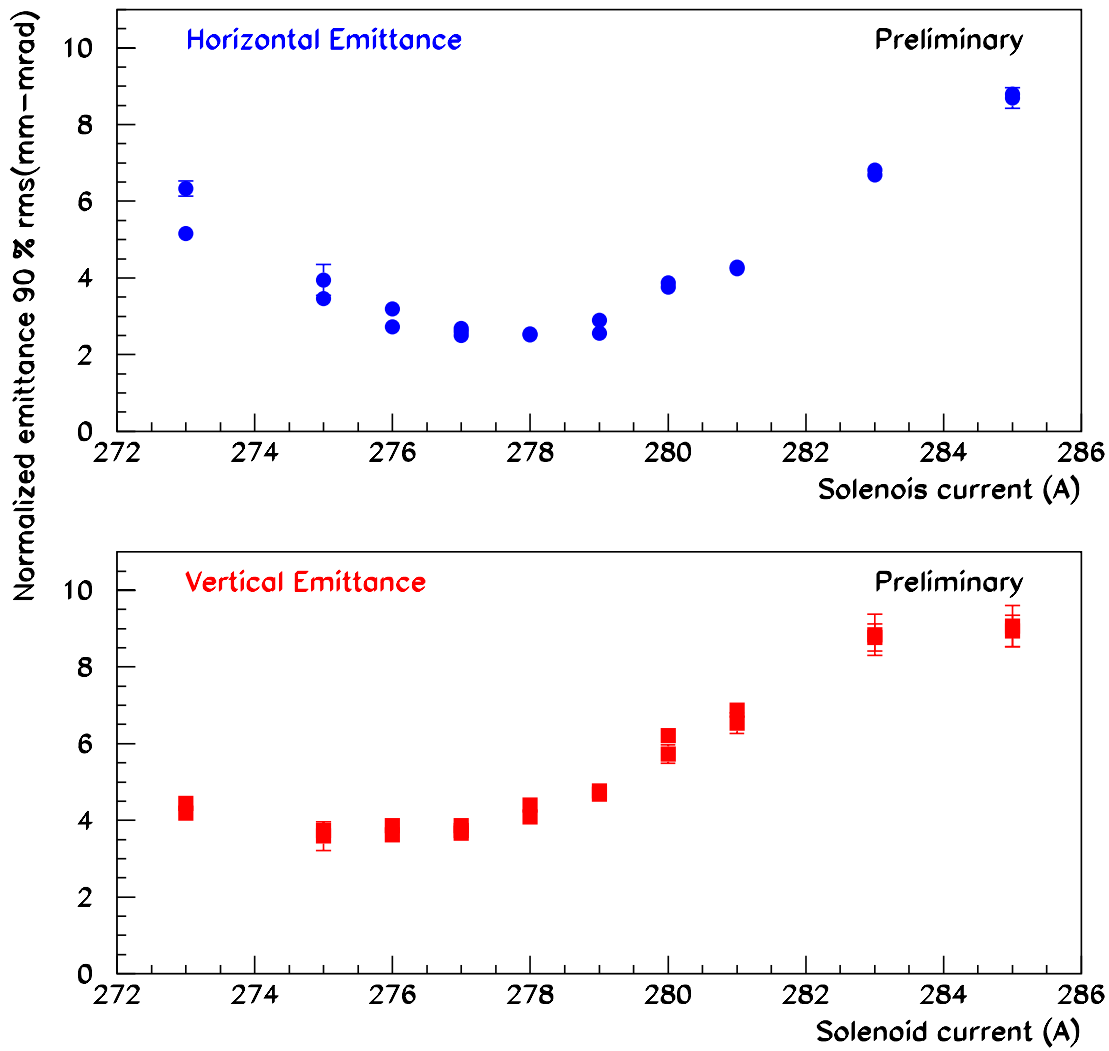






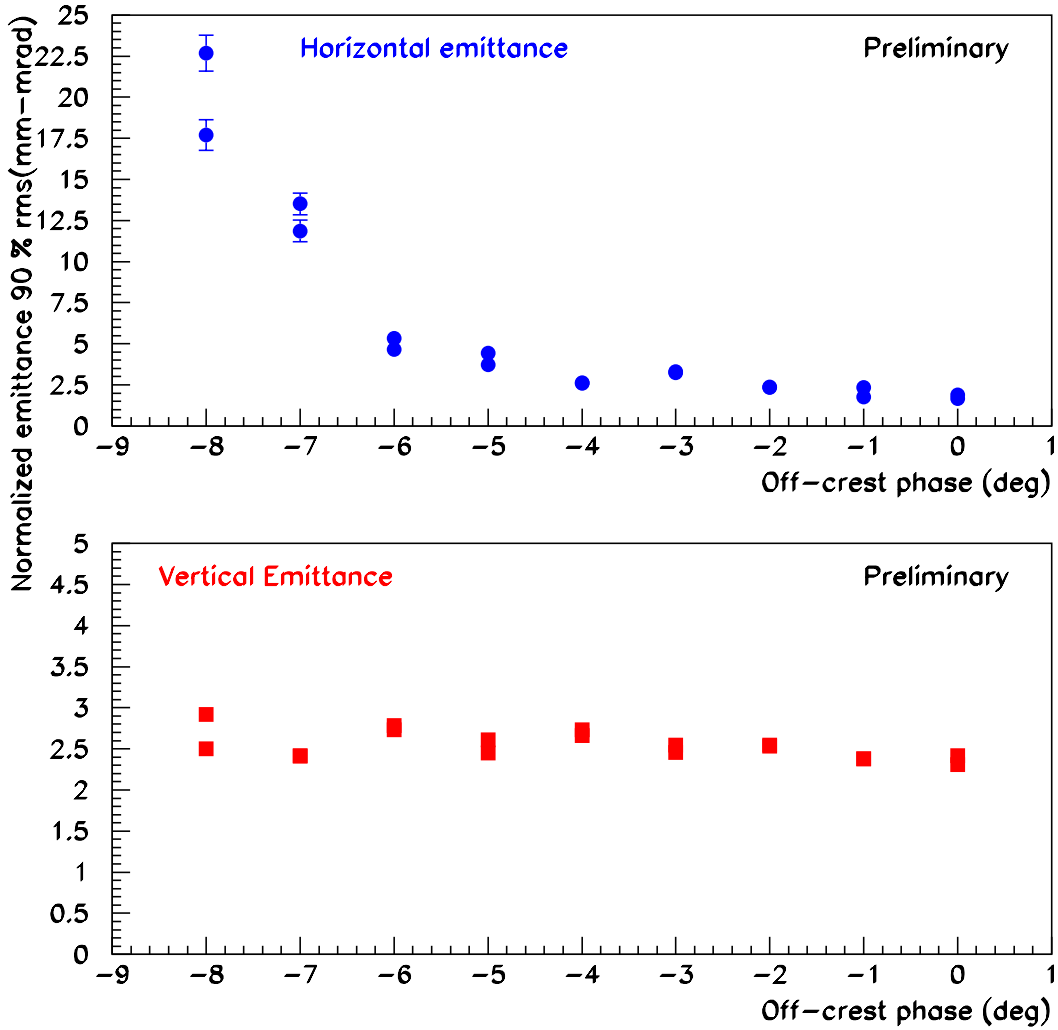
Emittance vs. solenoid current

- RF gun solenoid scan: for the correct solenoidal field, the space charge induced emittance growth is compensated (Carlsten scheme)
- 1 bunch, 1 nC, 125 MeV
- Magnetic field on cathode compensated (bucking 20 A)
- Beam through chicane, but with on crest acceleration (no bunch compression)
- Spot sizes are estimated calculating the rms from 90% intensity cut



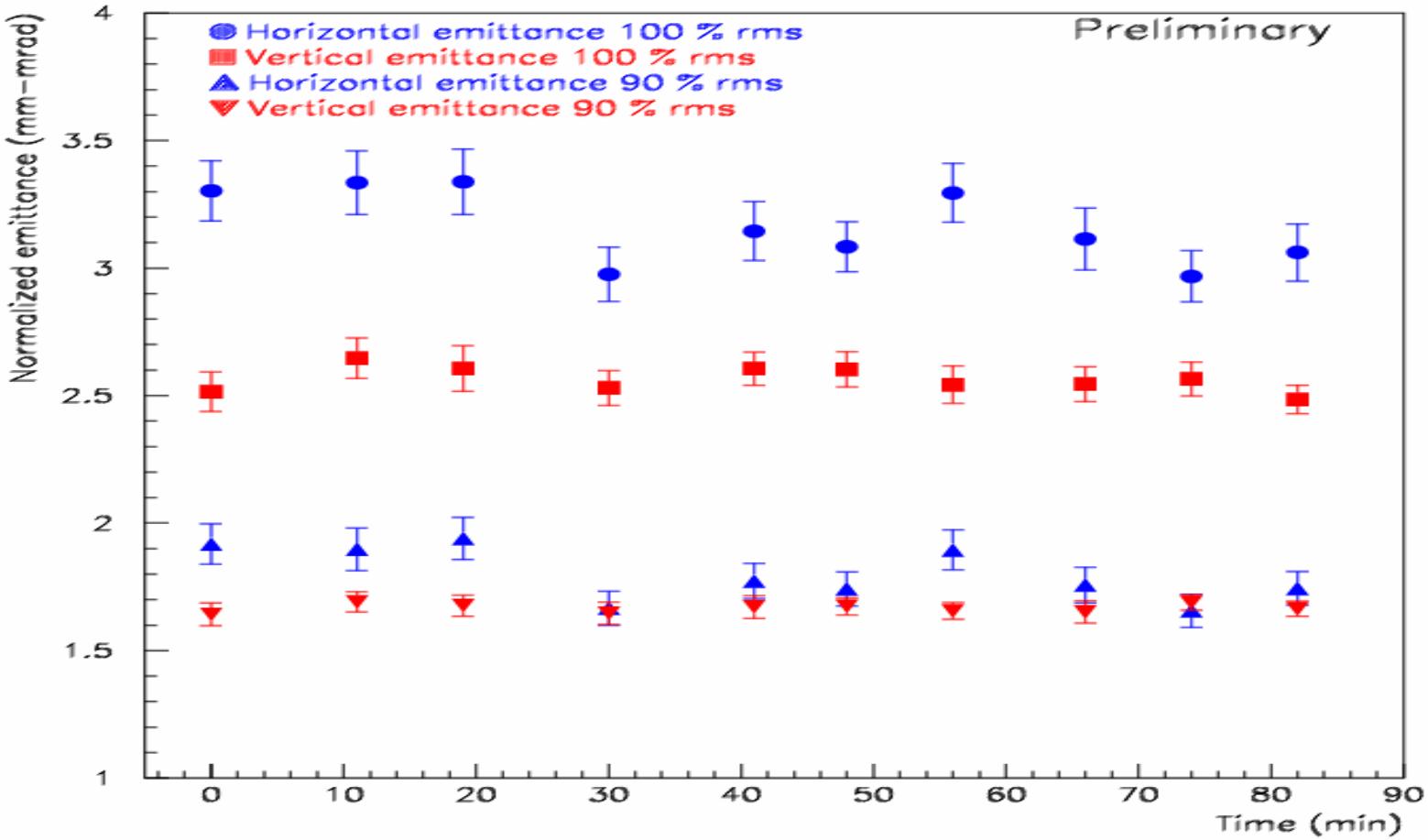
Emitttance for off-crest phasing

- Often the horizontal projected emittance growth when going to off-crest acceleration
  - as required for bunch compression (max compression 10..12 dg off crest)
- 1 nC, 1 bunch, 127 MeV
- 90 % rms values
- Dispersion may not have been compensated correctly



Reproducibility

- 10 measurements over about 1.5 hours keeping the same conditions
- 1 nC, 1 bunch, 127 MeV, on-crest acceleration
- 90 (triangles) and 100 % rms values



Summary

- Emittance measurements at TTF uses the four screen method
  + fast measurement
  + small systematic error (except: matching required)
- Method of calculating the beam size uses 90% intensity cut to calculate the rms (100 % numbers always gven as well)
- We expect to speed up the measurement even more when the wire scanners are available