Status of Low Emittance Tuning at CESR TA

D. Rubin, D. Sagan, J. Shanks, J. Sexton, S. Chapman, M. Forster, S. Peck

presented by M. Billing

CLASSE

Cornell University

Oct. 2, 2009

Objectives

Attain sufficiently low vertical emittance to enable exploration of

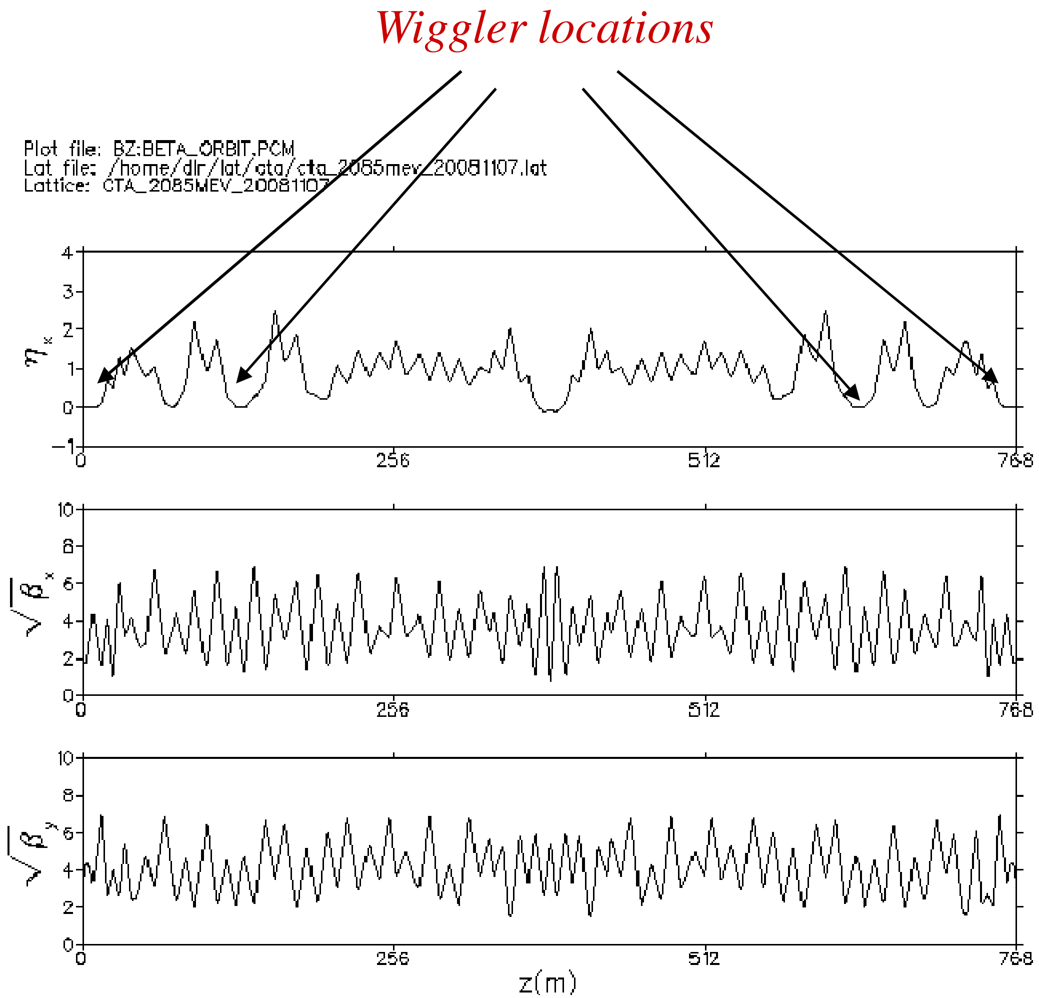
- dependence of electron cloud on emittance
- emittance dilution effect of e-cloud

- Design/install low emittance optics ($1.5 < E_{beam} < 5.0$ GeV)
  - Exploit damping wigglers to reduce damping time and emittance
- Develop beam-based techniques for characterizing beam position monitors
  - BPM offsets, Gain mapping, ORM and transverse coupling measurements ==> BPM tilt
- Also for measuring and minimizing sources of vertical emittance including
  - Misalignments
  - Orbit errors
  - Focusing errors
  - Transverse coupling
  - Vertical dispersion
- Develop single bunch/single pass measurements of vertical beam size
- Characterize beam current dependence of lifetime in terms of beam size
- Measure dependencies of beam size/lifetime on
  - Beam energy
  - Bunch current
  - Species

Low Emittance Optics - 2 GeV

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

Energy [GeV]	2.085
Wiggler [T]	1.9
Q_x	14.57
Q_y	9.6
Q_z [4.5MV]	0.055
ε_x[nm]	2.6
α_p	6.76e-3
σ_z[mm]	12.2
σ_E/E[%]	0.81



Status of Accelerator Optics

CTA Optics, 28-Sep-2009

All at $Q_h = 14.57$, $Q_v = 9.62$

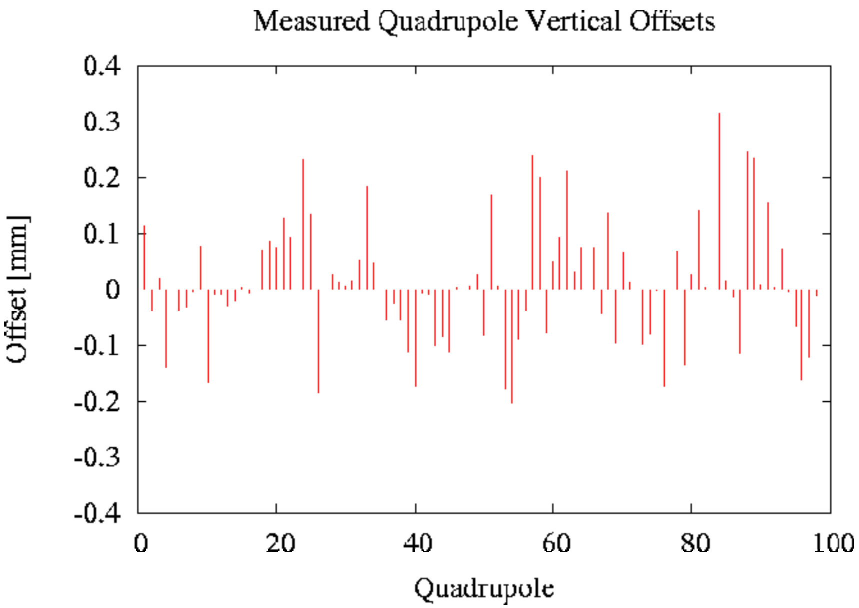
Lattice [cta_]	E[GeV]	Wigglers (1.9T/pm)	ε_x[nm]	Polarity of Q0	Status
1800mev_20090607*	1.8	12/0	2.3	HF	e+ inj/ no ramp
2085mev_20090516	2.085	12/0	2.5	HF	e+/e- inj & xBSM bump
2300mev_20090608	2.3	12/0	3.3	HF	e+ inj/ no xBSM bump
3000mev_q0h_20090822	3.0	6/0	10	HF	e+ inj & xBSM bump
3000mev_q0v_20090821	3.0	6/0	9.8	VF	e+ inj & xBSM bump
4000mev_20090814	4.0	0 /0	42	VF	e+ xBSM bump /no e-
4000mev_23nm_20090816	4.0	6 /0	23	VF	e+ xBSM bump/ e- inj
5000mev_pmwig_20090314	5.0	0/2	90	VF	e+/e- inj, e+ xBSM
5000mev_40nm_20090513	5.0	6/0	40	VF	e+/e- inj, e+ xBSM

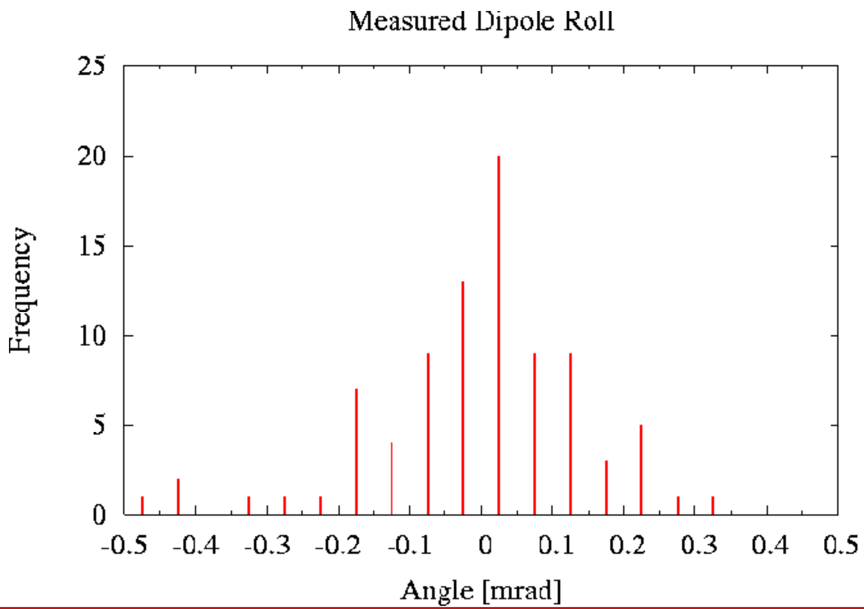
* Orbit/phase/coupling correction and injection but no ramp and recovery

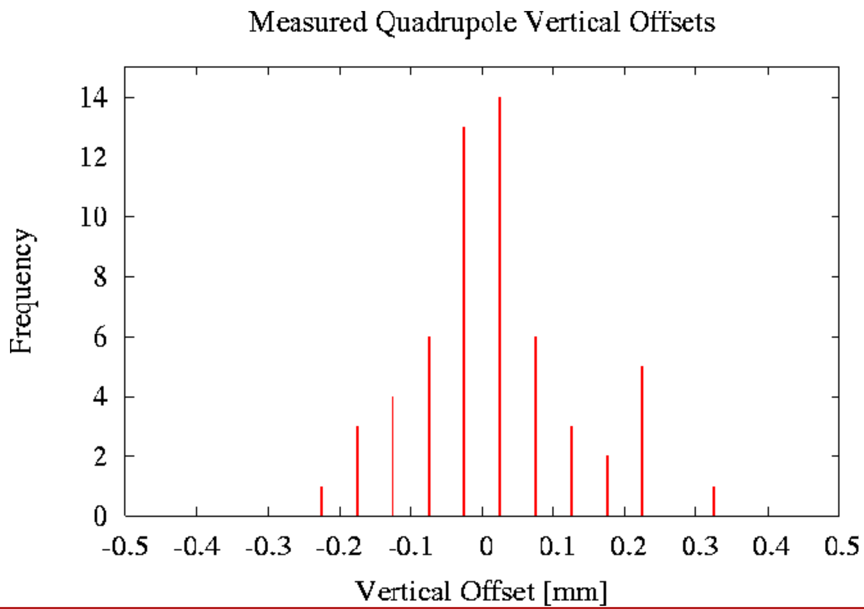
In all other optics there has been at least one ramp and iteration on injection tuning and phase/coupling correction

Magnet Alignment

Survey network complete
Major resurveying complete:
- Quad offset σ ~ 134μm
- Bend roll σ ~ 160μrad
- Sextupoles σ < 300μm







Sensitivity to Misalignment

Effectiveness of emittance tuning depends on magnet misalignments and BPM performance.

We investigated correction algorithms assuming various combinations of survey errors and BPM errors

	Parameter	Nominal Target	Worse (90% Success)	Status Sept. 09
Element Misalignment	Quad/Bend/Wiggler Offset [μm]	150	300	134
	Sextupole Offset [μm]	300	600	< 300
	Rotation (all elements)[μrad]	100	200	160
	Quad Focusing[%]	0.04	0.04	0.04
BPM Errors	Absolute (orbit error) [μm]	10	100	100
	Relative (dispersion error*)[μm]	8	20	40-50
	Rotation[mrad] (Button to Button Gain errors)	1	2	~10

*The actual error in the dispersion measurement is equal to the differential resolution divided by the assumed energy adjustment of 0.004

Low Emittance Tuning Simulation

Vertical emittance (pm) after one-at-a-time fit:
(Orbit then dispersion then coupling)

Magnet Alignment	BPM Errors	Mean	1 σ	90% Success	95% Success
Nominal	None	1.6	1.1	3.2	4.0
"	Nominal	2.0	1.4	4.4	4.7
"	Worse	2.8	1.6	4.8	5.6
2 x Nominal	None	7.7	5.9	15	20
"	Nominal	8.0	6.7	15	21
"	Worse	11	7.4	20	26

With *nominal* magnet alignment,
we achieve emittance of < 6 pm for 95% of seeds
with *nominal* and *worse* BPM resolution

Correction Algorithm

1. Measure and correct orbit using all dipole correctors
2. Measure and correct betatron phase and coupling using all quadrupoles and skew quads.
3. Measure orbit & coupling & vertical dispersion
4. Fit simultaneously using skew quads and vertical steerings

$$\text{Min}\left(\Sigma_{ijk}\ \{w_v[\text{kick}_i]^2 + w_{sq}[k_j]^2 + w_{\eta 2}[\Delta\eta_k]^2 + w_c[C_k]^2\}\right)$$

Correction Algorithm

Modeling of correction procedure

Magnet Alignment	BPM Errors	Fit $\Delta y, \eta_y, C_{12}$	Mean	1 σ	90% Success	95% Success
2 x Nominal	Worse	One-at-a-time	11	7.4	20	26
"	"	Simultaneous	6.5	6.7	9.6	11.3

- 2 x nominal survey alignment
- 20 µm relative and 100µm absolute BPM resolution
- 2 mrad BPM tilt

→ Correction algorithm yields tuned emittance < 12 pm for 95% of seeds

Alignment is close to *nominal*

BPM resolution between *nominal* & *worse* (initial state of new system)

but BPM *tilt* ~ 10mrad (systematic measurement error)

Measurement and Correction

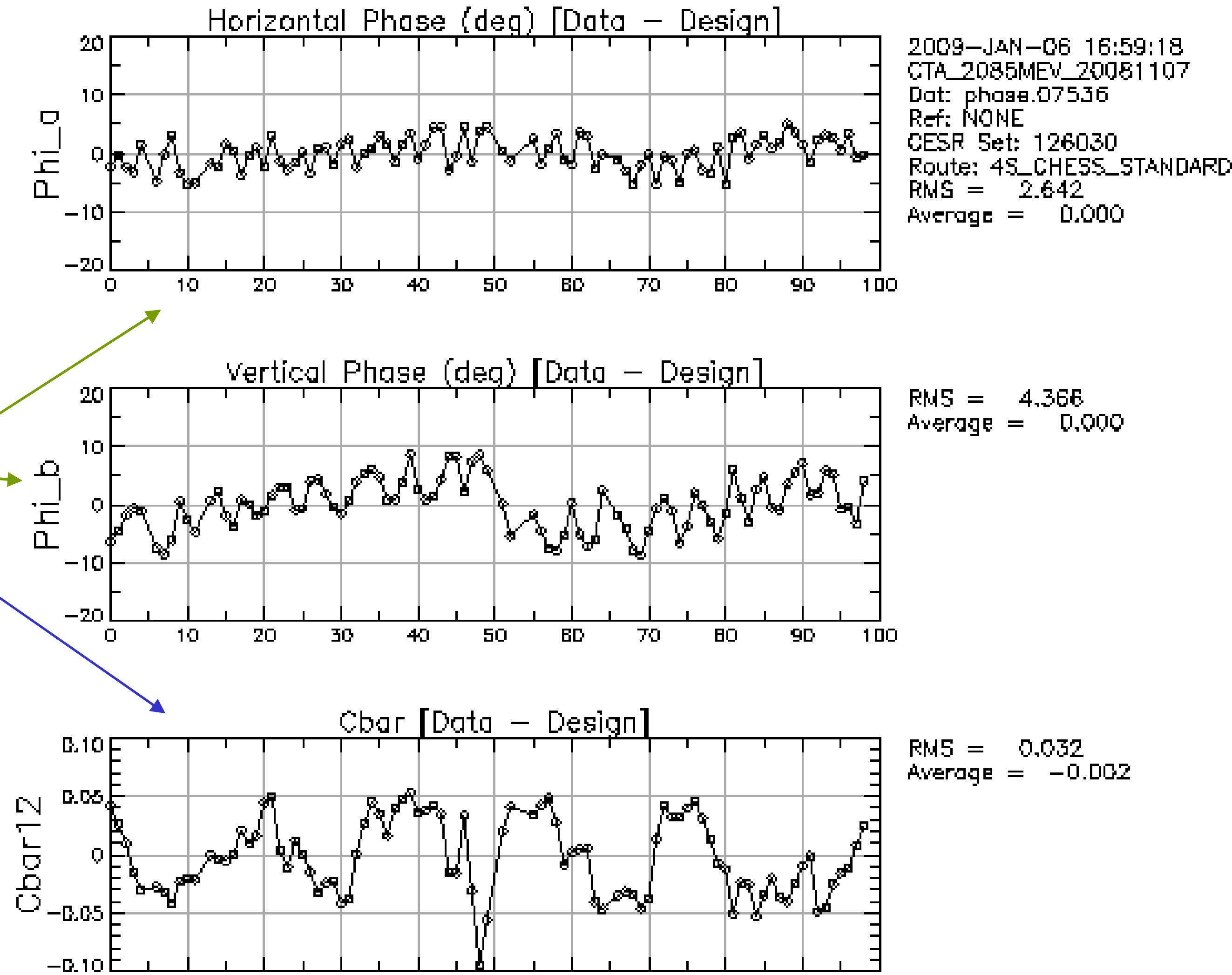
Low emittance tuning
Experimental procedure

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)



Measured with older relay BPM system

Measurement at January 09 startup after 2 month CHESS (5.3GeV) run

Measurement and Correction

Low emittance tuning
Experimental procedure

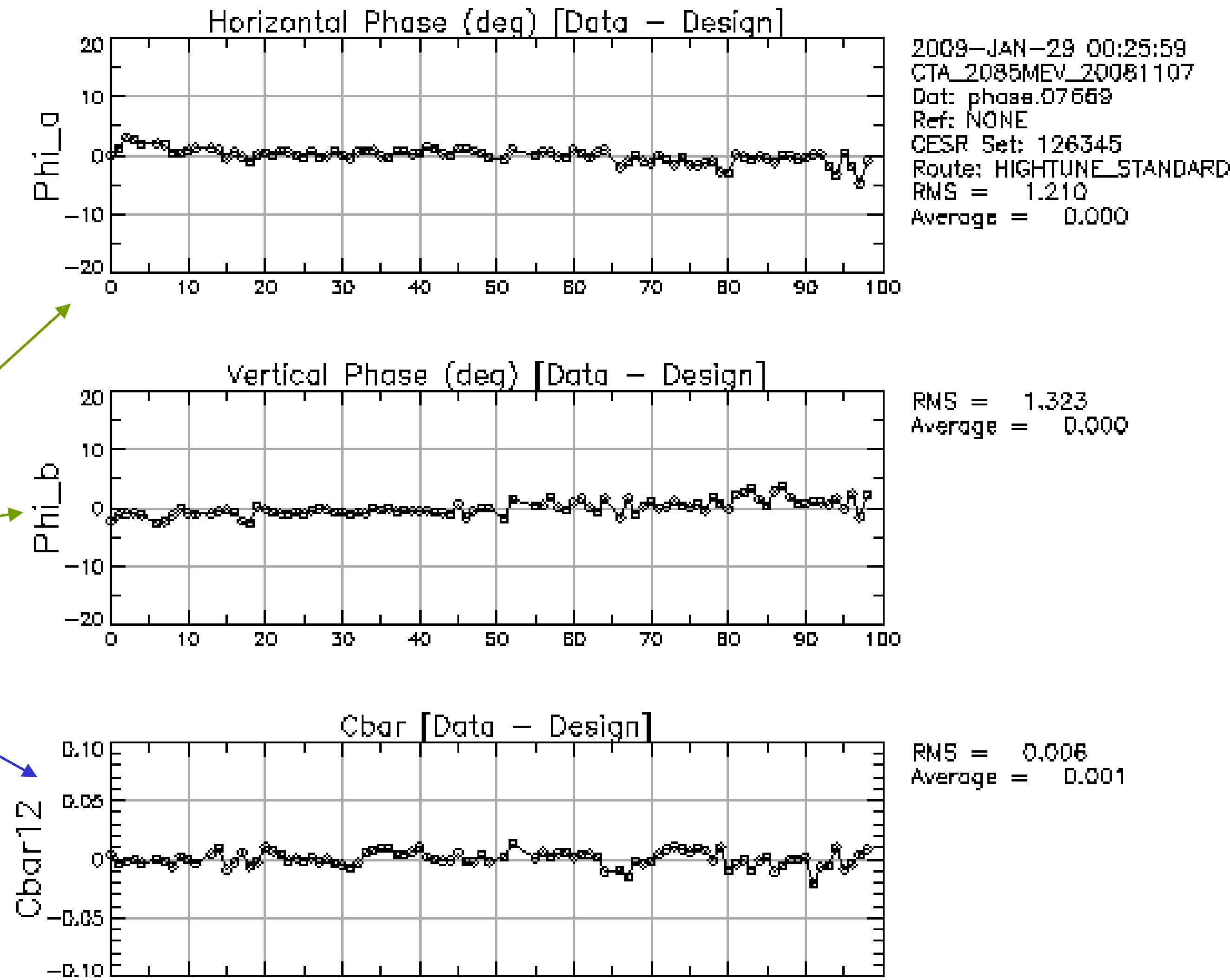
LET - initialization

-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 ($\sqrt{\langle \bar{C}_{12}^2 \rangle} \sim 0.6\%$)

Measured with older relay BPM system



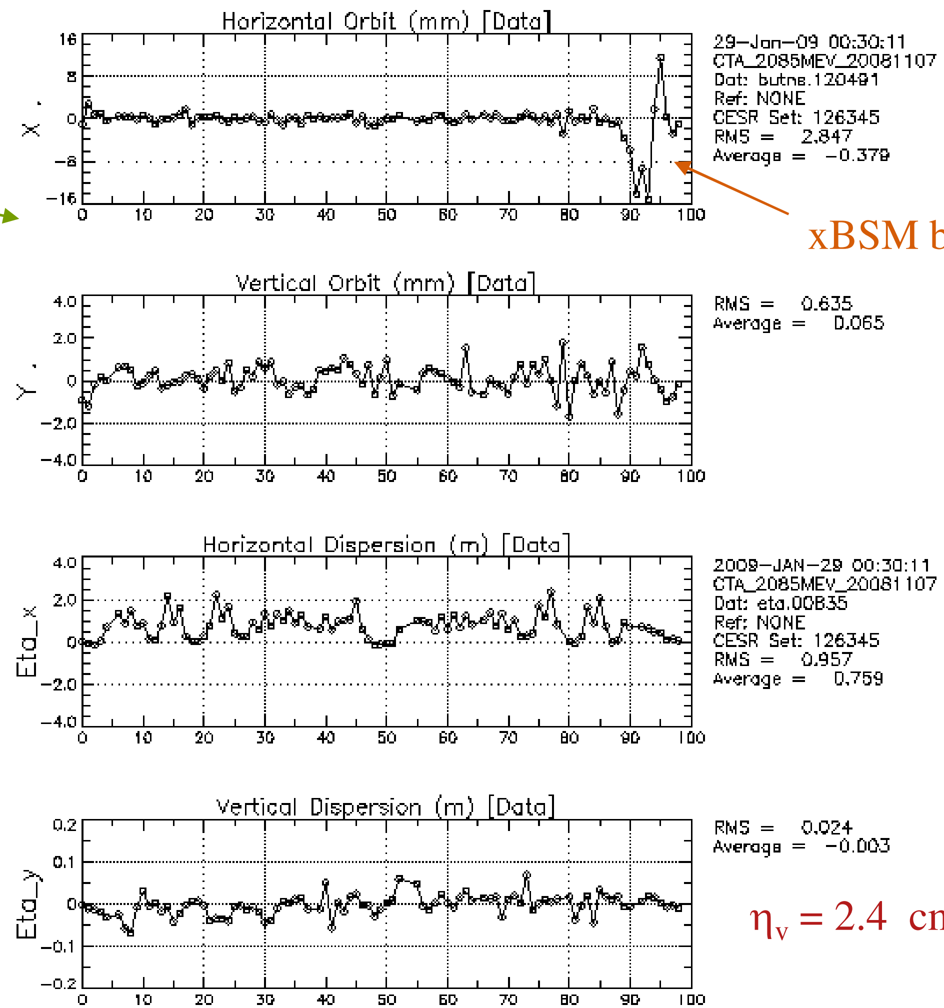
β-phase and coupling after correction

Measurement and Correction

Low emittance tuning

Orbit

A feature of the orbit is the closed horizontal bump required to direct xrays onto x-ray beam size monitor



xBSM bump

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

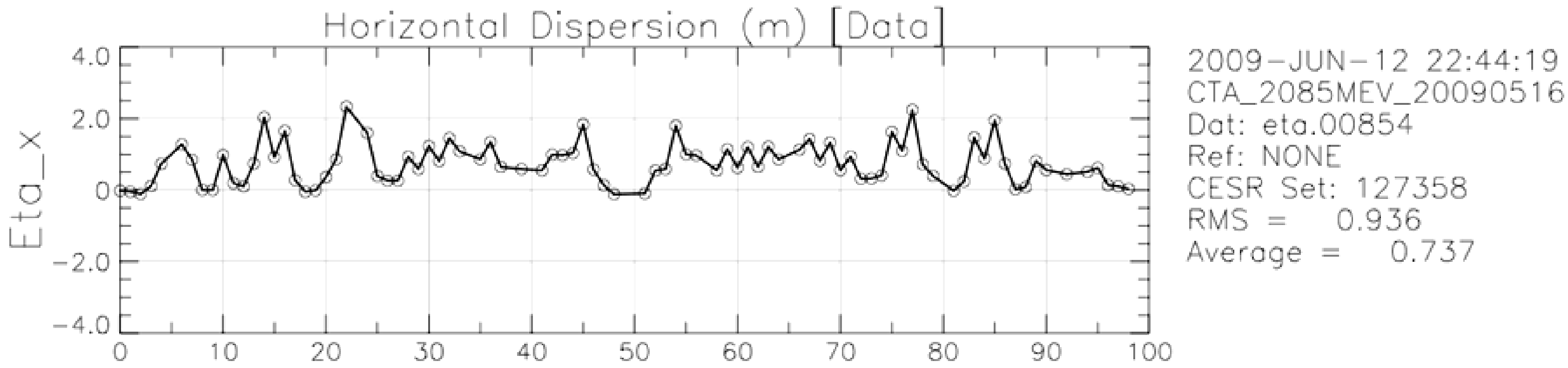
Residual vertical dispersion
RMS ~ 2.4cm - Signal or systematic?
Accuracy of dispersion measurement is limited by BPM systematics

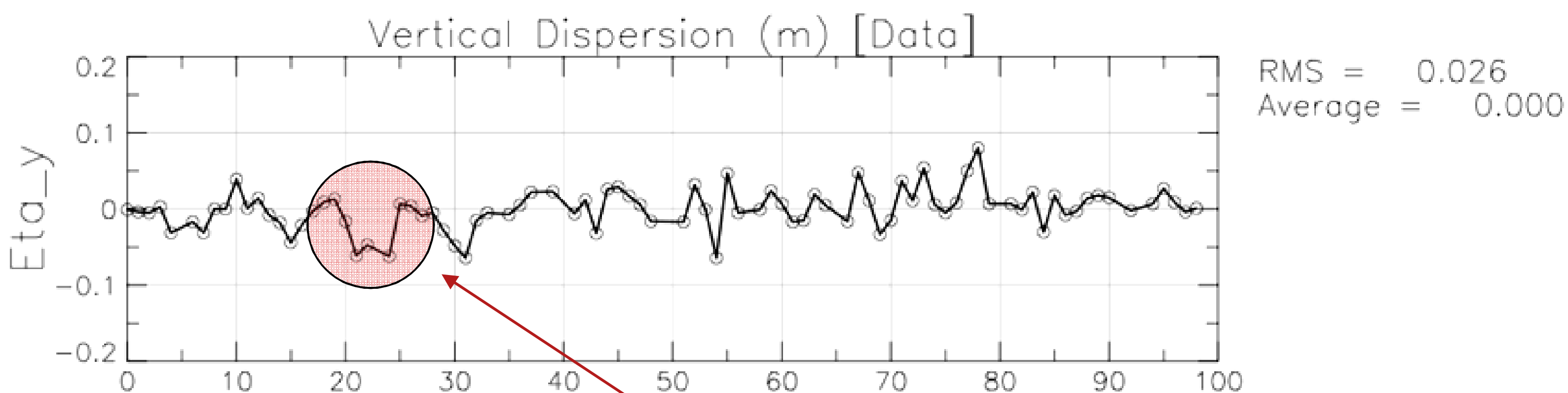
$\eta_v = 2.4$ cm rms

Measured with older relay BPM system

Note: Residual vertical dispersion 1 cm, corresponds to $\varepsilon_v \sim 10$pm

BPM Systematics





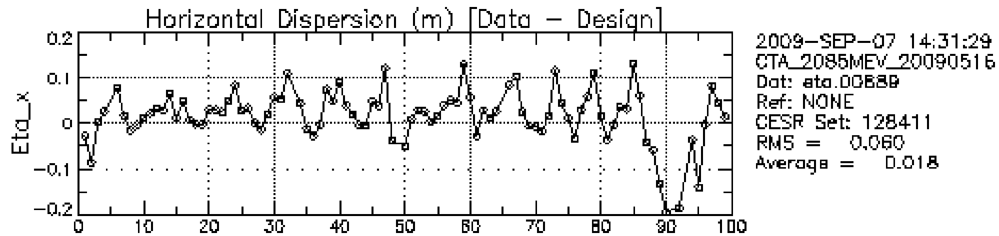
$\eta_v \sim \eta_h \, \theta_{BPM\text{-}tilt}$

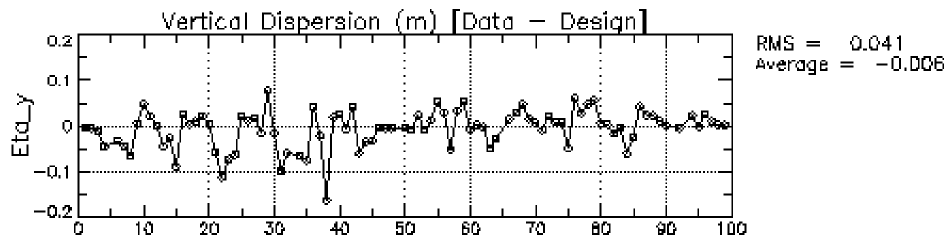
Real or ~ 25 mrad BPM tilt ?

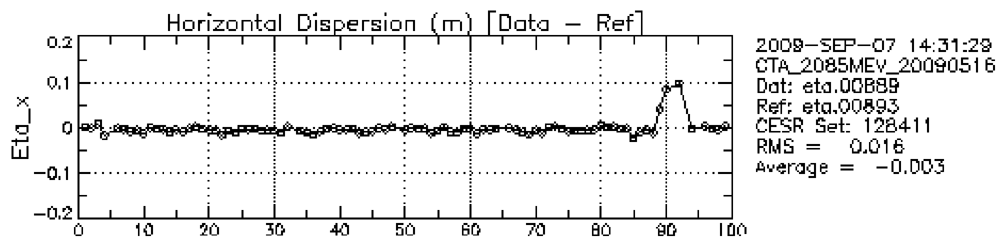
CBPM II Modules: V Dispersion

After Installation of 80+ CBPM II modules

Dispersion Measurement

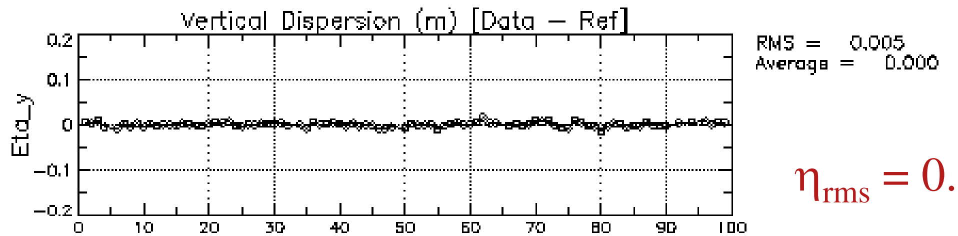






New digital BPMs ⟷ Old relay BPMs

Reproducibility



$\eta_{rms} = 0.5$ cm

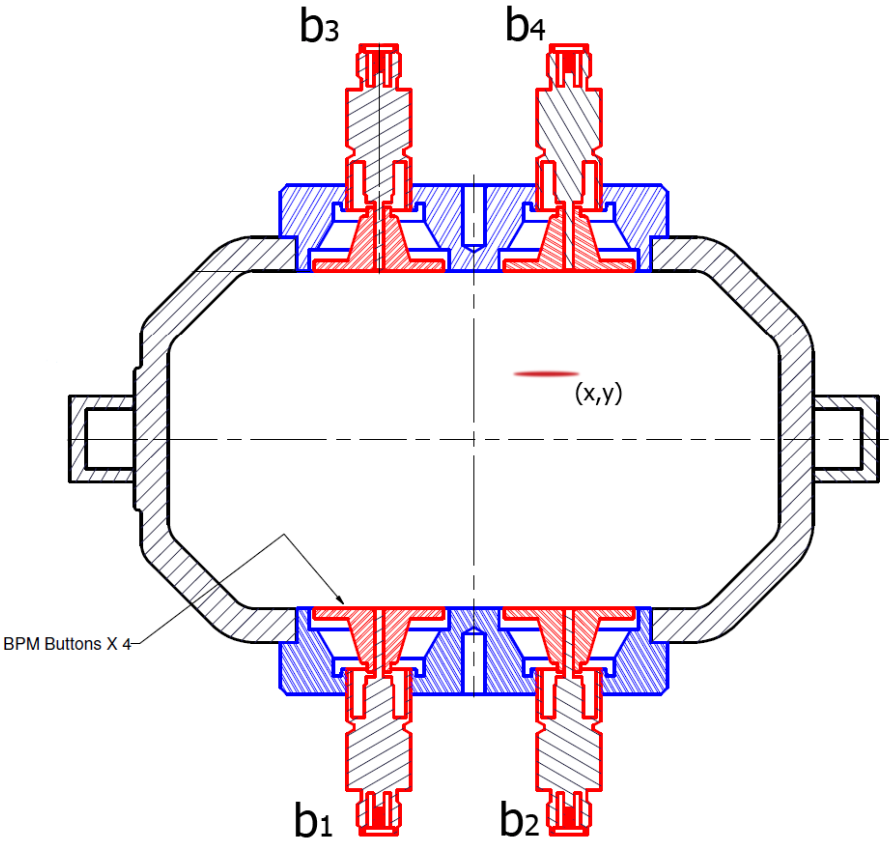
BPM Systematics - Gain Mapping

- For each x-y position in the BPM there is a corresponding set of button intensities. $B_i = I\,F_i(x,y)$
  - Measure B_i and invert to find x,y
  - If there are gain errors g_i then

    $B_i / g_i = I\,F_i(x,y)$
  - Multiple position measurements allow a best fit determination of g_i
  - For measurement *j*

$$b_{ij} = g_i \cdot I_j \cdot F_i(x_j, y_j) + b_i^{offset}$$

$$\chi^2 = \sum \left(b_{ij}^{(meas)} - b_{ij}^{(model)}\right)^2$$



- Initial measurements and analyses have been completed to test the procedure.
- Another set of measurements will be undertaken after the final CBPM modules are installed.

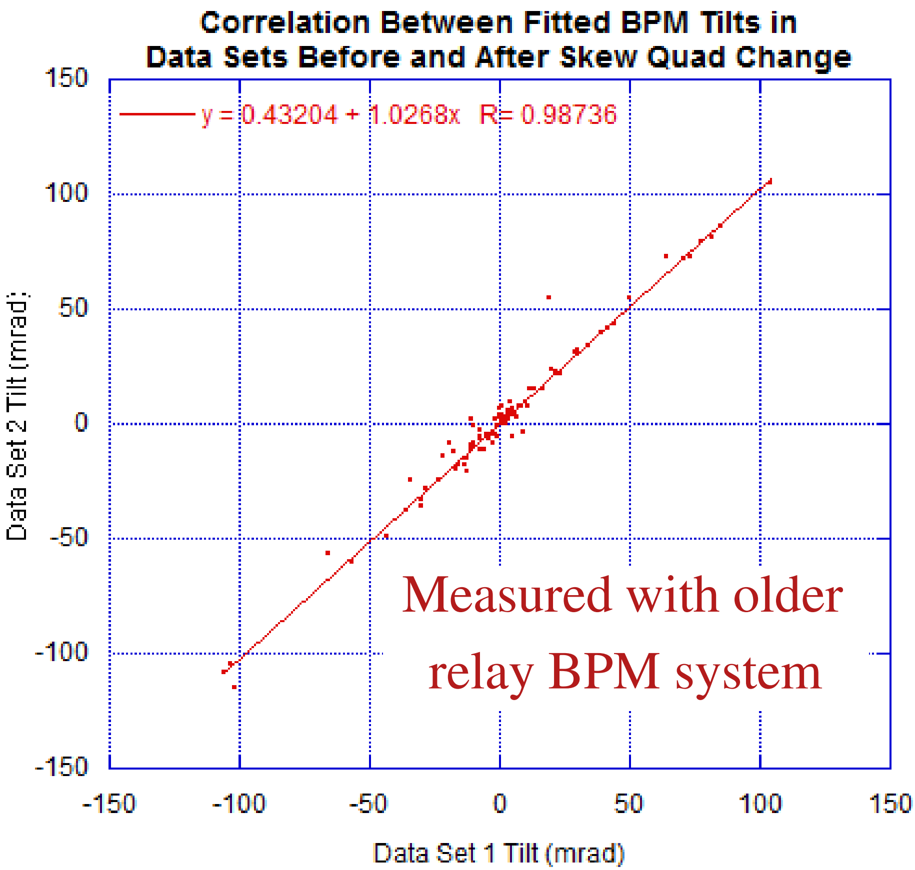
Test of ORM Analysis for BPM Tilts

BPM tilt

- “measured” $\eta_v \sim \theta\eta_h$
  where θ = BPM tilt

Since $<\eta_h> \sim 1$m, BPM tilt must be less than 10mrad if we are to achieve $\eta_v <1$cm

We use ORM and phase/coupling measurement (Jan. 2009) to determine θ:



ORM data set ~ 140 measured orbit differences
- Take data set 1
- Vary 8 skew quads and repeat
- Take data set 2

Fit each data set using all quad(k), skew(k), BPM(θ)

Correlation of fitted BPM tilt (θ)
$\Delta\theta < 10$ mrad

Consistent with $\sigma_{BPM}(\Delta x) \sim 35\,\mu m$

BPM Tilts via Coupling Measurements

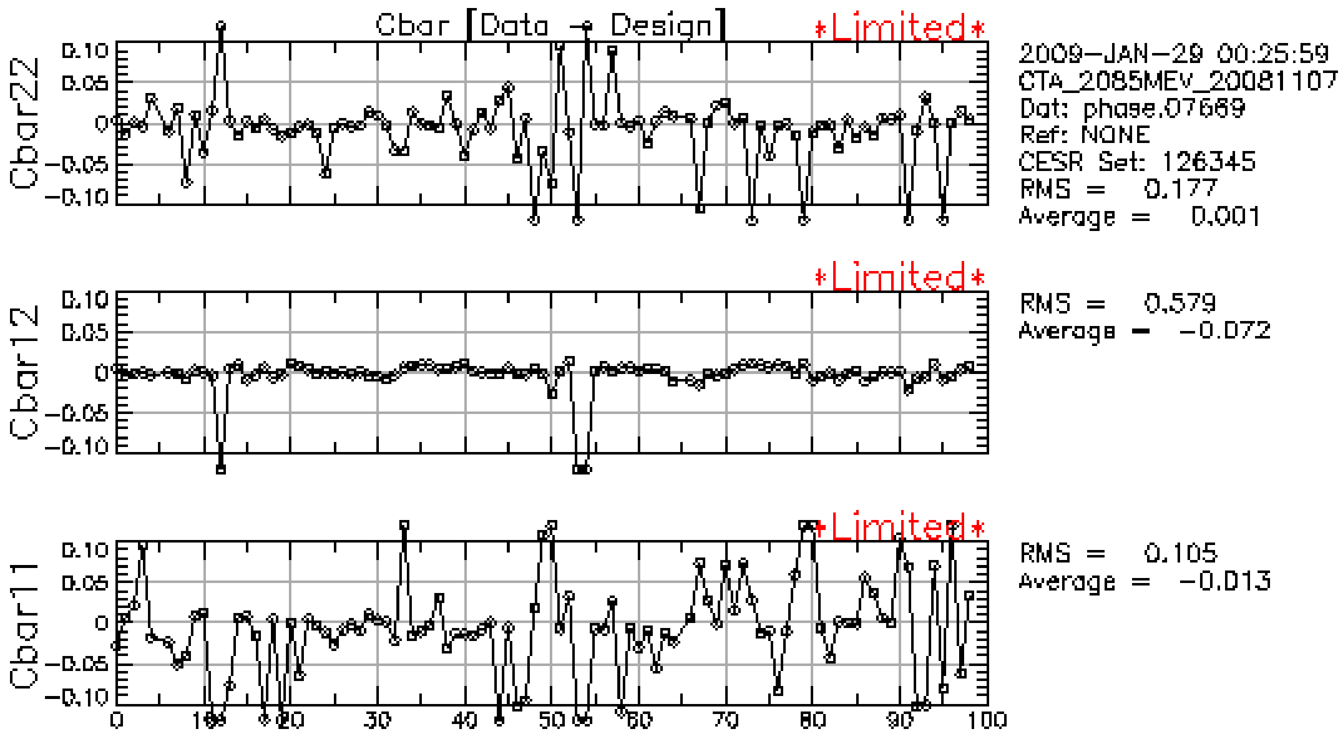
Alternate Method via Measurement of C_{11}, C_{12}, C_{22}

discriminates BPM tilt and transverse coupling (since C_{12} independent of tilt)

C_{11} & C_{22} measure tilt of beam ellipse
(which can easily be confused with tilt of BPM)

C_{12} measures component of vertical motion that is out of phase with horizontal
(~ insensitive to BPM tilt)

Measured with older relay BPM system



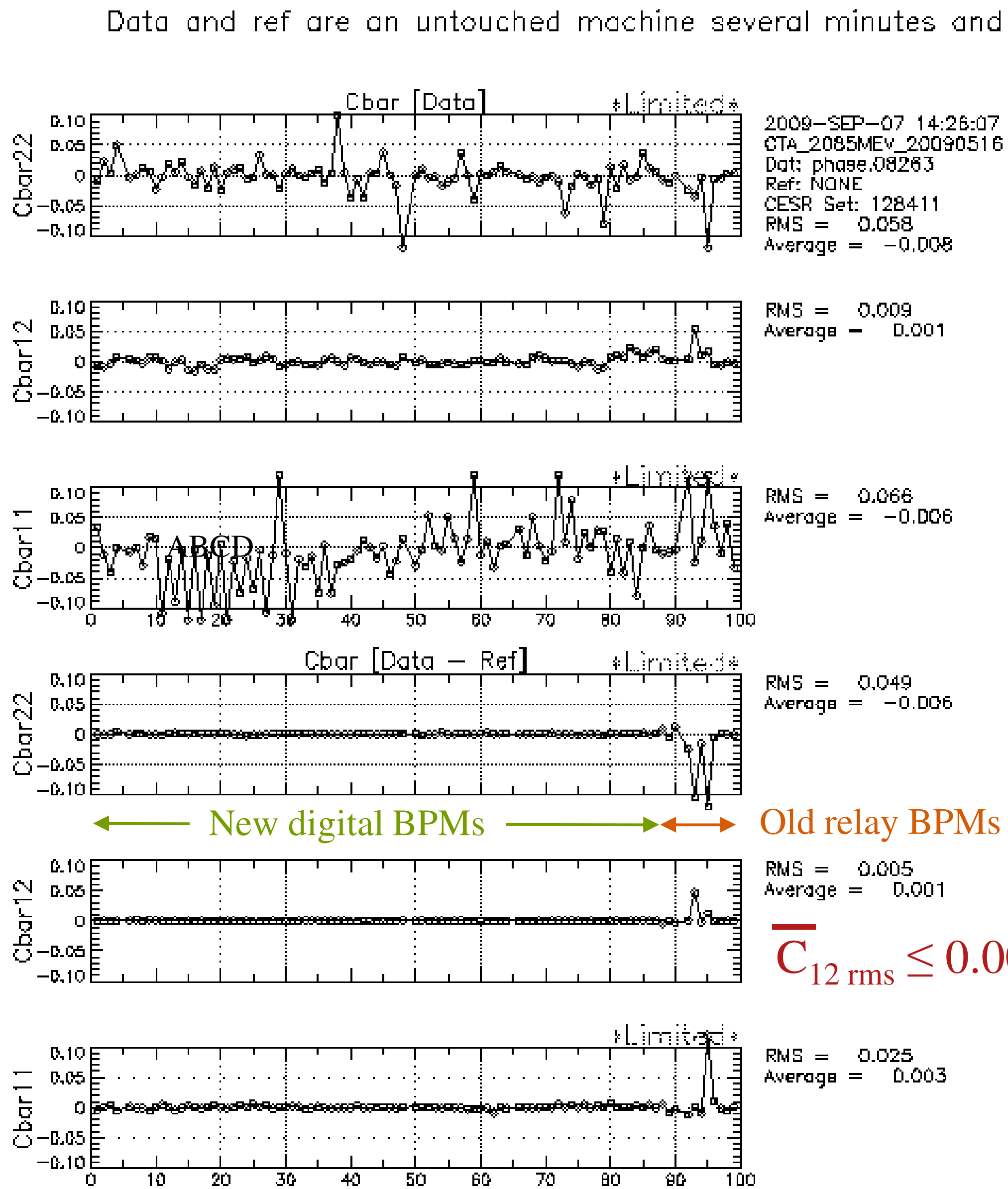
Quality measurement of C_{11} & C_{12} would give a direct measure of tilt

CBPM II Modules: Coupling

After Installation of 80+ CBPM II modules

Coupling Measurement

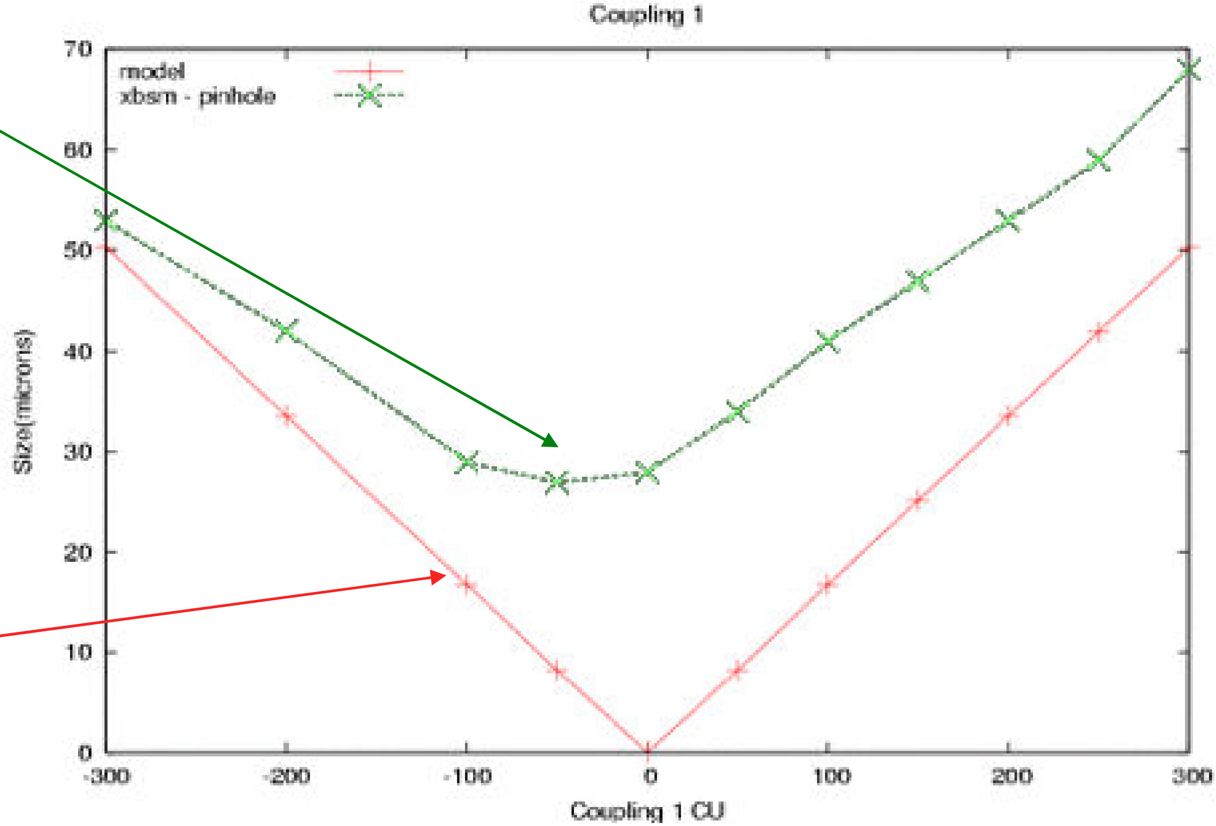
Reproducibility



$\overline{C}_{12\ \mathrm{rms}} \leq 0.005$

Coupling & V Dispersion Controls

Measurement
With x-bsm
Pinhole optics



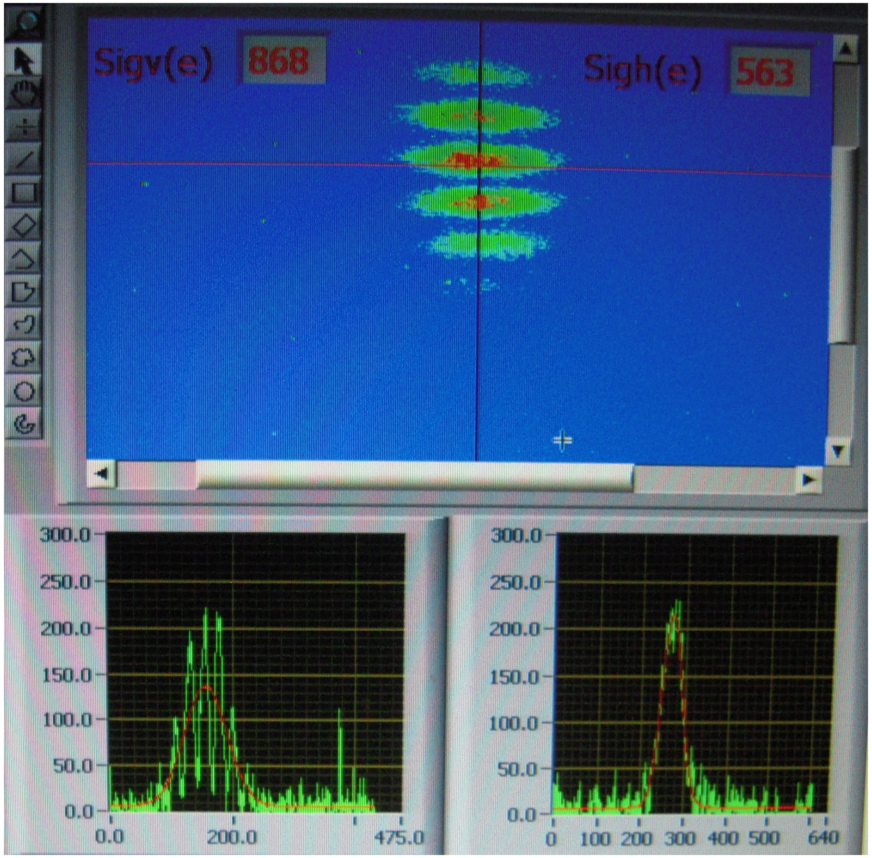
Model
- no errors

Coupling_1 - closed coupling bump -

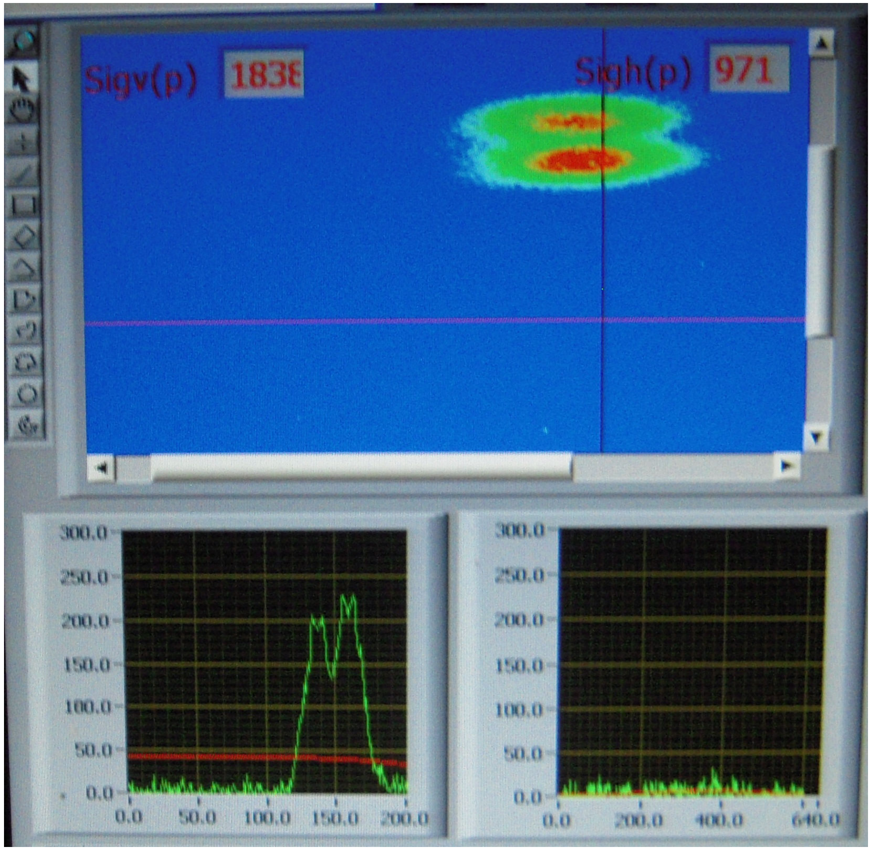
beam size changes due to vertical emittance and finite vertical dispersion at xbsm source

vBSM Images

Visible Light Beam Size Monitor



Interferometer Image



Vertical Polarization Image

Lifetime Measurements

Touschek lifetime

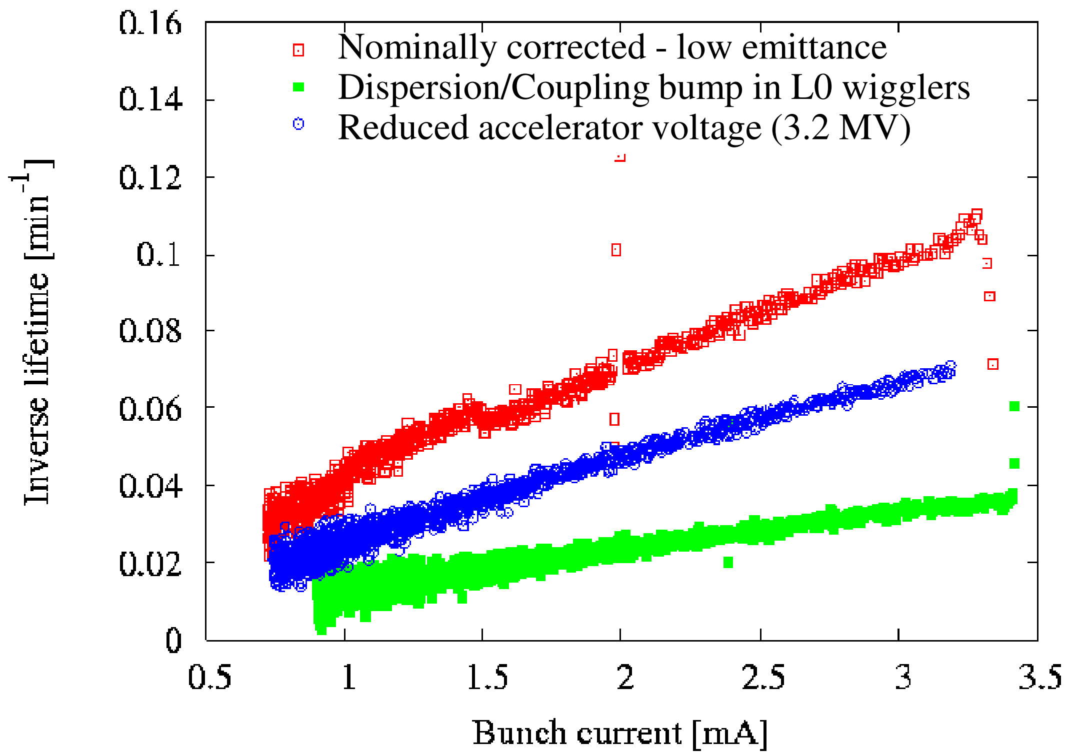
CesrTA operates in a regime where lifetime is current dependent

Intrabeam scattering kicks particles outside of energy aperture

Touschek lifetime depends on energy aperture

$$\frac{dI}{dt} = -\frac{1}{c}I - \frac{1}{b}I^2$$

$$1/\tau_{eff} = -\frac{1}{I}\frac{dI}{dt} = \frac{1}{c} + \frac{1}{b}I$$



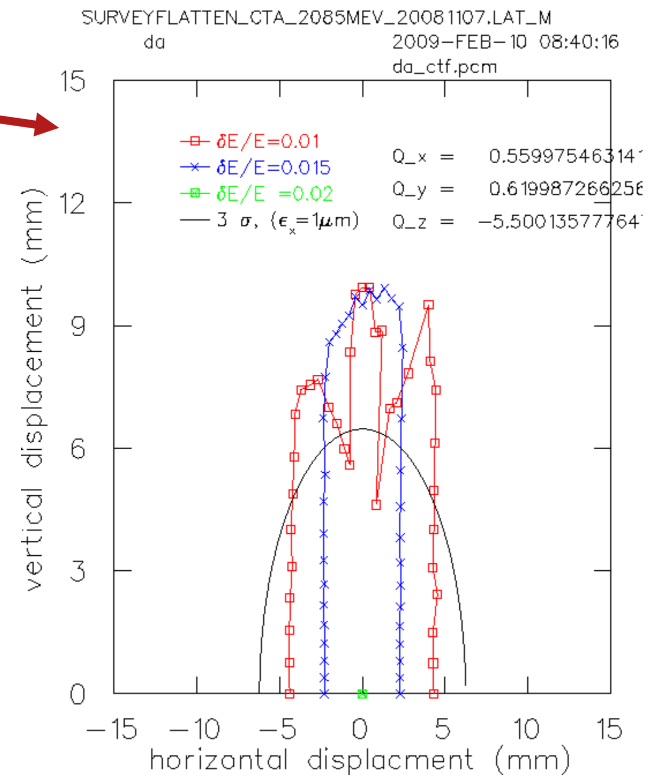
The Touschek parameter (b) decreases with:

- increasing beam size
  (introducing η_v in damping wigglers)
- increasing bunch length
  (reduced accelerating voltage)

Dynamic Energy Aperture

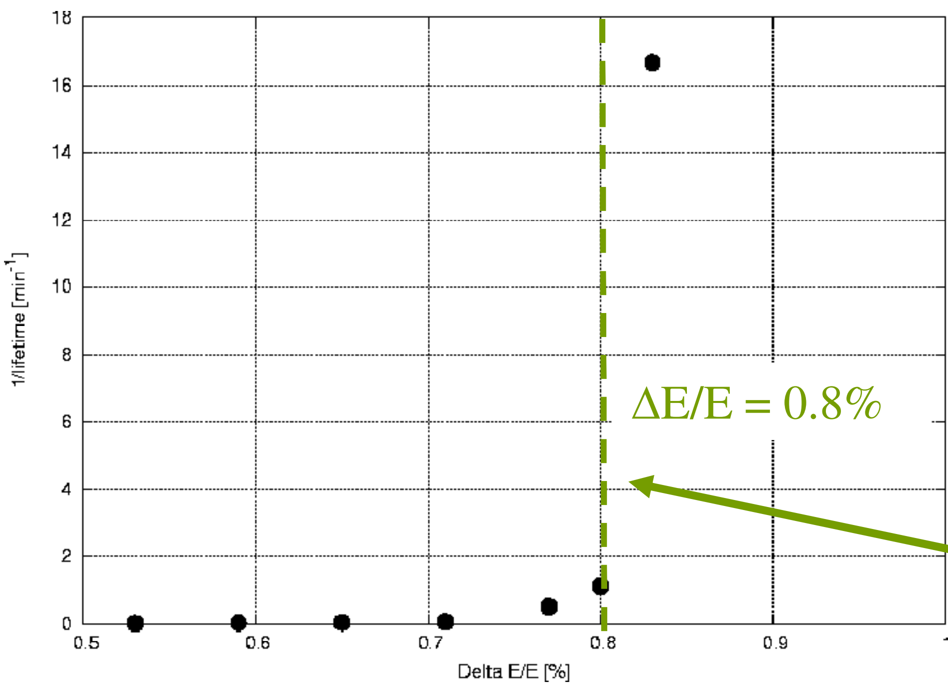
Interpretation of lifetime measurements requires knowledge of dynamic energy acceptance

Tracking study indicates energy acceptance ~1.0%



Tracking model includes: 1) magnet misalignments 2) wiggler and quadrupole nonlinearity 3) orbit errors

Nonlinearity of dipole correctors and sextupoles has not yet been included.



Determine energy acceptance experimentally by measuring lifetime vs energy offset

$\Delta E/E \sim 1/\alpha_p (\Delta f_{RF}/f_{RF})$

$\rightarrow$Energy acceptance > 0.8%

Intra Beam Scattering

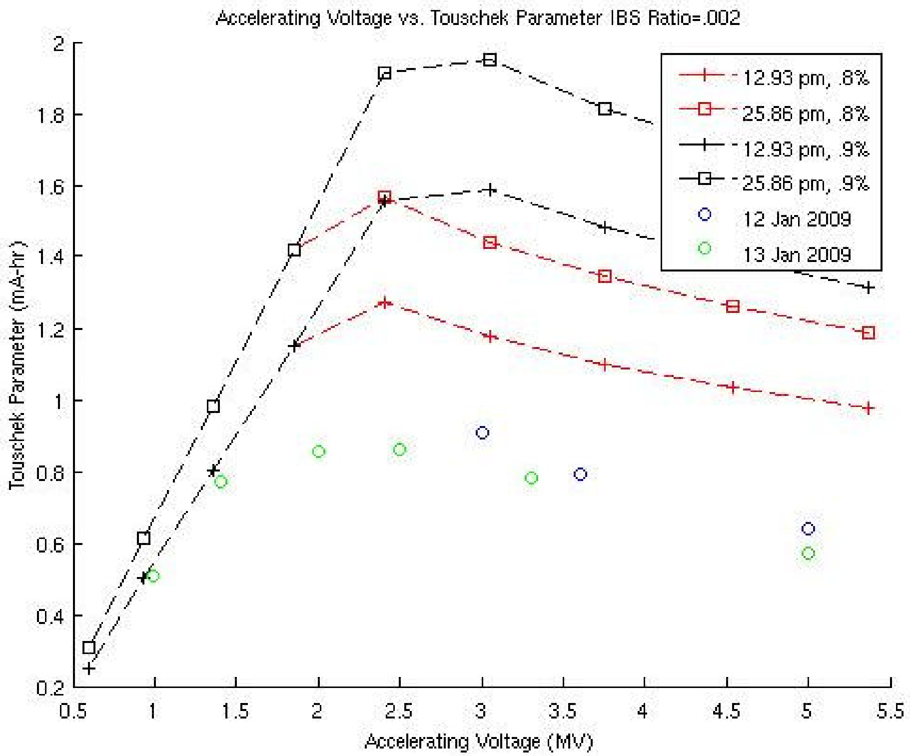
Calculate Touschek parameter vs accelerating voltage for:

- dynamic energy acceptance 0.8% < ΔE/E < 0.9%
- ε_v (zero current): $0.5\%\ \varepsilon_h \leq \varepsilon_v \leq 1\%\ \varepsilon_h$

With IBS

- assuming zero current ε_v is due exclusively to residual η_v

The lifetime measurements suggest zero current beam size set by ε_v < 12 pm



Plan to measure

- vertical emittance
- and lifetime vs bunch current

Strong energy dependence for

- Touschek lifetime ~ E^2
- IBS emittance dilution ~ E^4

To measure dependencies: 1.8 to 5.3 GeV

Priorities from workshop: Critical & Very High

(Moderate priority items not included below) [work undertaken]

- Precision dispersion and coupling measurements
  - Requires CBPM II modules [80% installed]
- Low emittance tuning controls
  - Coupling controls [designed, partially tested]
  - Vertical dispersion controls [basic design finished]
  - Low strength sextupoles (uniform) [installed]
- Instrumentation
  - BPM - tilts - C_{11} & C_{22} vs C_{12} [preliminary studies complete]
  - Measurement of betatron phase advance for different bunches in a train [software testing underway]
  - xBSM - xray beam size [see DPP talk, next]
  - vBSM (visible light beam size) using interferometer and vertical polarization [imaging functional, studying detector tilt, data analysis underway]
  - Touschek lifetime measurements [analyzed at one energy, TBD at others]

Objectives: Reprise

Attain sufficiently low vertical emittance to enable exploration of

- dependence of electron cloud on emittance
- emittance dilution effect of e-cloud

- Design/install low emittance optics ($1.8 < E_{beam} < 5.0$ GeV)
  - Have loaded and corrected optics at all energies
- Develop beam-based techniques for characterizing beam position monitors
  - 80% CBPM installed; offsets measured, 1st Pass for Gains/Tilts via ORM ==> BPM tilt
- Also for measuring and minimizing sources of vertical emittance including
  - Misalignments - Survey: important errors within specs
  - Orbit errors - Standard quad centering procedure for BPMs
  - Focusing errors - new CBPM: ϕ_h, $\phi_v < 0.2$ degrees
  - Transverse coupling - new CBPM: C_{12} reproduces to 0.01 as needed
  - Vertical dispersion - new CBPM: η_v reproduces to 5 mm as needed
- Single bunch/single pass measurements of vertical beam size - first data taken
- Beam current dependence of lifetime in terms of beam size - preliminary data
- Measure dependencies of beam size/lifetime on - to be done
  - Beam energy
  - Bunch current
  - Species