Cornell University
Laboratory for Elementary-Particle Physics

CesrTA
Low Emittance Tuning

D. Rubin, Cornell University

12-January-2010

Low Emittance Tuning

CesrTA Low Emittance Tuning Program Goals

- Develop instrumentation and techniques for real time measurement of emittance diluting optical errors
  Focusing errors, transverse coupling, vertical dispersion
- Test algorithms for identifying and correcting the sources of those errors
- Achieving and maintaining low vertical emittance in various machine configurations as required by the CesrTA experimental program (electron cloud, IBS, etc.)

Optical functions by resonant excitation

- Measurement of horizontal and vertical amplitude and phase at each BPM at normal mode tunes yields beta-function, betatron phase advance, transverse coupling
- Measurement of horizontal and vertical amplitude and phase at the synchrotron tune gives horizontal and vertical dispersion

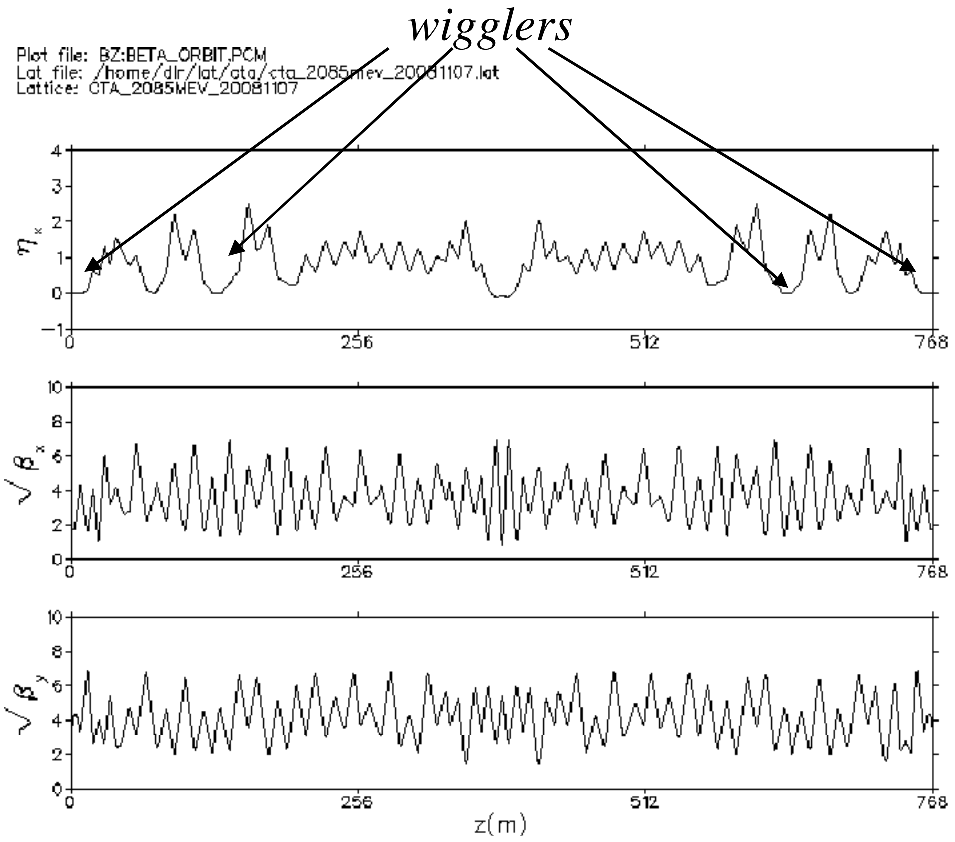
Detailed characterization of the beam position monitors is essential to accurate measurement of optical errors

- Gain mapping
- BPM tilts

Dependence of emittance on tunes

Low Emittance Optics - 2GeV

Twelve 1.9T wigglers in zero dispersion straights yield 10-fold reduction in radiation damping time and 5-fold reduction in horizontal emittance



wigglers

Dispersion

$\sqrt{\beta_x}$

$\sqrt{\beta_y}$

z(m)

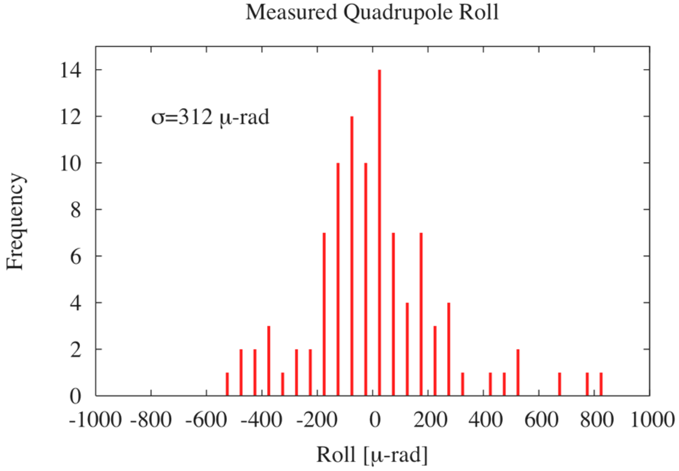
Circum[m]	768.4
Energy [GeV]	2.085
Wiggler[T]	1.9
Qx	14.57
Qy	9.6
Qz [4.5MV]	0.055
ε_x[nm]	2.6
α_p	6.76e-3
σ_l[mm]	12.2
σ_E/E[%]	0.81

Low Emittance Tuning

Effectiveness of low emittance tuning depends on

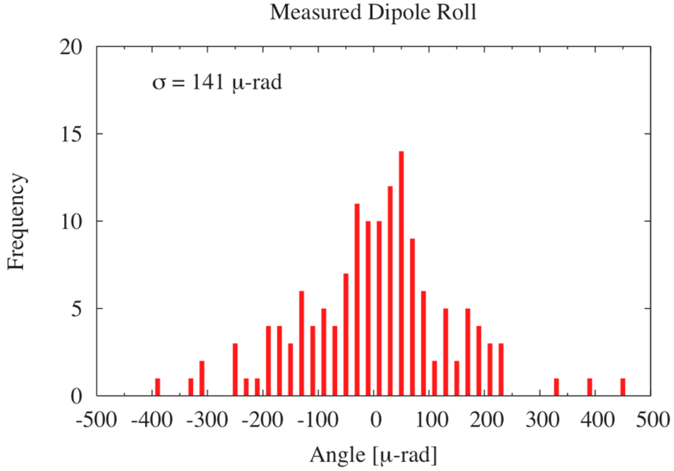
1. Survey and alignment of magnetic elements and beam position monitors
2. Accuracy of beam position measurements
   (essential for measuring emittance diluting optical and alignment errors)
3. Analysis software for extracting sources of emittance dilution from measurements
4. Distribution of corrector magnets to compensate for errors found in 3.

Magnet Alignment and Survey



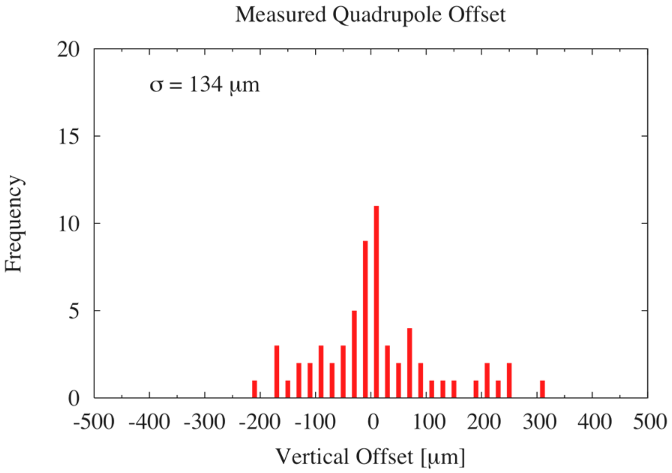
Measured Quadrupole Roll

Quad roll σ ~ 300 μrad



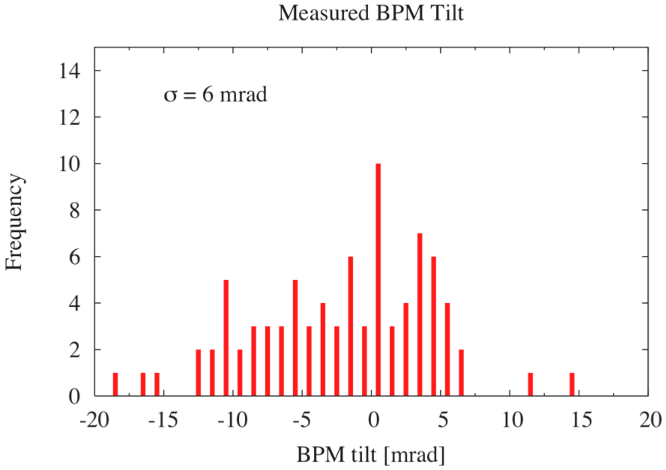
Measured Dipole Roll

Bend roll σ ~ 150 μrad



Measured Quadrupole Offset

Quad offset σ ~ 134 μm



Measured BPM Tilt

BPM tilt σ ~ 6 mrad

Beam Position Monitors

Precision beam position monitors are essential for the measurement of transverse coupling and vertical dispersion required for low emittance tuning

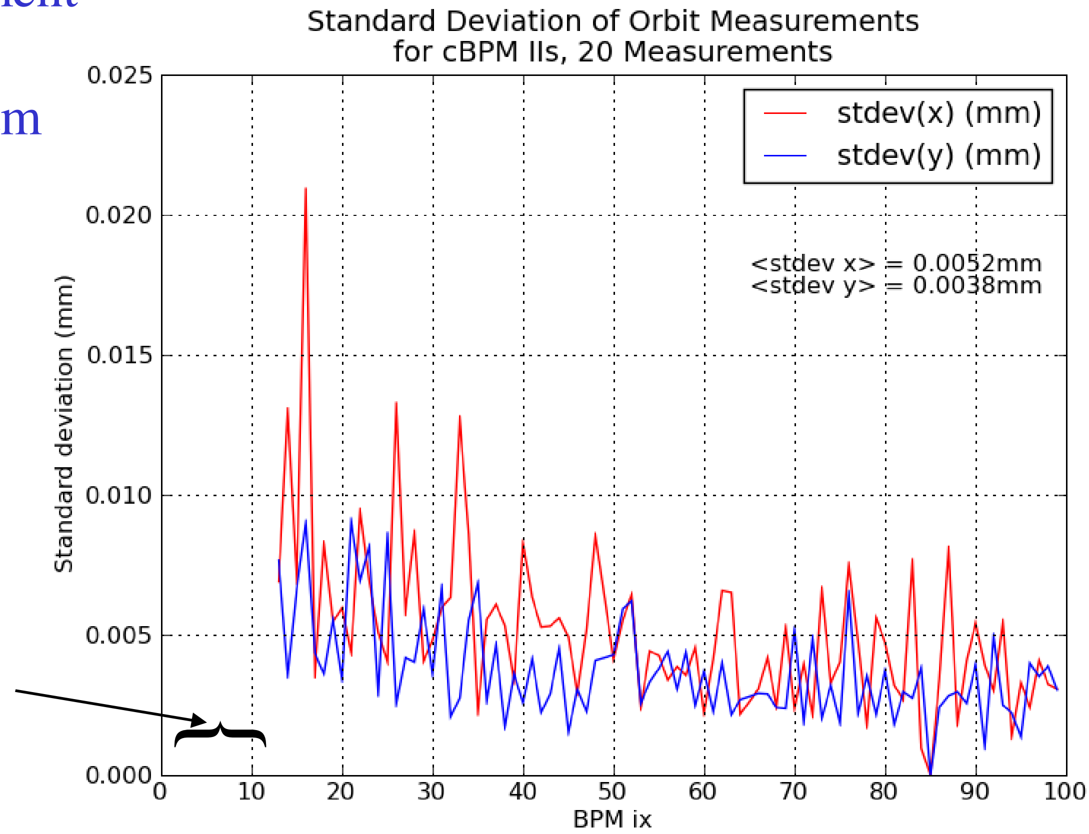
As of the start of the current CTA run (11/09), the old analog BPM electronics has been replaced with high precision, high band width, digital electronics

Preliminary measurements suggest that the intrinsic resolution of the new system is
< 10μm for difference measurements
< 5mm for measurement of dispersion
< 0.1% for measurement of transverse coupling

Realization of that precision depends on an understanding of the systematics, namely
- button to button gain variations
- BPM tilt

Intrinsic resolution of digital beam position monitors

The noise limit on the measurement of position differences with the new digital BPM system is < 5μm

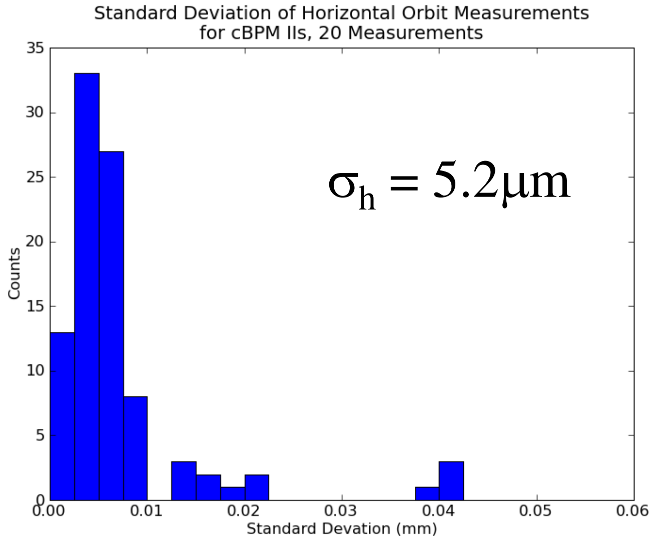


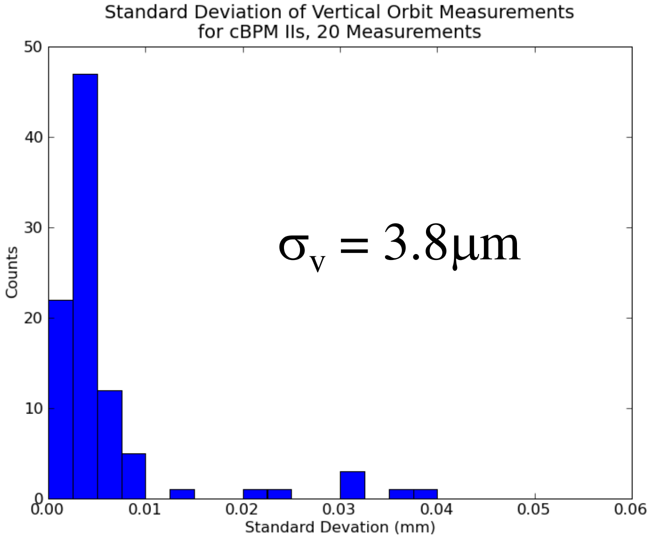
Prototype (and soon to be replaced) digital system (0:12)

Beam Position Monitors

Intrinsic resolution of digital beam position monitors

We measure $\sigma_{dif} \sim 5.2\mu m / 3.8\mu m$
(1000 turn average)


Standard Deviation of Horizontal Orbit Measurements for cBPM IIs, 20 Measurements


Standard Deviation of Vertical Orbit Measurements for cBPM IIs, 20 Measurements

Beam Position Monitors

Principle source of vertical emittance in CESR is vertical dispersion

The noise limit on the measurement of vertical dispersion is ~2.5mm

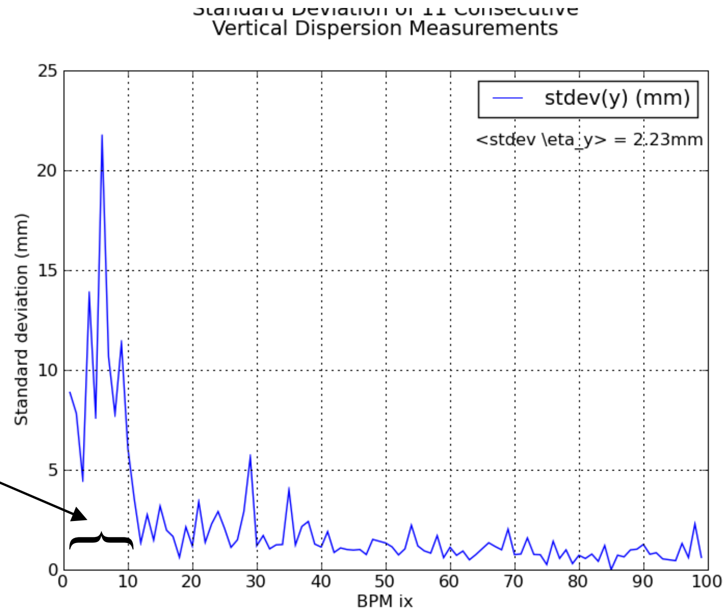
(with new digital BPMs)

Standard deviation of 11 sequential dispersion measurements

$\sigma \sim 5.2$ mm - η_h

$\sigma \sim 2.3$ mm - η_v

Old system

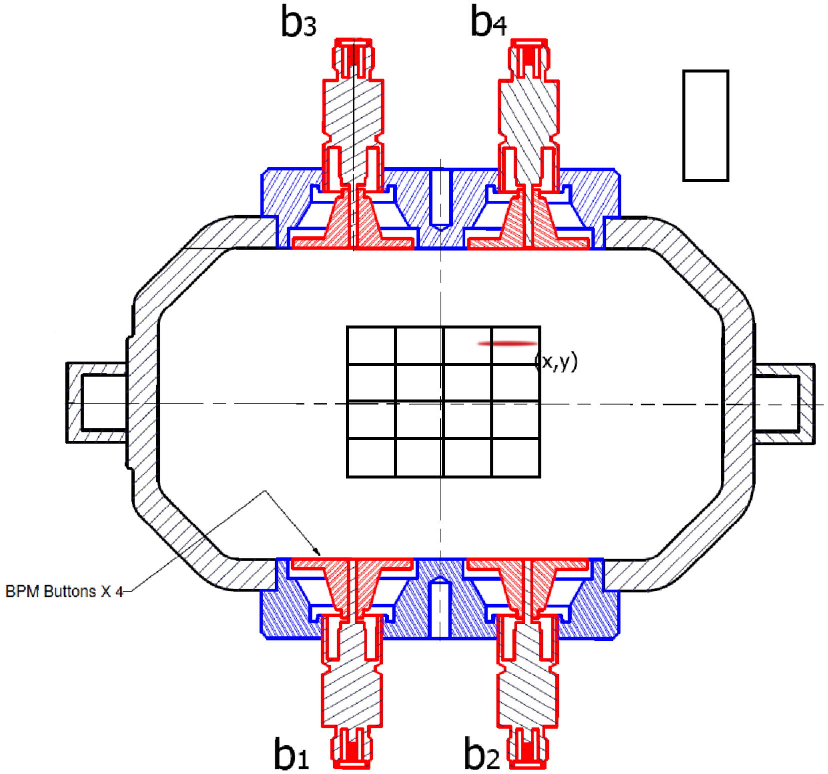


At present, dispersion measurement accuracy is limited by systematics (especially button to button gain errors and BPM tilt)

BPM systematics

Button to button gain errors

Any difference in the effective button gains, electronic or physical, couple real horizontal dispersion into measured vertical dispersion (and the horizontal dispersion is large)



Characterization of BPM Gain Errors

Signal at each button depends on bunch current (*k*) and position (*x*,*y*)

$$B_1 = kf(x,y)$$

$$B_1 \approx k\left(f(0,0) + \frac{\partial f}{\partial x}x + \frac{\partial f}{\partial y}y + \frac{1}{2}\frac{\partial^2 f}{\partial x^2}x^2 + \frac{1}{2}\frac{\partial^2 f}{\partial y^2}y^2 + \frac{\partial^2 f}{\partial x \partial y}xy + \ldots\right)$$

$$B_1 \approx k(c_0 + c_1 x + c_2 y + c_3 x^2 + c_4 y^2 + c_5 xy)$$

Signals on the four buttons are related by symmetry

$$B_2 = kf(-x,y)$$
$$B_3 = kf(x,-y)$$
$$B_4 = kf(-x,y)$$

Combining sums and differences we find the following relationship, good to second order

$$B_1 - B_2 - B_3 + B_4 = \frac{1}{k}\left(\frac{c_5}{c_1 c_2}\right)(B_1 - B_2 + B_3 - B_4)(B_1 + B_2 - B_3 - B_4)$$

$$B(+--+) = \frac{c}{k}B(+-+-)B(++--)$$

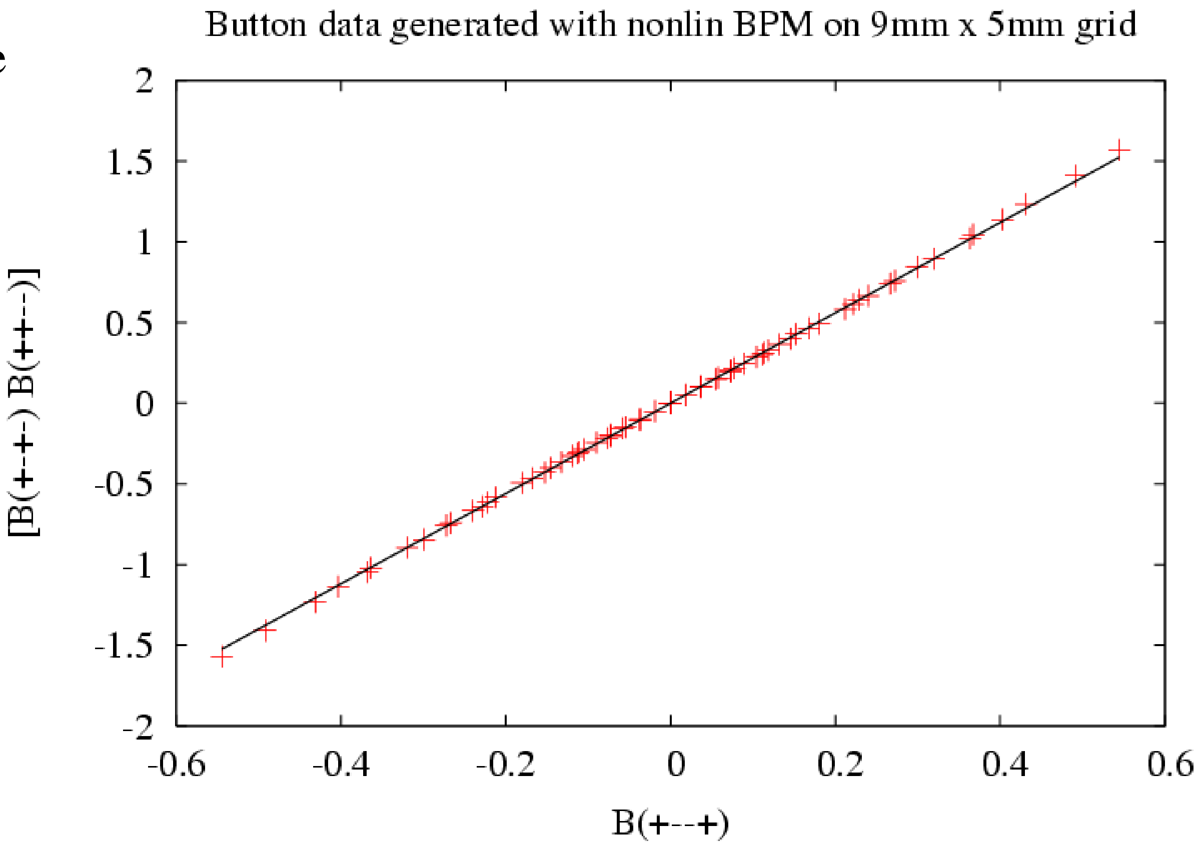
Gain characterization simulation

$$B(+--+) = \frac{c}{k} B(+-+-) B(++--)$$

Using a map that reproduces the "exact" dependence of the button signals on the bunch positions we generate B_1,B_2,B_3,B_4 for each of 45 points on a 9mm x 5mm grid

In first order *c=0,* and therefore B(+--+) = 0. Evidently the first order approximation is not very good enough this range.

The small deviations from the straight line at large amplitudes is a measure of the higher than second order contributions.

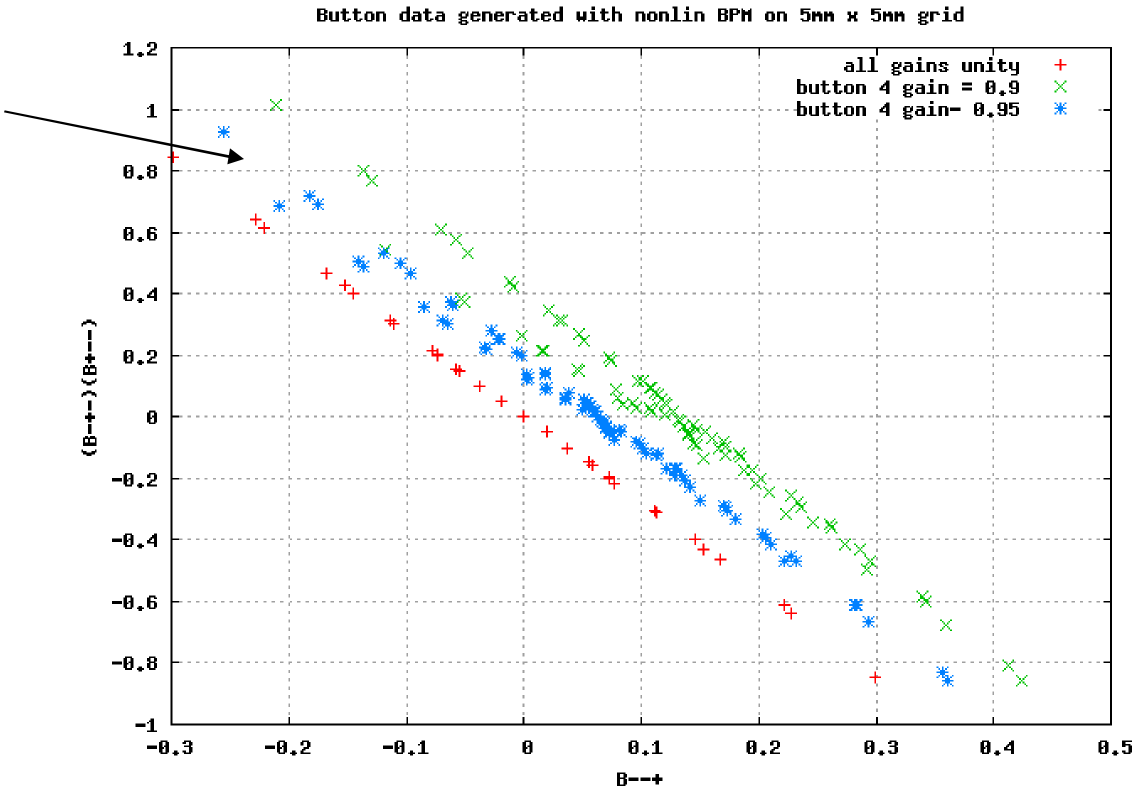


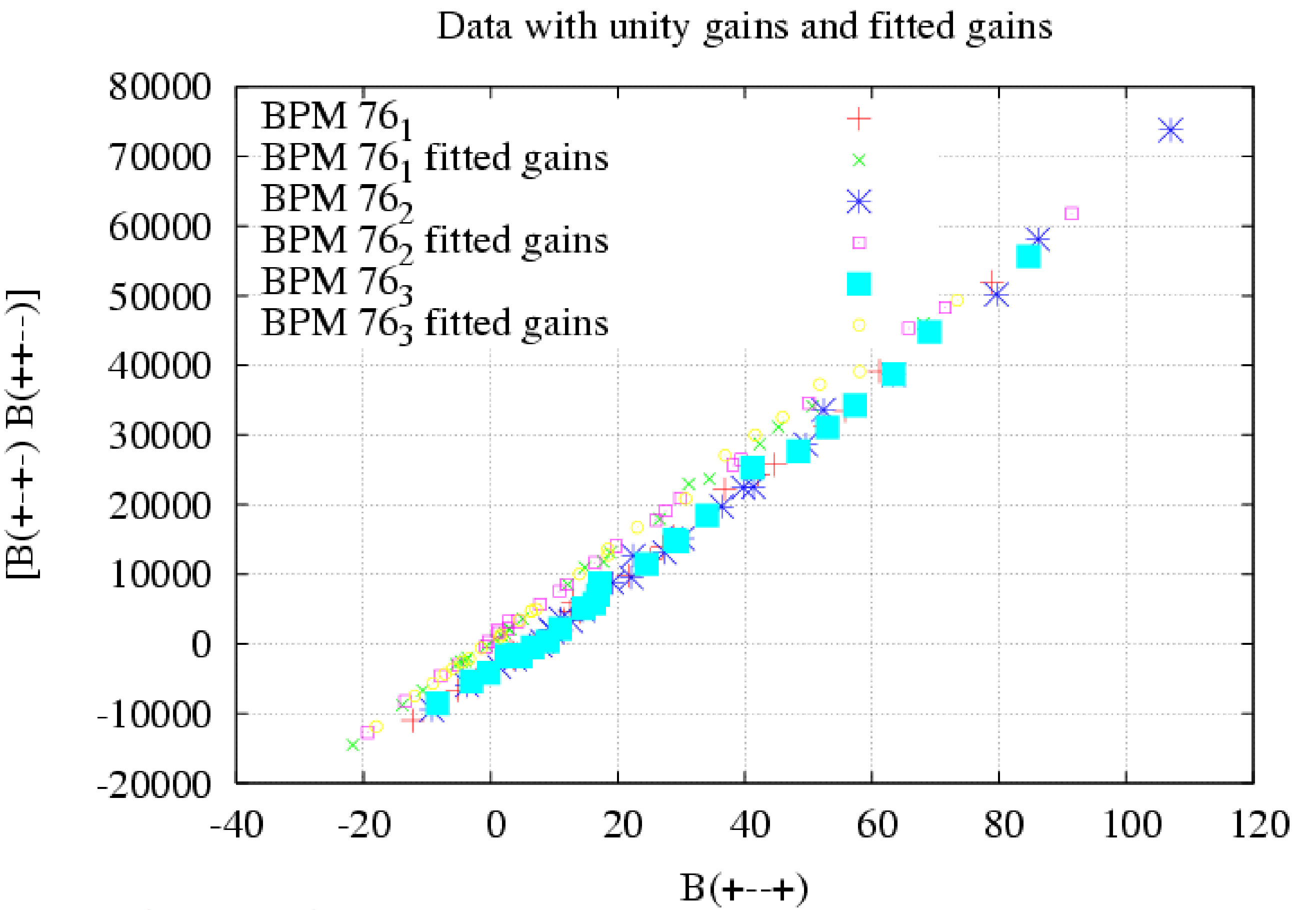
Gain characterization simulation

$$B(+--+) = \frac{c}{k}B(+-+-)B(++--)$$

Introduce gain errors

Zero offset, nonlinearity, and multi - valued relationship i n is a measure of gain errors.

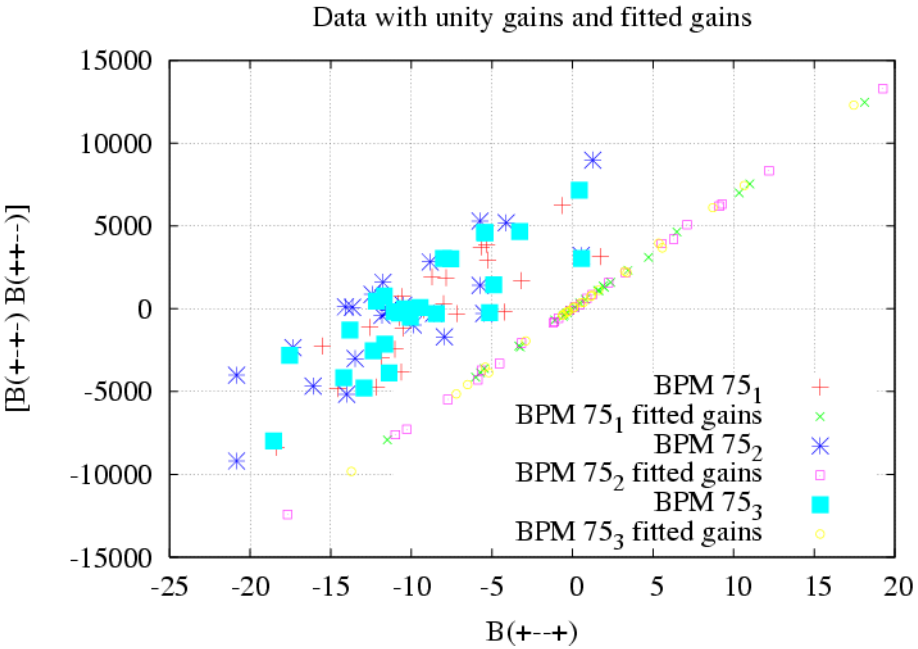




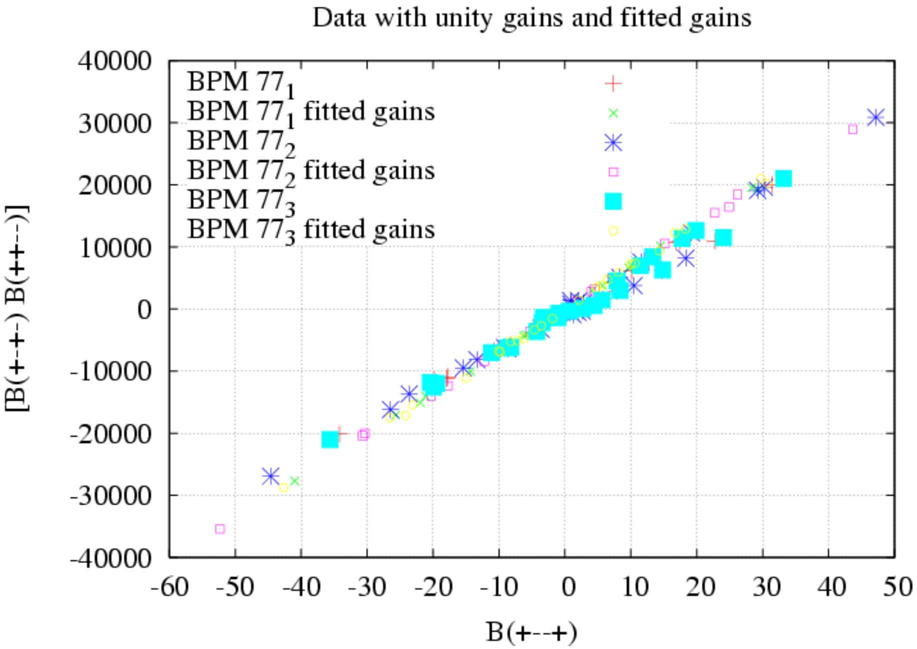
Minimize

$$\sum_i \left[(g_1 B_1^i - g_2 B_2^i - g_3 B_3^i + g_4 B_4^i) - \frac{c}{I}(g_1 B_1^i - g_2 B_2^i + g_3 B_3^i - g_4 B_4^i)(g_1 B_1^i + g_2 B_2^i - g_3 B_3^i - g_4 B_4^i)\right]^2$$

with respect to g_j to determine gains



BPM 75



BPM 77

Fit typically reduces χ^2 by two orders of magnitude

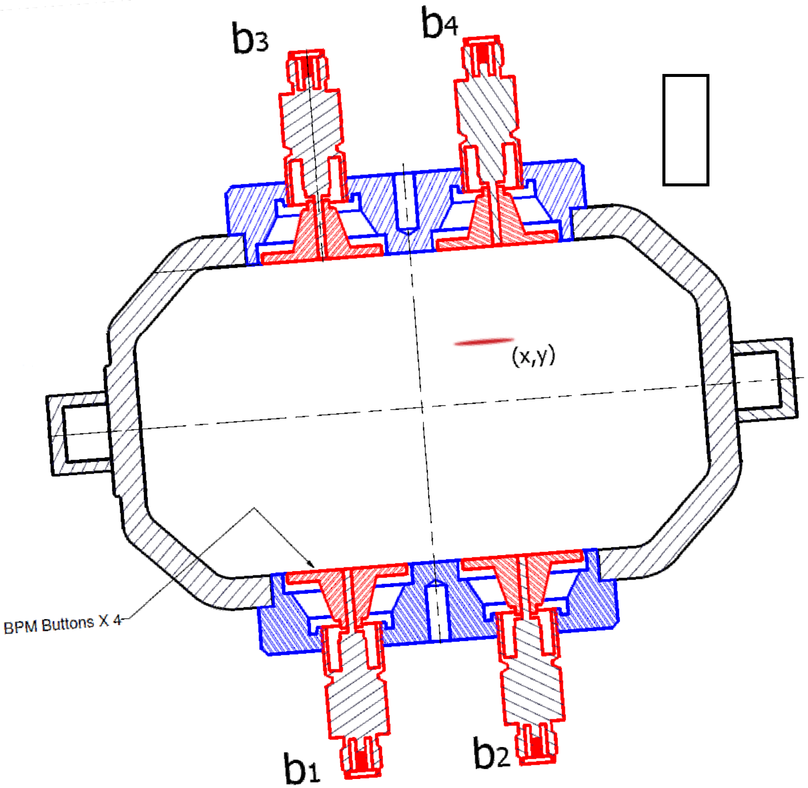
BPM systematics

BPM tilt

A physically tilted BPM couples horizontal dispersion to measured vertical

Since $\langle\eta_h\rangle \sim 1$m, and a residual vertical dispersion of 1cm yields 10pm emittance, we must determine BPM tilt to better than 10mrad.

(Survey of BPM tilts (with a level) gives ~ 6mrad rms)



Beam based measurement

- Resonantly excite beam at horizontal tune
- Measure relative horizontal and vertical amplitude and phase at each BPM
- $\bar{C}_{12} = (A_y/A_x)\sin(\varphi_x-\varphi_y)$ measures "out of phase" coupling component and is insensitive to tilt
- $\bar{C}_{22} = (A_y/A_x)\cos(\varphi_x-\varphi_y)$ measures "in phase" coupling component and in the absence of coupling $A_y=\theta_{tilt} A_x$

So we minimize $\bar{C}_{12}$ using skew quad correctors.

→ measurement of $\bar{C}_{22}$ gives BPM tilt.

Low Emittance Tuning

After characterizing the BPM system, with measurements of gain and tilt, we diagnose optical and alignment errors with measurements of

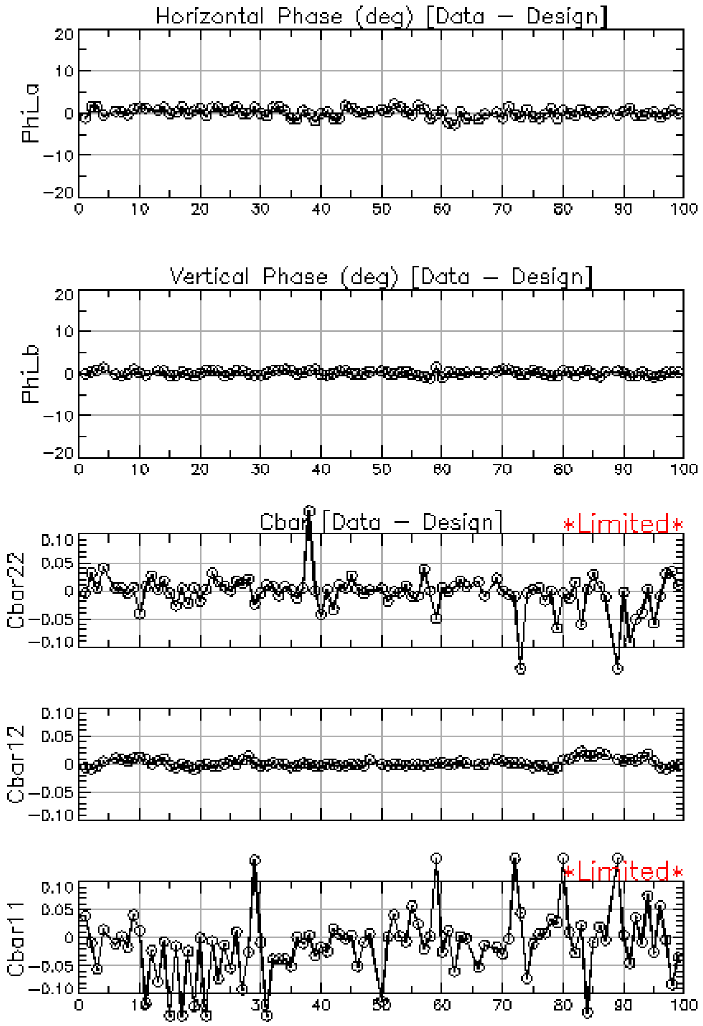
- Orbit
- Betatron amplitude and phase, and coupling
- Dispersion

Fit machine model to measurements using quads, skew quads, and steering.

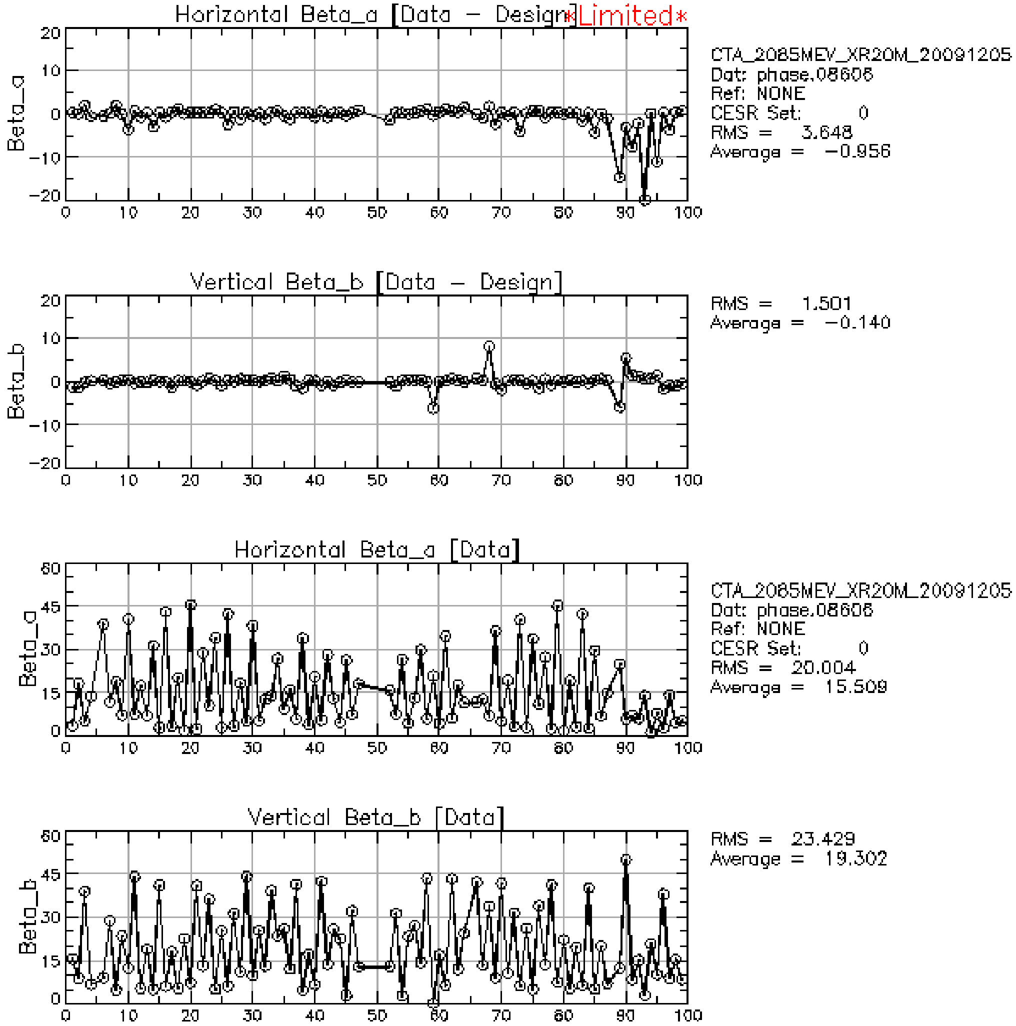
Load corrections and measure again

Measurement of optical functions

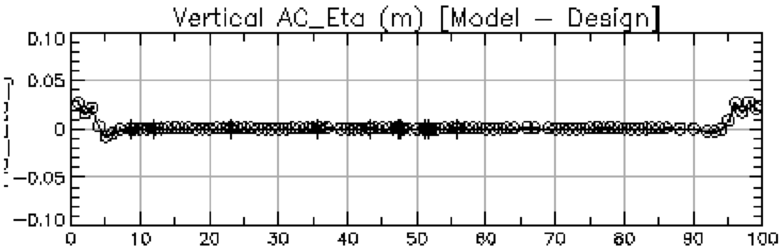
starting point



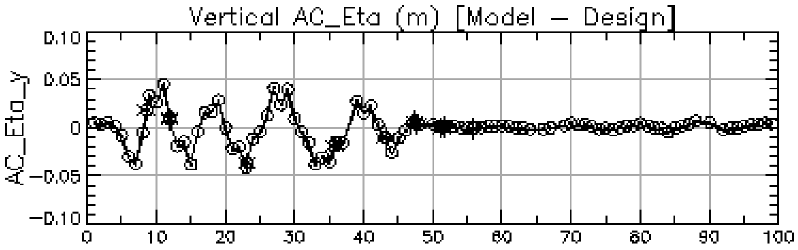
starting point



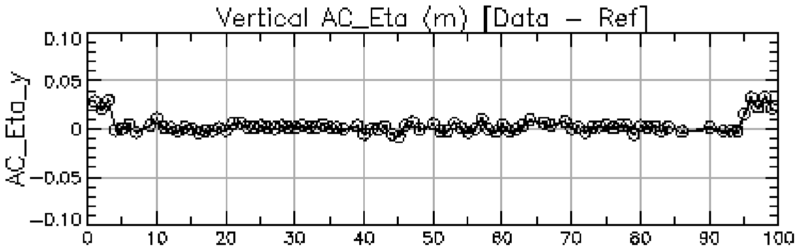
AC dispersion



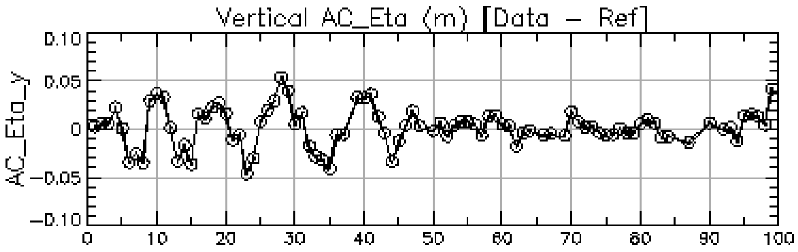
Modeled dispersion bump
in L0 wiggler straight



Modeled dispersion bump
in arc

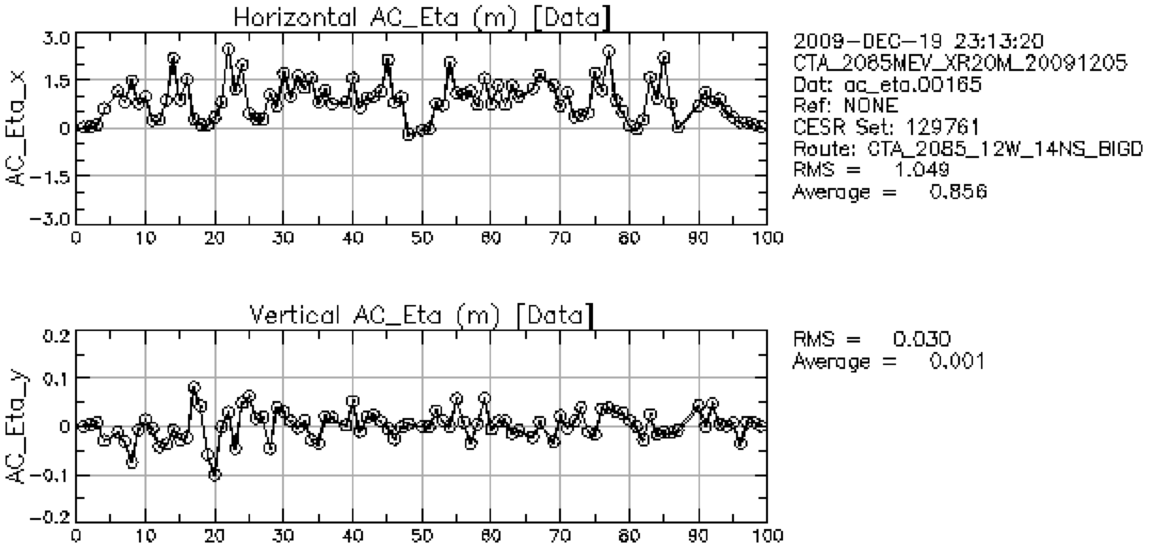


Measured effect of L0 η bump



Measured effect of arc η bump

Measurement of dispersion



Horizontal AC_Eta (m) [Data]

```
2009-DEC-19 23:13:20
CTA_2085MEV_XR20M_20091205
Dat: ac_eta.00165
Ref: NONE
CESR Set: 129761
Route: CTA_2085_12W_14NS_BIGD
RMS =     1.049
Average =    0.856
```

Vertical AC_Eta (m) [Data]

```
RMS =    0.030
Average =    0.001
```

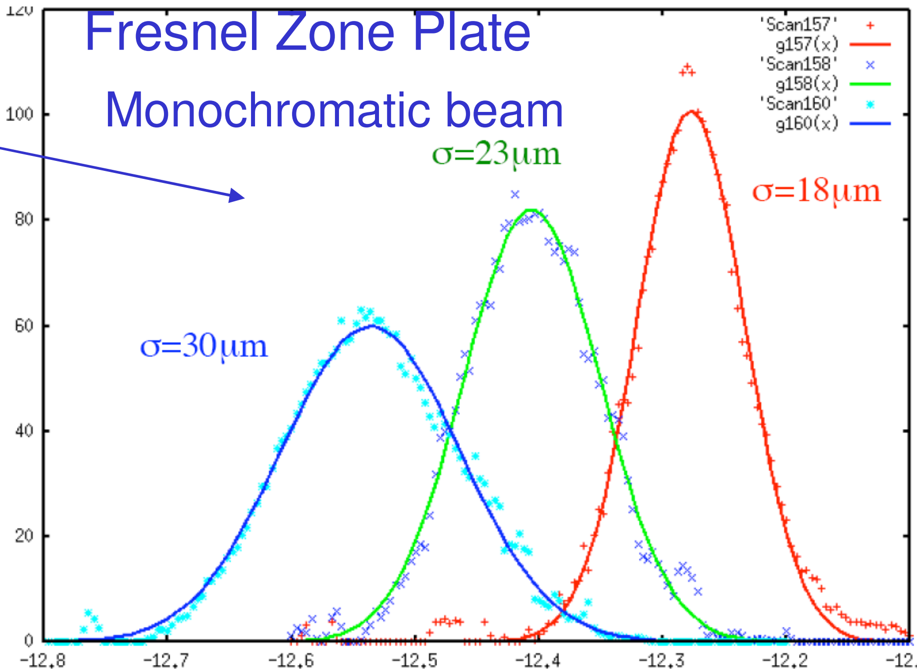
LET summary

1. Magnets are aligned well enough to achieve sub 20pm vertical emittance (according to simulation)
1. Intrinsic measurement accuracy of the beam position monitors and the disposition of corrector magnets is adequate to achieve sub 20pm emittance (according to simulation)
2. Dispersion measurement is compromised by systematic effects at a level of 2-3cm. We require $\sigma_\eta < 1.4$cm to achieve sub 20pm emittance
3. We have developed techniques for reducing the systematic errors
    1. Gain mapping to measure button to button gain variation
    2. Measurement and analysis of coupling matrix elements to extract BPM tilt

xBSM Snapshots

X-ray beam size monitor

- Scan of coupling knob
- Coded aperture measurements
- Smallest recorded size (January 09): ~15 μm →ε_v~ 40 pm (preliminary)



Fresnel Zone Plate

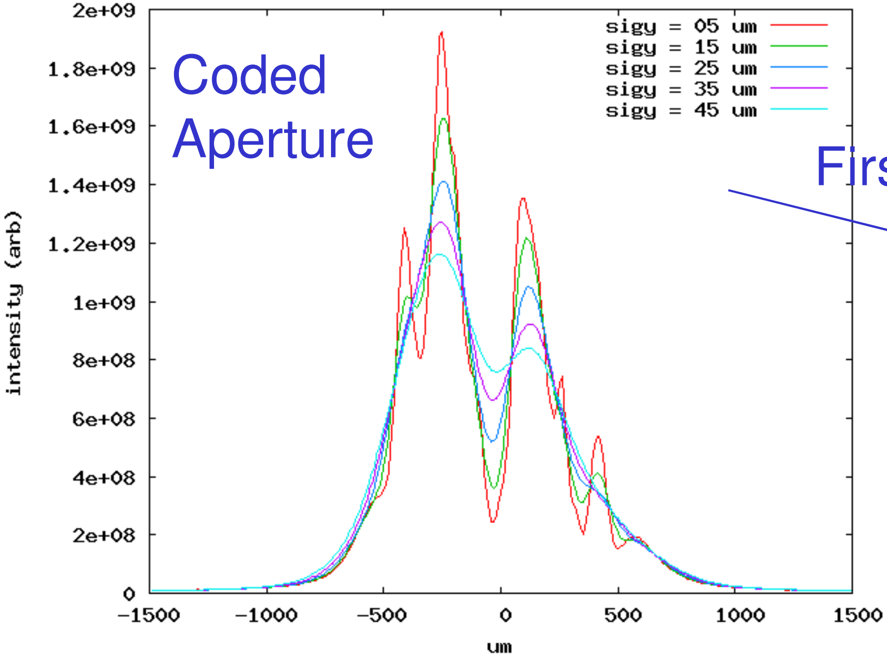
Monochromatic beam

σ=23μm

σ=18μm

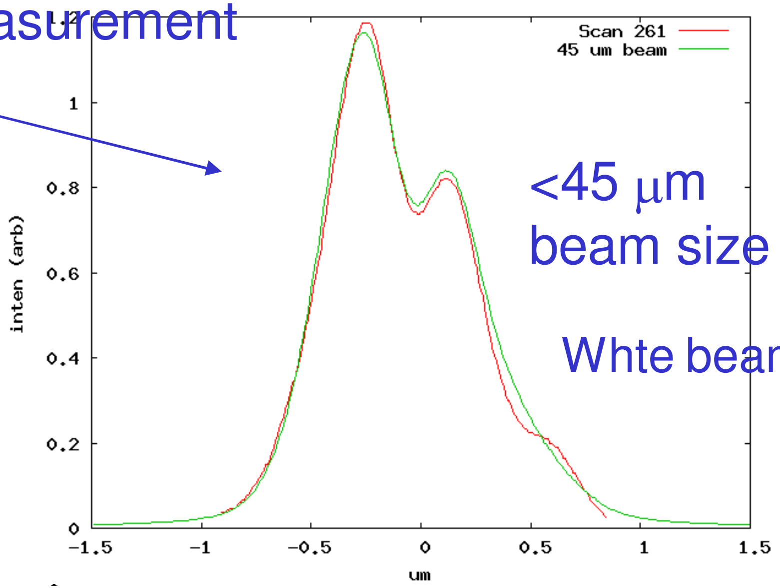
σ=30μm

Simulations



Coded Aperture

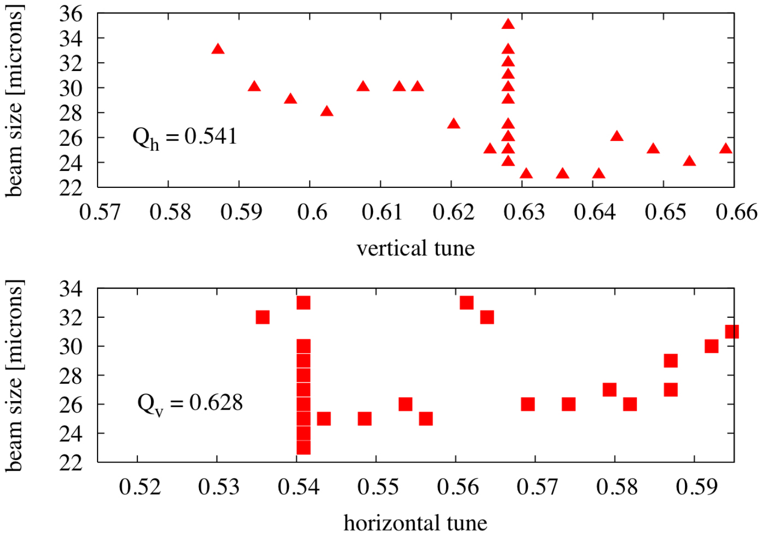
First measurement

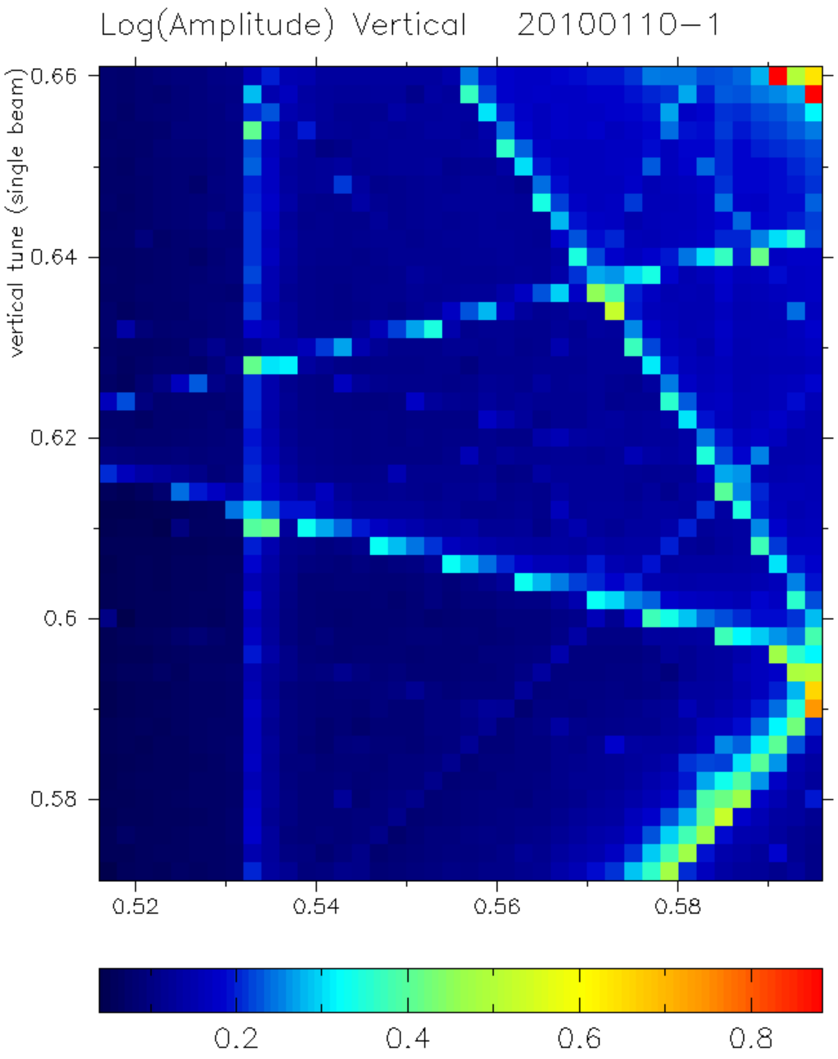


<45 μm beam size

Whte beam

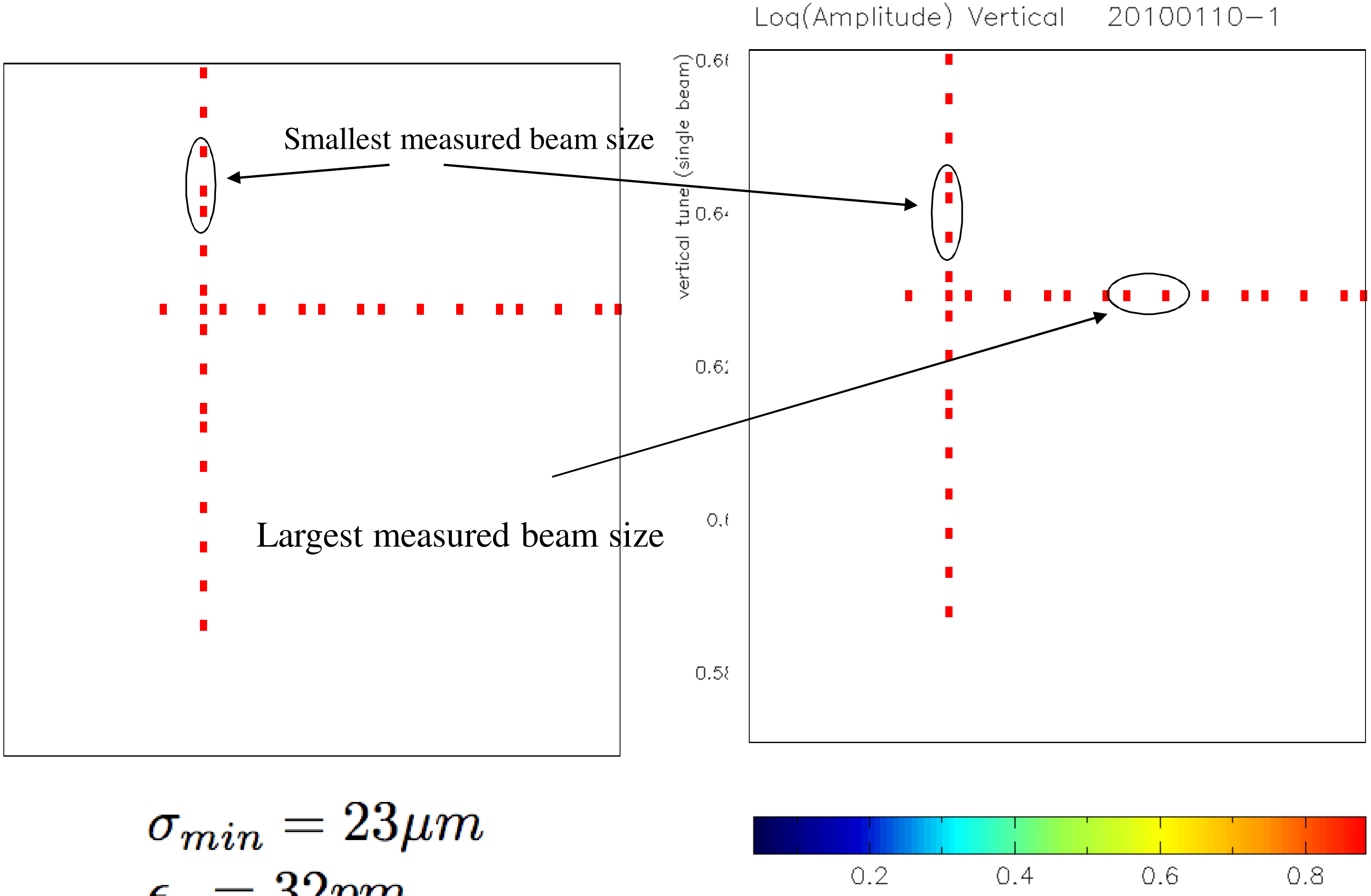
Tune dependence





X-ray beam size monitor
Gives turn by turn beam size

Tune dependence



Smallest measured beam size

Largest measured beam size

$$\sigma_{min} = 23\mu m$$
$$\epsilon_v = 32pm$$

Summary

- Status of low emittance tuning instrumentation and procedure
  - Survey and alignment - First round complete. We will continue to improve
  - LET with digital BPM system and xbsm yields $\varepsilon_v \sim 32$pm (limited by systematic errors in measurement of vertical dispersion, tunes, ?)
  - High precision BPMs installed with demonstrated 5μm differential measurement accuracy
  - Procedure for measuring BPM "coupling" and gain errors has been vetted in simulation and is being tested with beam.
    (Essential to measuring and minimizing η_v)
  - Highly developed analysis and fitting software in everyday use
  - Simulation indicates that given our measured magnet alignment errors and the accuracy of our new BPM system, we can achieve sub 20pm vertical emittance via our LET procedure
  - xray beam size monitor gives the few micron resolution required to measure <20pm emittance and emittance diluting effects
  - Explore tune plane
  - And other sources of emittance dilution, power suppy noise, tune spread, feedback noise, etc.

Measurement and correction

Low emittance tuning

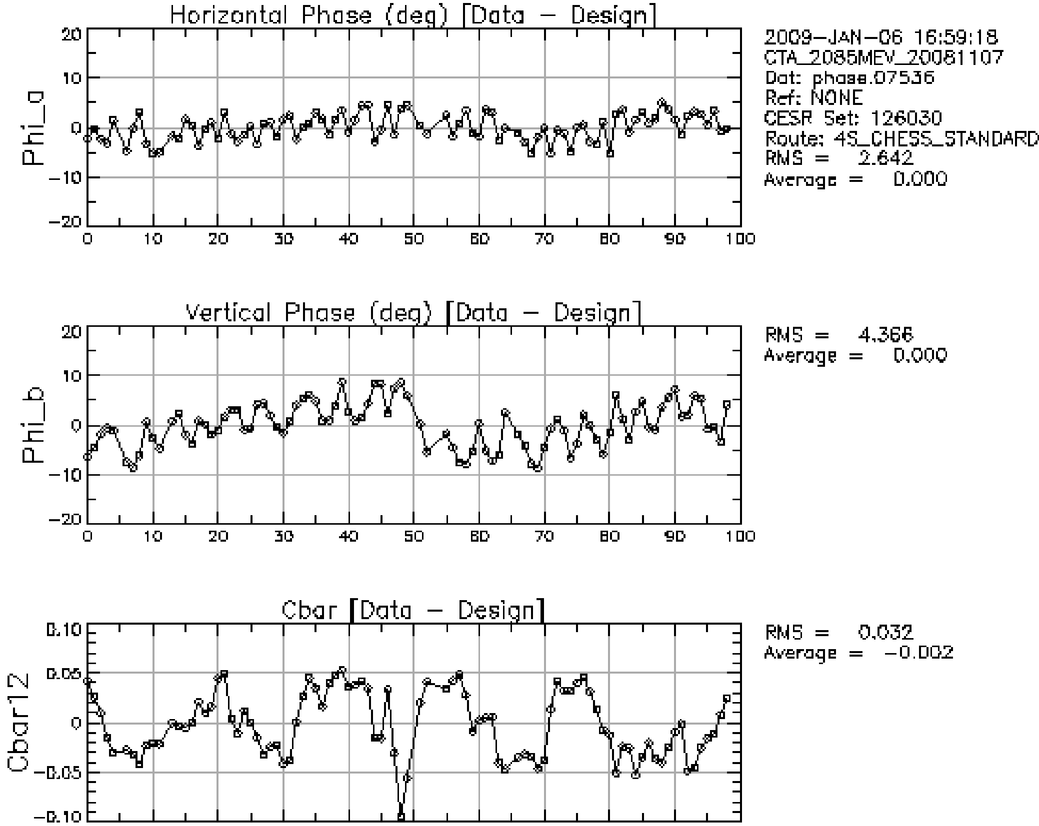
Experimental procedure

LET - initialization

-Measure and correct orbit using all dipole correctors

-Measure β-phase and transverse coupling

(Phase measurement insensitive to BPM offset, gain, and calibration errors)



Direct measurement of β-functions is new with digitial BPMs and has yet to be incorporated into fitting and correction procedure

LET procedure

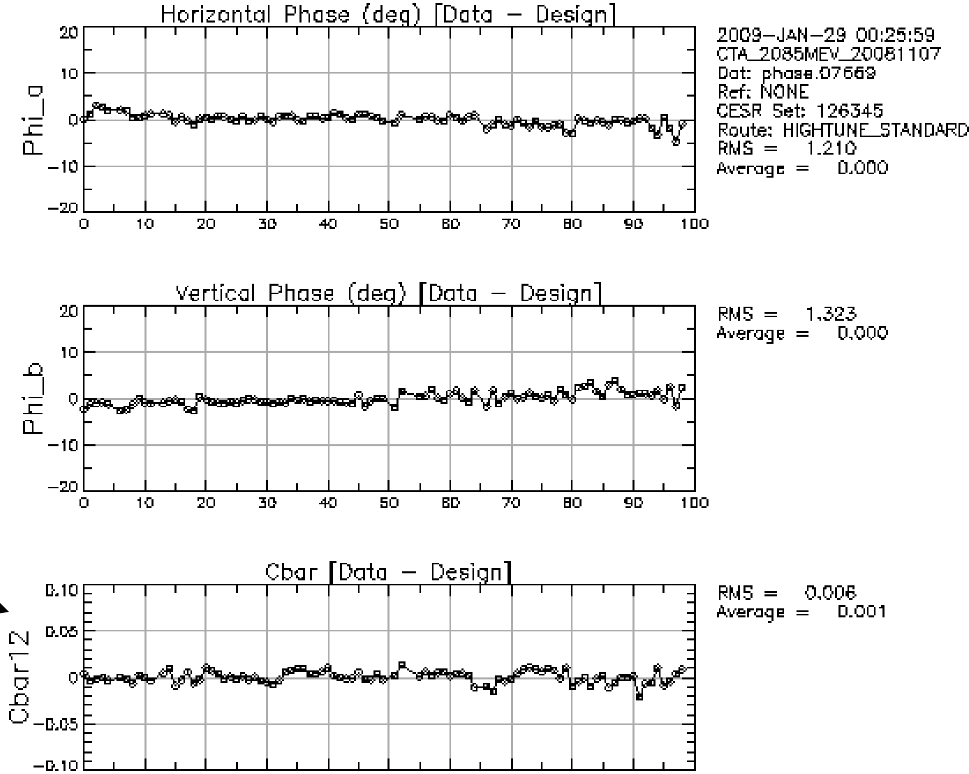
Low emittance tuning
Experimental procedure

LET - initialization

-Measure and correct orbit using all dipole correctors

- Correct β-phase using **all** 100 quads
  Remeasure - ($\sqrt{\langle\Delta\phi^2\rangle} < 1.5^\circ$

-Correct transverse coupling using 14 skew quads. Remeasure ($\sqrt{\langle\bar{C}_{12}^2\rangle} \sim 0.6\%$)



Note that

$$\bar{C}_{12} \sim \frac{x}{y} \rightarrow \frac{\epsilon_y}{\epsilon_x} \sim \left(\bar{C}_{12}\right)^2$$

β-phase and coupling after correction

Dispersion measurement

Low emittance tuning

Dispersion measurement accuracy is limited by BPM systematics: gain and tilt errors

-Measure vertical dispersion and fit using skew quads (14) and vertical steering (~60)

RMS residual vertical dispersion ~ 3.3cm

The signal is lost in the noise associated with the gain and tilt errors

Note: Residual vertical dispersion 1cm, corresponds to ε_v ~ 10pm

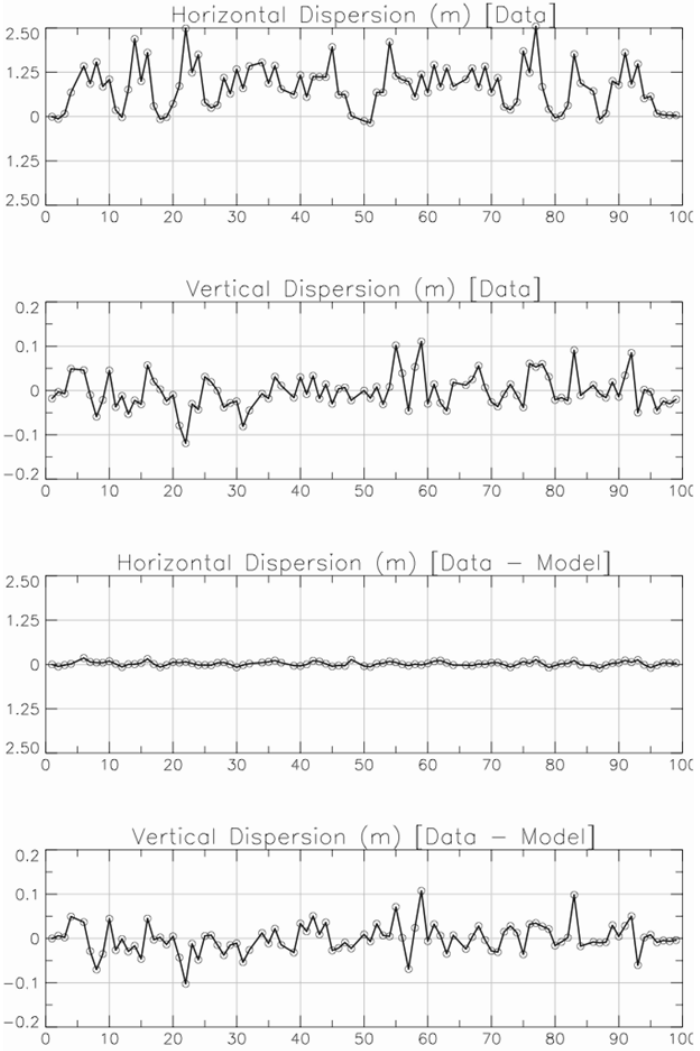
Measured dispersion

η_h data

η_v data

η_h Data-(fitted model)

η_v Data-(fitted model)



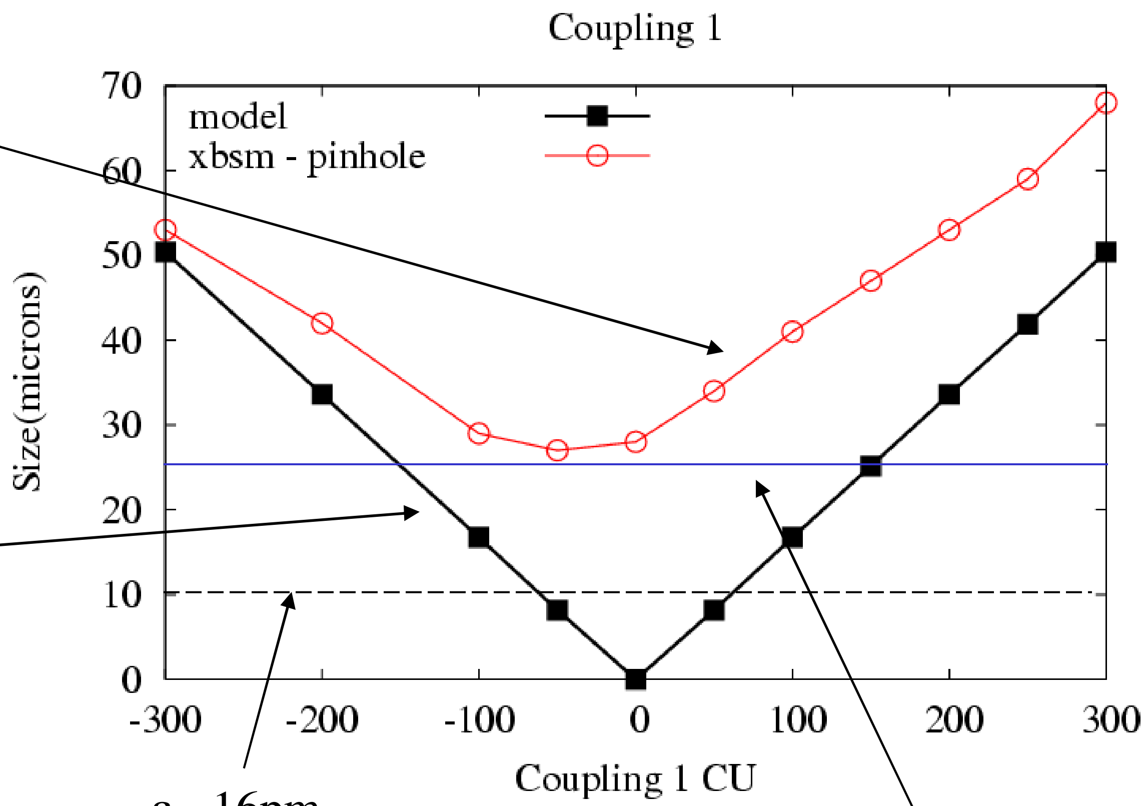
Beam position monitor

X-bsm test

Measurement

With x-bsm pinhole optics
(Pinhole optics cannot resolve
beam size smaller than 25μm
Fresnel zone plate to 2μm)

model



ε_v~16pm

Pinhole resolution
limit

Coupling_1 - closed coupling bump through wigglers -
beam size due to vertical emittance and
finite vertical dispersion at xbsm source

Low Emittance Tuning

How well can we expect to eliminate sources of emittance dilution?

Alignment achieved

quad offset 150μm

quad roll 300μrad

bend roll 150μrad

Measurement capability

BPM absolute accuracy σ_{abs} =100μm

BPM differential accuracy σ_{dif} <10μm

BPM gain errors σ_{gain} < 0.2% [after gain mapping]

BPM tilt errors < 10 mrad [after measurement and analysis of coupling]

Corrector magnets

14 skew quads

60 vertical steerings

100 quadrupoles

78 sextupoles

- In simulation we generate data based on measured alignment tolerances and BPM measurement accuracy
- Fit model to “measured” data using available correctors
- Load corrections and achieve

ε_v < 15pm 95% of seeds