Low Emittance Tuning in CESR TA

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June 25, 2009

Objectives

Attain sufficiently low vertical emittance to enable exploration of

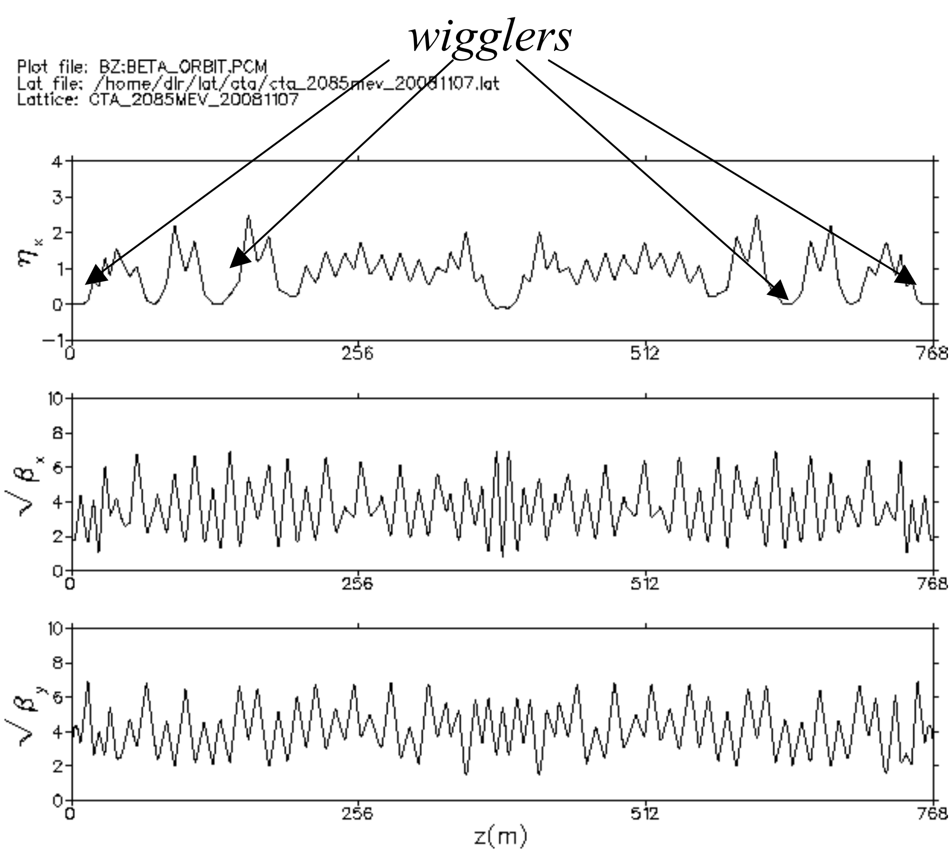
- dependence of electron cloud on emittance
- emittance diluting effect of e-cloud

- Design/deploy 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
- And for measuring and minimizing sources of vertical emittance including
  - Misalignments
  - Orbit errors
  - Focusing errors
  - Transverse coupling
  - Vertical dispersion
- Develop single bunch/single pass measurement of vertical beam size
- Characterize current dependence of lifetime in terms of beam size
- Measure dependencies of beam size/lifetime on
  - Beam energy
  - Bunch current
  - Species
  - Etc.

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

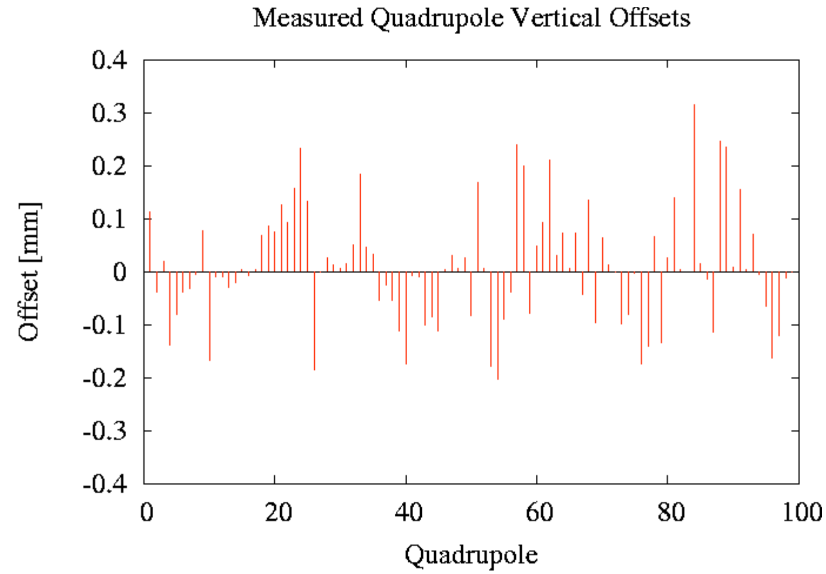
Energy [GeV]	2.085
Wiggler[T]	1.9
Qx	14.57
Qy	9.6
Qz [4.5MV]	0.055
ε_x[nm]	2.6
α_p	6.76e-3
σ_l[mm]	12.2
σ_E/E[%]	0.81

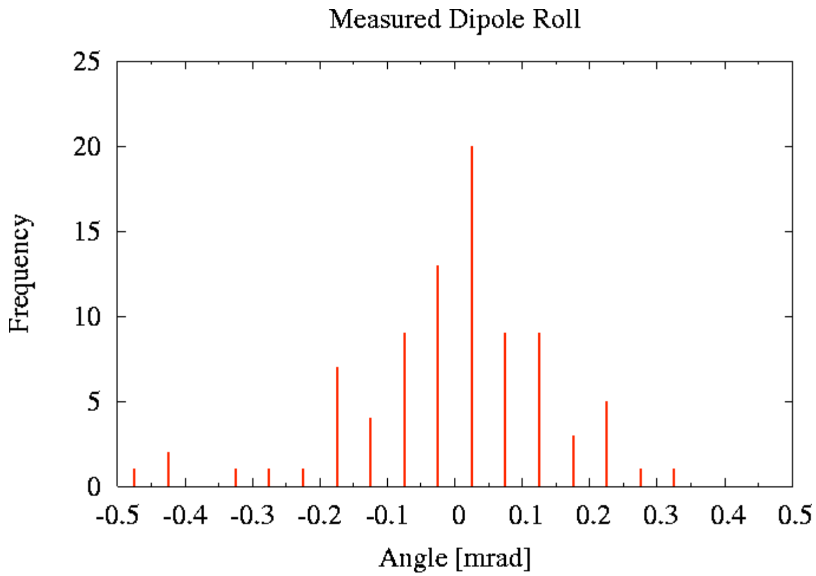


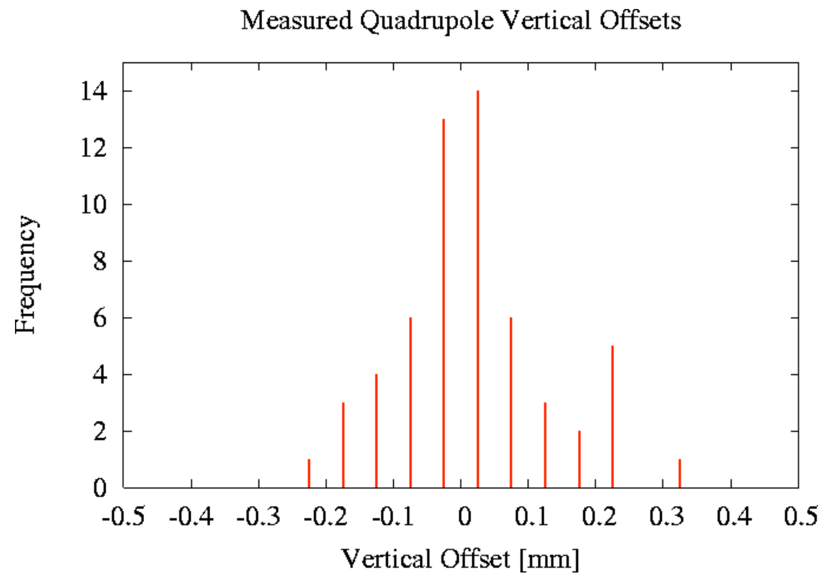
Magnet Alignment

Survey network 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	Status June 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

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

Alignment	BPM Errors	Mean	1 σ	90%	95%
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 5-10pm 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 & dispersion
4. Fit simultaneously using skew quads and
   vertical steerings

(Minimize $\Sigma_{ijk}\, w_v[\mathrm{kick}_i]^2 + w_{sq}[k_j]^2 + w_{\eta 2}[\Delta\eta_k]^2 + w_c[C_k]^2$)

Modeling of correction algorithm

Alignment	BPM Errors	Fit $\Delta y, \eta_y, C_{12}$	Mean	1 σ	90%	95%
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
- 20μm relative and 100μm absolute BPM resolution
- 2mrad BPM tilt

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

Alignment is close to nominal
BPM resolution close to *worse* (even now with existing system)
but BPM *tilt* ~ 10mrad (systematic measurement error)

Measurement and correction

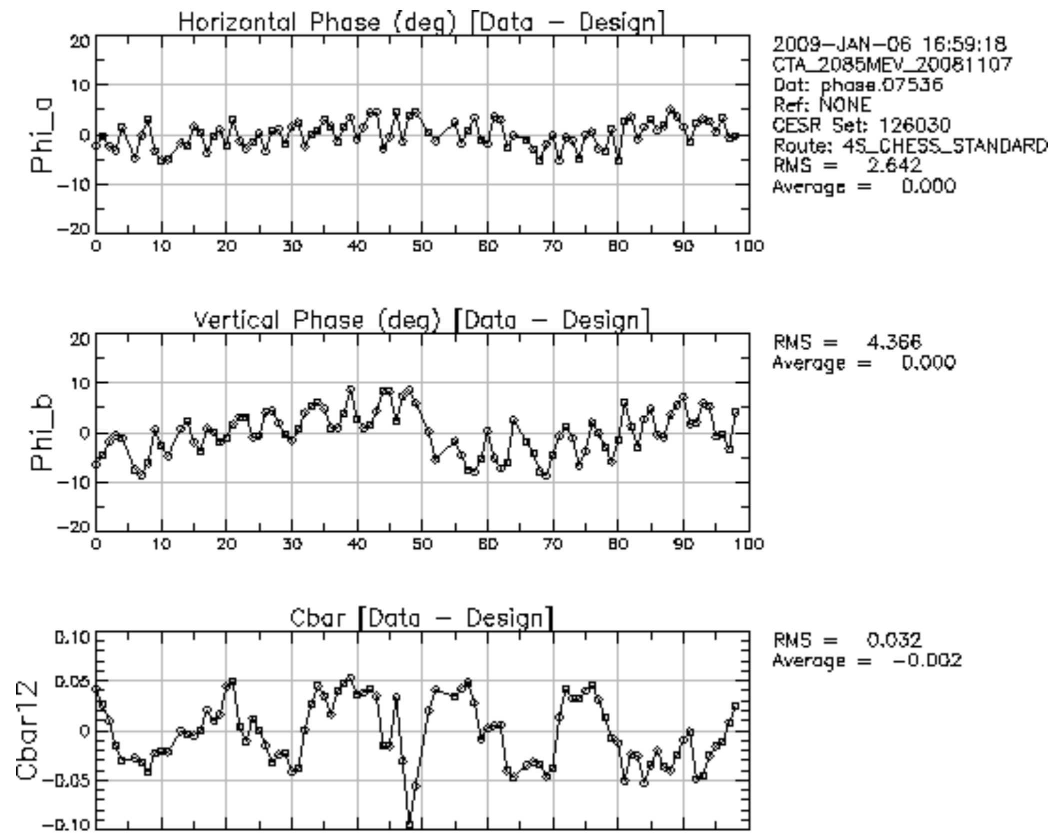
Low emittance tuning
Experimental procedure

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)



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

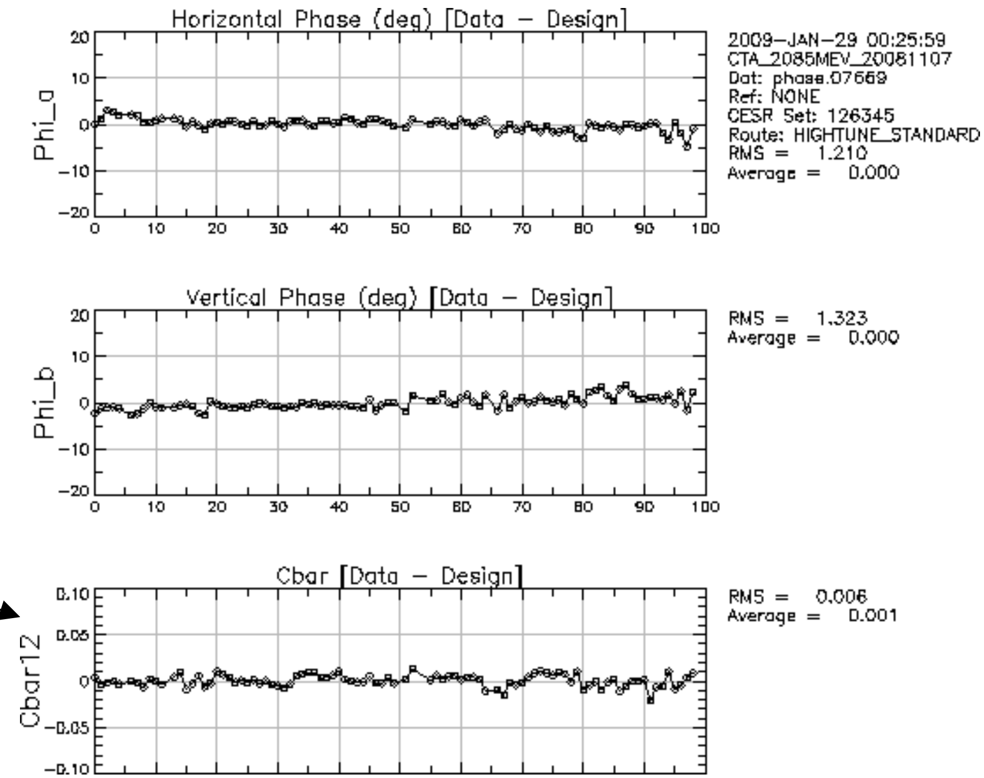
Low emittance tuning
Experimental procedure

LET - initialization

-Measure and correct orbit using all dipole correctors

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

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



β-phase and coupling after correction

Low emittance tuning

Orbit

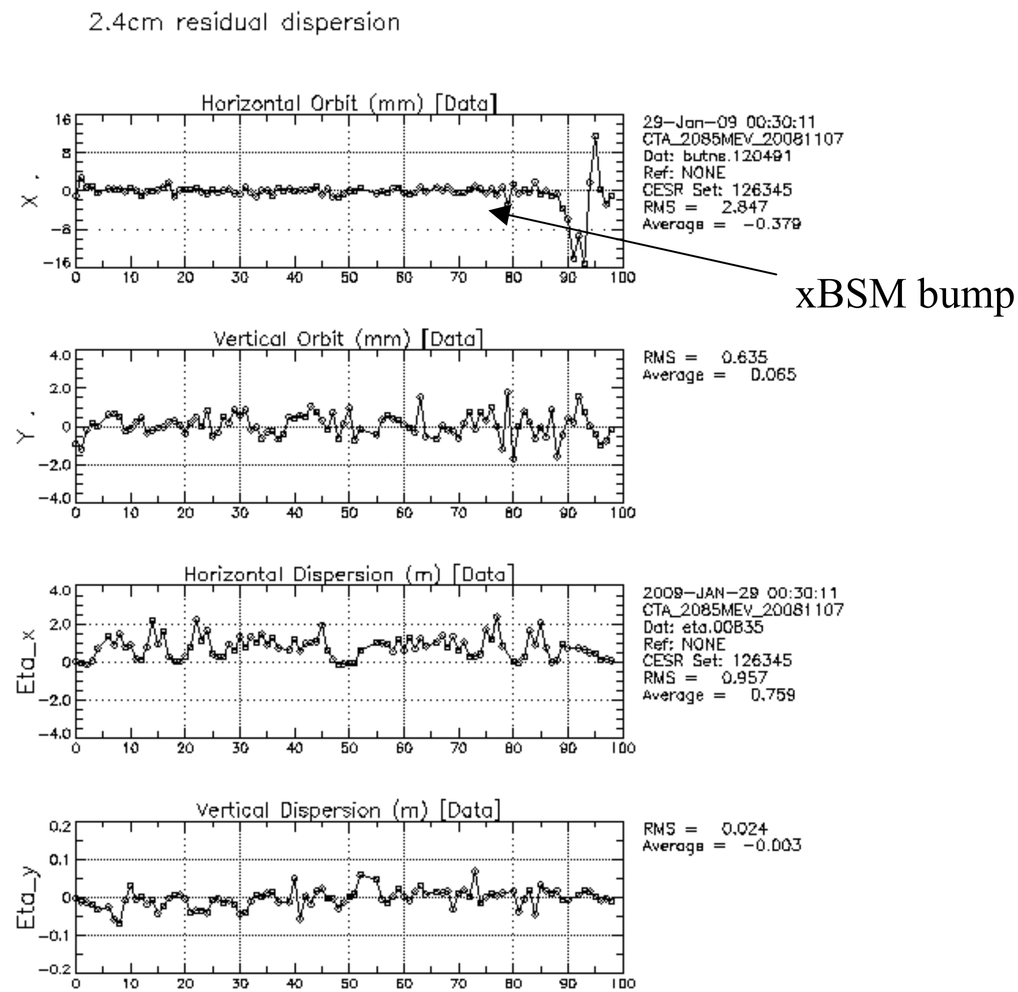
A feature of the orbit is the closed horizontal bump required to direct xrays onto x-ray beam size monitor

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

Residual vertical dispersion

RMS ~ 2.4cm - Signal or systematic?

Accuracy of dispersion measurement is limited by BPM systematics



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

Low emittance tuning

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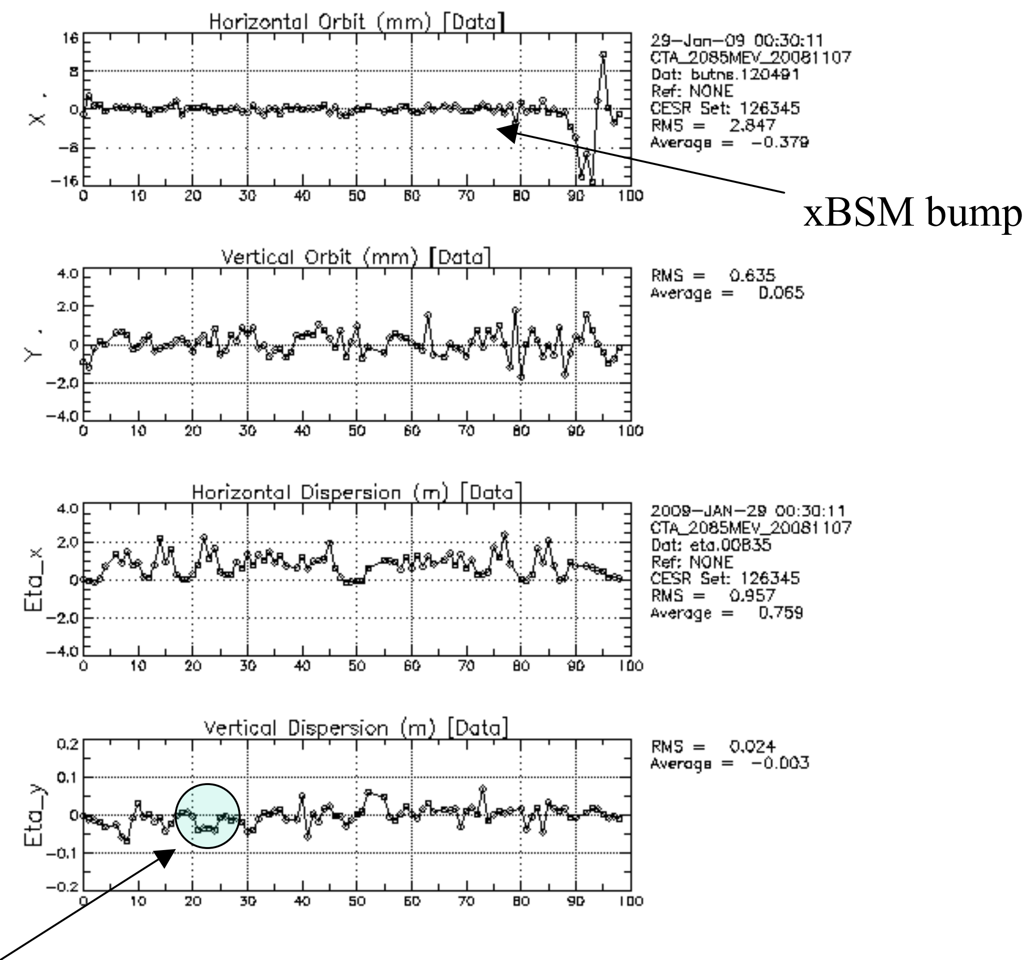
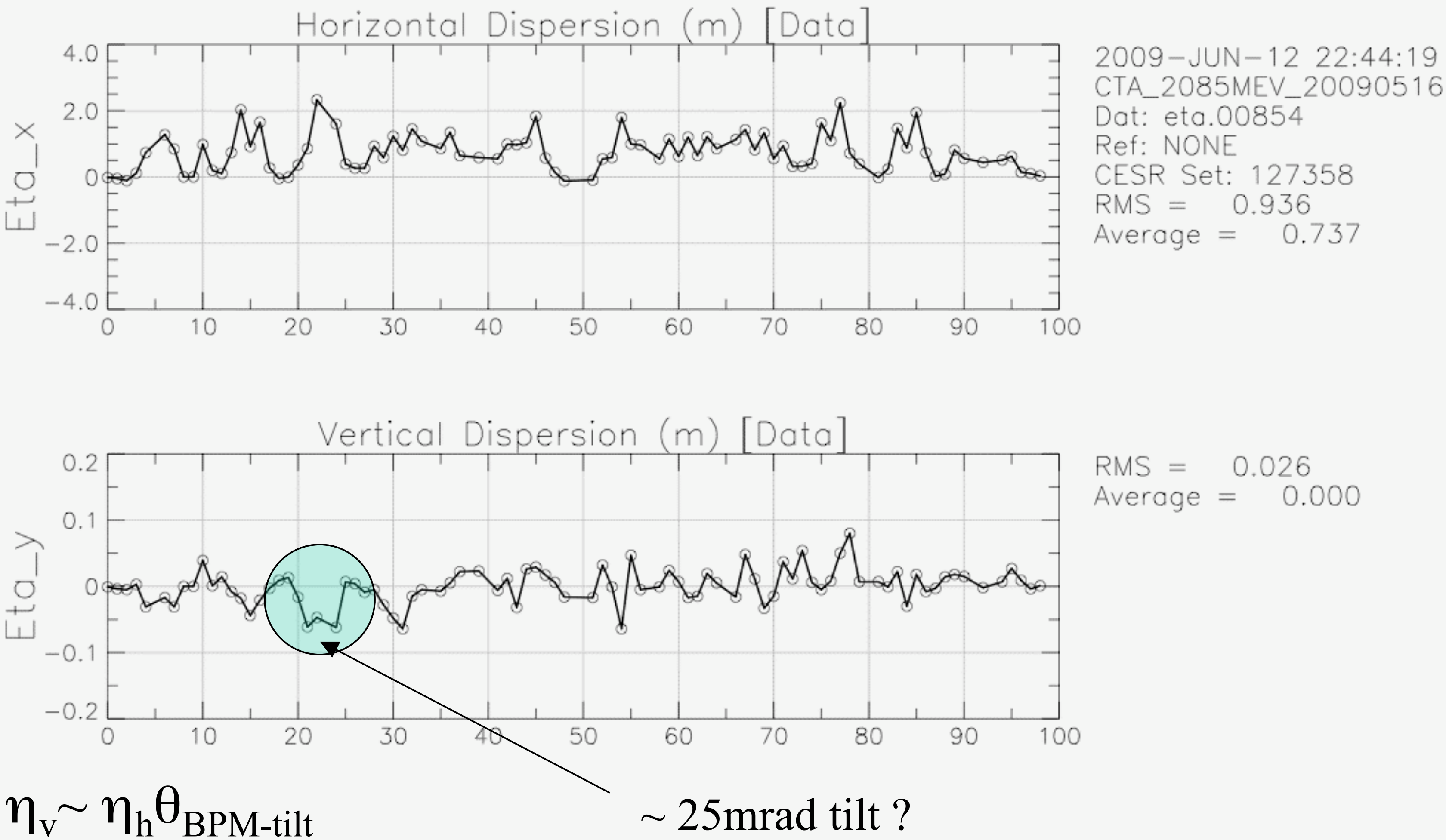
2.4cm residual dispersion



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

BPM systematics



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

Lifetime

Touschek lifetime

CesrTA operates in a regime where lifetime is current dependent

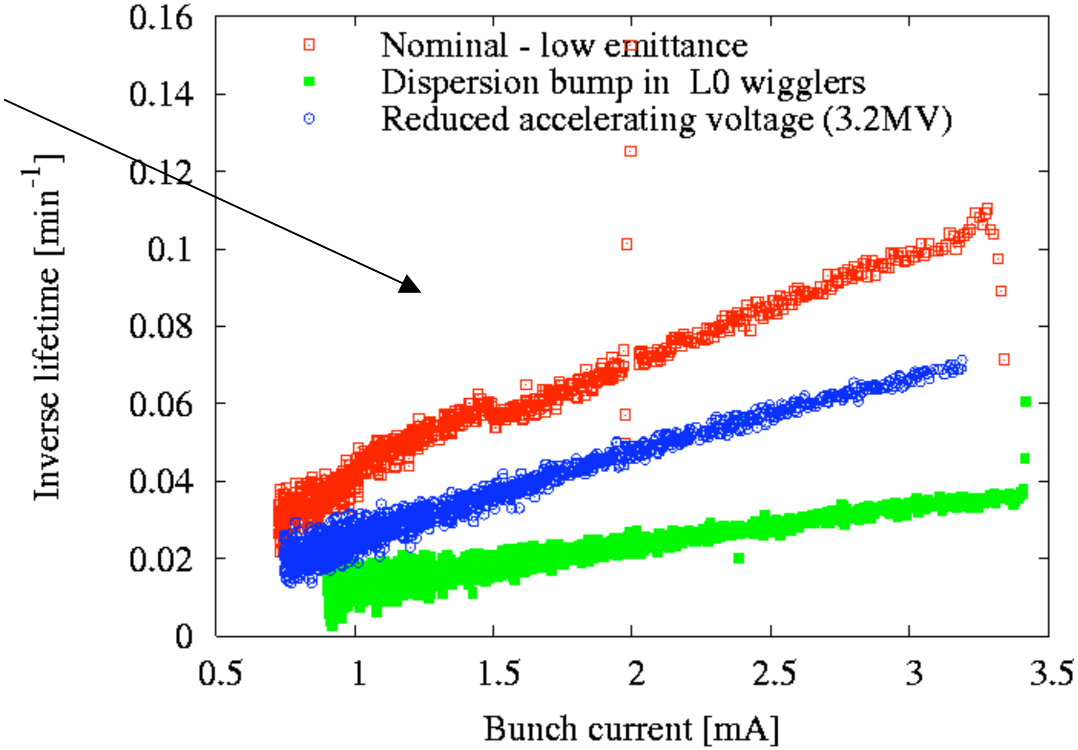
Intrabeam scattering kicks particles outside of energy aperture

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)

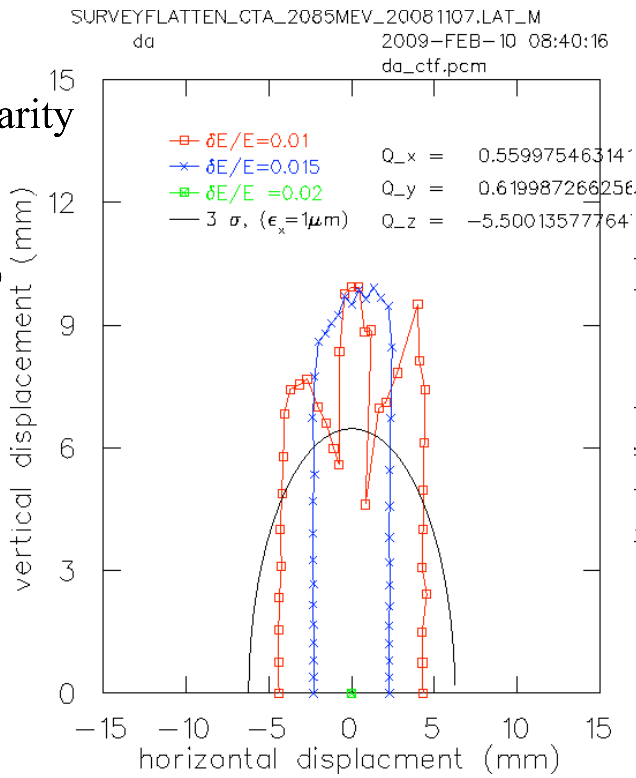


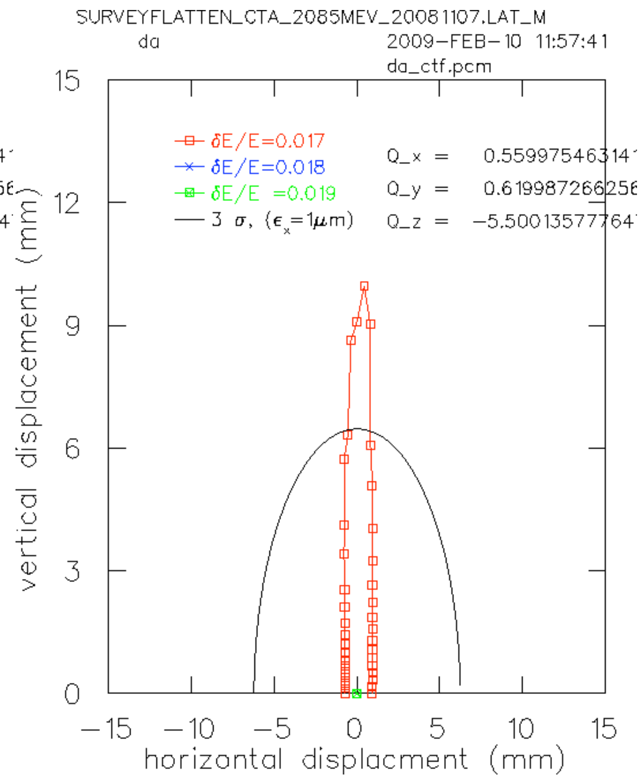
Dynamic energy aperture

Interpretation of lifetime measurements requires knowledge of dynamic energy acceptance
Tracking study indicates energy acceptance ~1.8%
(lifetime measurements suggest significantly smaller energy acceptance)

Tracking model includes:
- magnet misalignments
- wiggler and quadrupole nonlinearity
- Orbit errors

→Energy acceptance ~ 1.8%





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

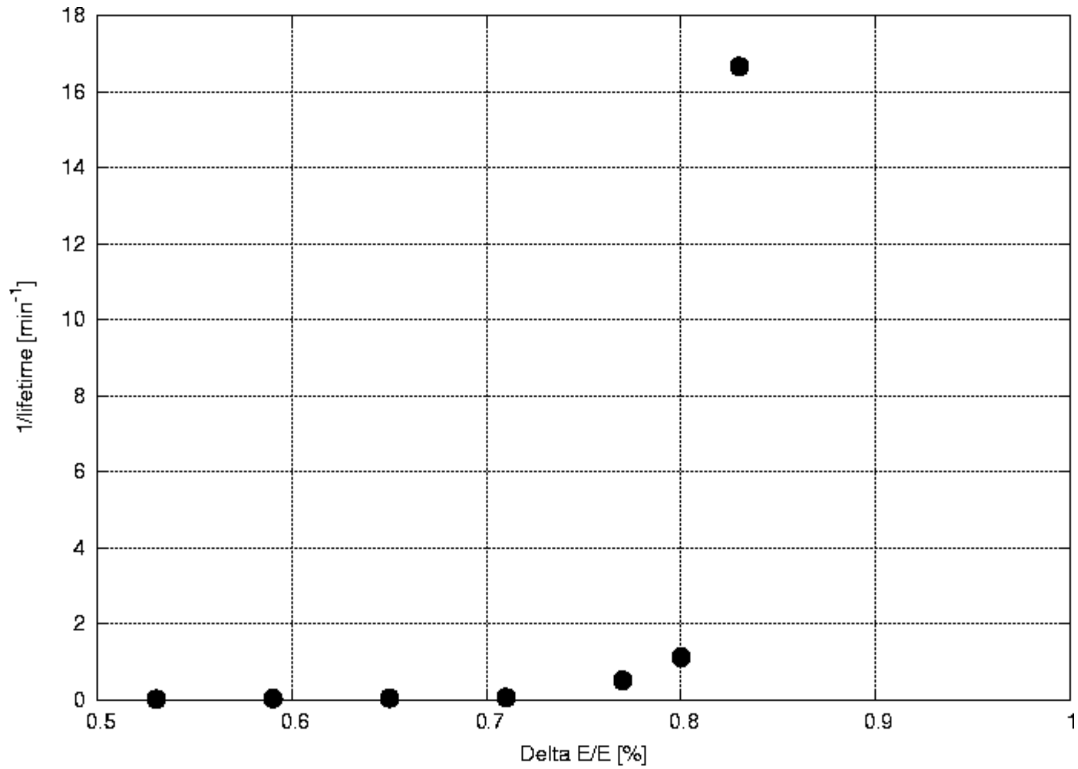
Energy Acceptance

Touschek lifetime depends on
beam size, energy, and energy acceptance

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%

It remains for us to reconcile measurement and tracking calculation of energy acceptance. Increased energy spread from Touschek scattering?

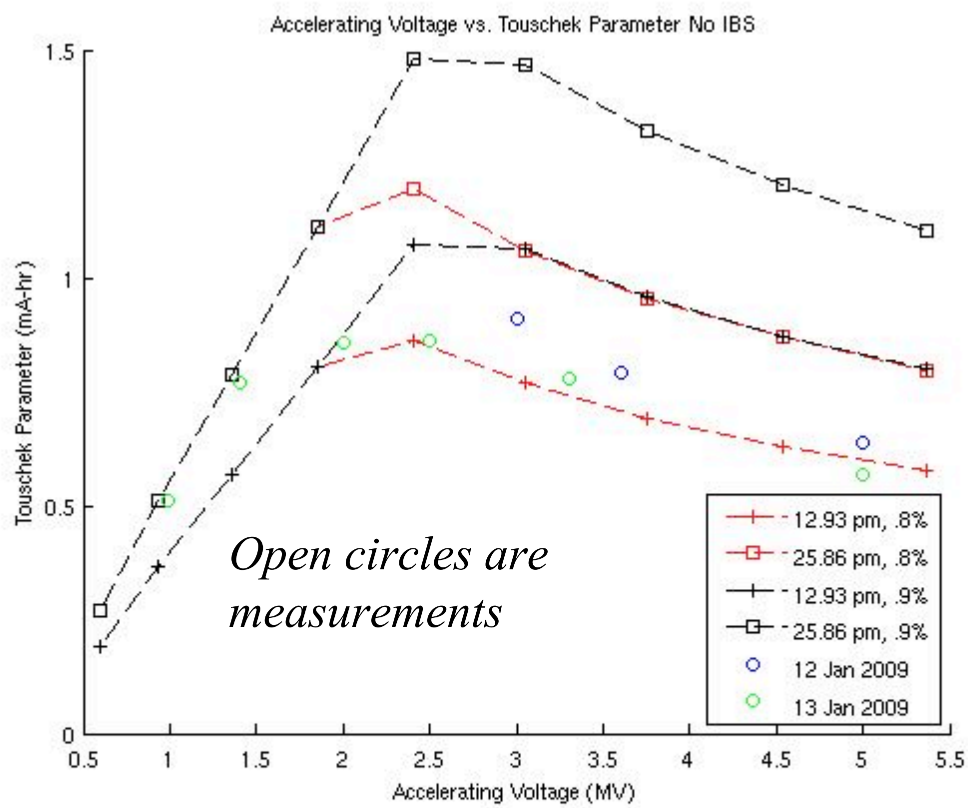


Collective Effects

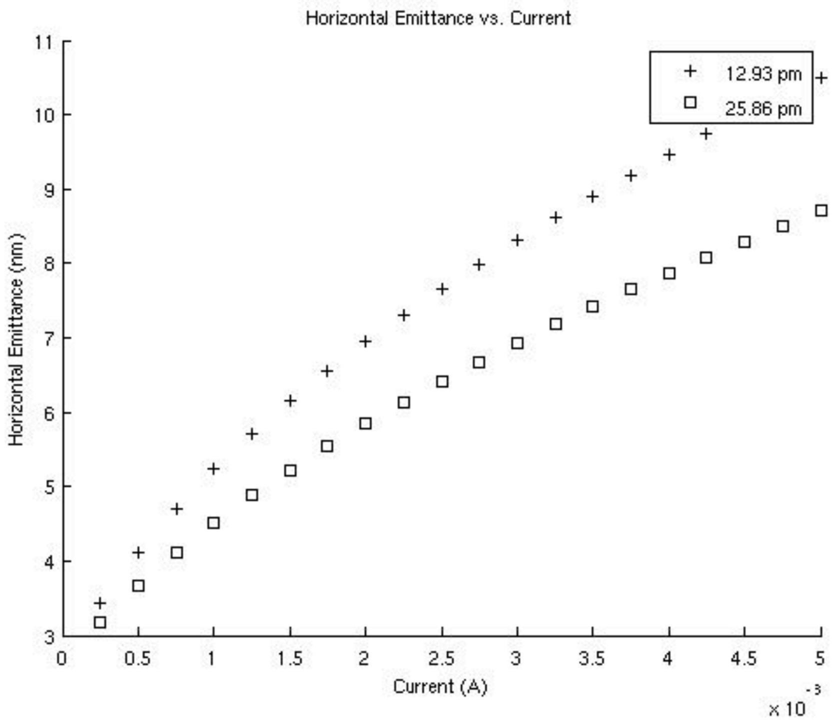
Calculate Touschek parameter vs accelerating voltage for:

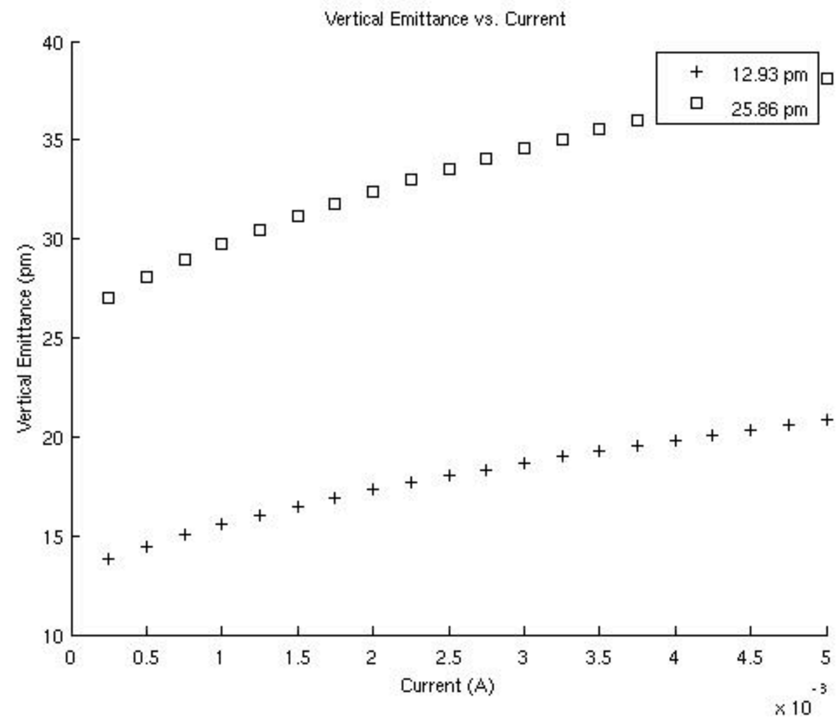
- dynamic energy acceptance 0.8% < ΔE/E < 0.9%
- ε_v (zero current) 0.5% ε_h and 1% ε_h

And assuming no IBS



Intra Beam Scattering





Dependence of emittance on bunch current

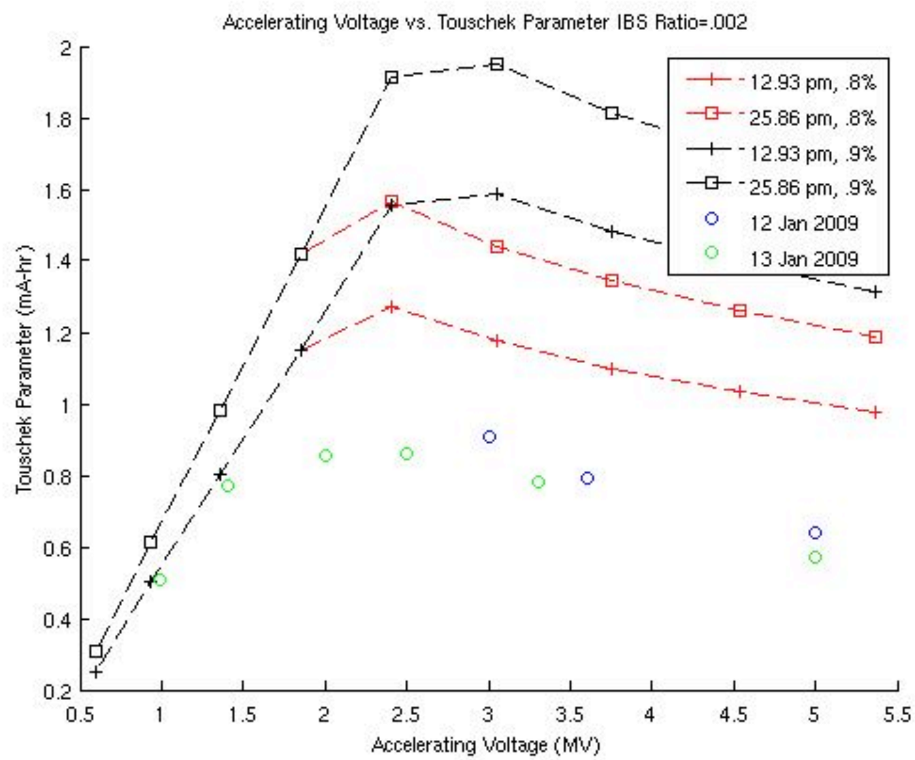
Intra Beam Scattering

Calculate Touschek parameter vs accelerating voltage for:

- dynamic energy acceptance 0.8% < ΔE/E < 0.9%
- ε_v (zero current) 0.5% ε_h and 1% ε_h

With IBS

- assuming zero current ε_v is due exclusively to residual η_v



Then lifetime measurements suggest zero current beam size << 12pm

Energy dependence

Our plan is to measure
vertical emittance (horizontal is more difficult)
and lifetime vs bunch current

Also

Both Touschek lifetime
and IBS emittance dilution have strong
energy dependence. ~ E^2 & E^4

We will measure dependencies from 1.8GeV -5.3GeV

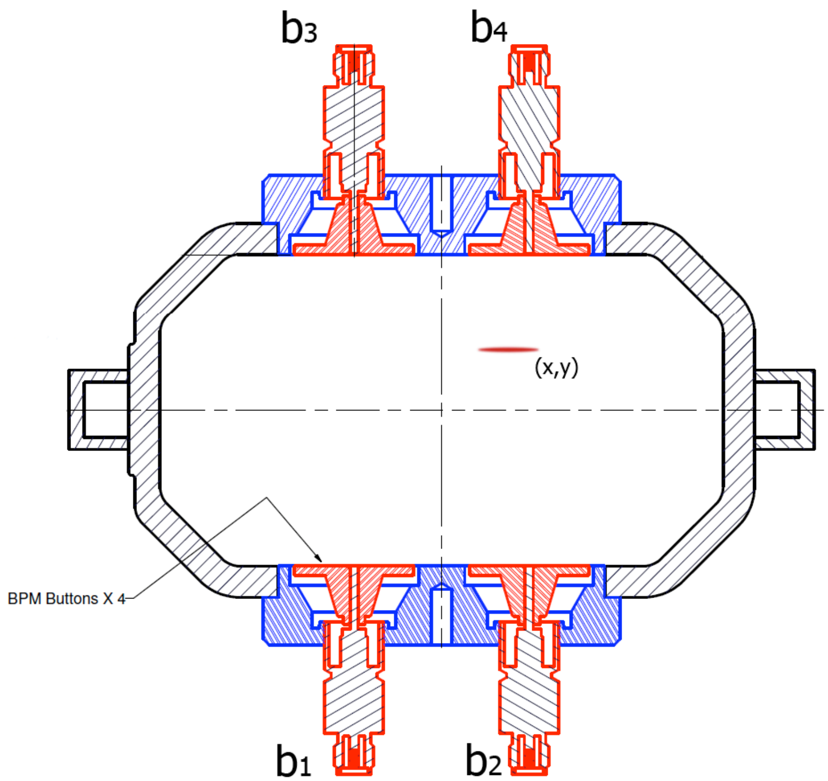
BPM systematics - gain mapping

- 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 then

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

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

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



BPM index	Fitted gains	Fitted offsets	Button sigmas
9W	[1.000, 0.881, 0.981, 0.861]	[92, 336, 142, 236]	[0.26%, 0.30%, 0.38%, 0.44%]
10W	[1.000, 0.924, 1.001, 0.977]	[115, 163, 133, 160]	[0.29%, 0.30%, 0.40%, 0.42%]

BPM tilt- ORM

BPM tilt

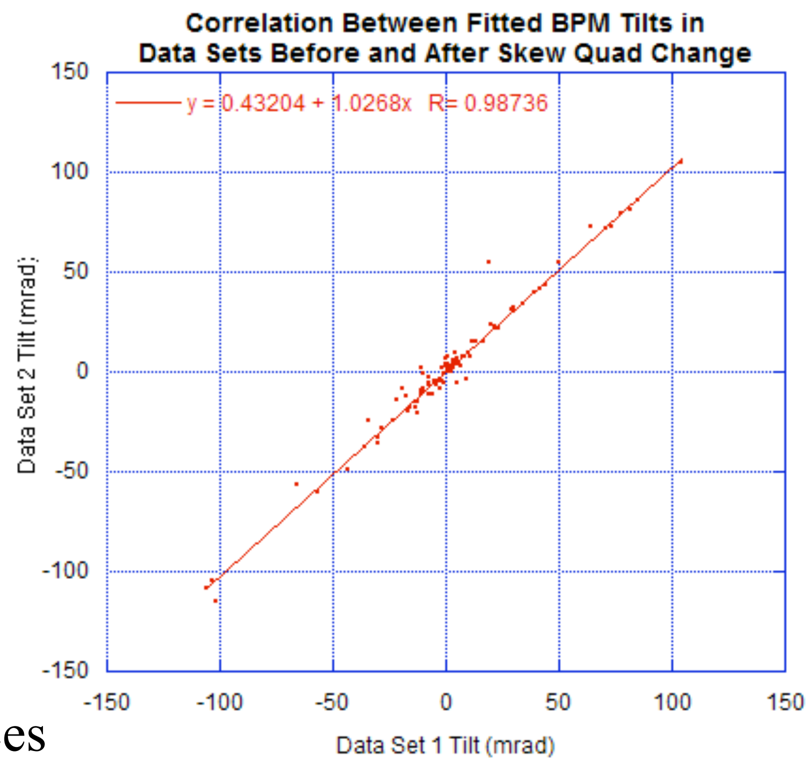
- "measured" $\eta_v \sim \theta\eta_h$
  where θ = BPM tilt

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 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

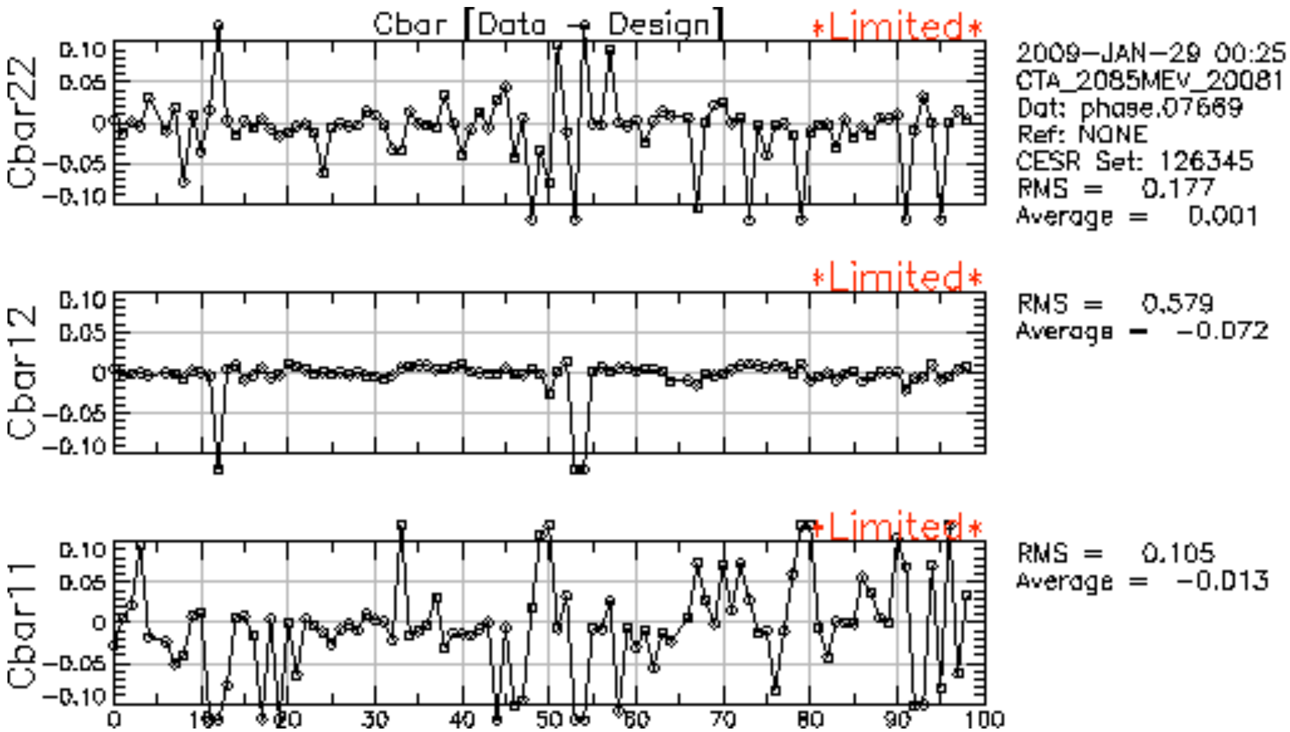
Consistent with $\sigma_{BPM}(\Delta x) \sim 35\mu m$

BPM tilt - Coupling measurement

- Measurement of C_{11}, C_{12}, C_{22} discriminates BPM tilt and transverse coupling (C_{12} independent of tilt)

C11 & C22 measure tilt of beam ellipse
(which can easily be confused with tilt of BPM)

C12 measures component of vertical motion that is out of phase with horizontal
(~ insensitive to BPM tilt)



Quality measurement of C11 & C12 would give a direct measure of tilt

Summary and Questions

- Measurement of vertical beam size is essential
  and we are very close to having it -
  (Dan Peterson and John Flanagan will tell us more tomorrow)
- Measurement of horizontal beam size is also important
  (Just how important and what are the possibilities?)
- To completely characterize IBS
  (which is probably necessary if we are to distinguish
  IBS from e-cloud effects)
- We will need to measure beam size at 1.8 to 5.3 GeV
  Is that possible with xBSM?
- A complementary measurement of beam size would be great
  Measurement of radiation pattern of vertically polarized visible light
  promises to provide just that. Are we getting there? What is the priority?
- Measurement of BPM tilt (gain errors) < 10 mrad (equivalent)
  is critical to dispersion measurement
  Is gain mapping the right strategy?
  Or better to devote effort to improving quality of coupling measurement ?
  Are there other systematic effects compromising the orbit measurement?
  and/or are there other strategies for identifying them?

Comments

- Precision dispersion and coupling measure requires CBPM II modules
- Low emittance tuning controls
    - Coupling controls
    - Vertical dispersion controls
    - Low strength sextupoles (uniform ?)
- Instrumentation
    - BPM - tilts - C_{11} & C_{22} vs C_{12}
    - BPM nonlinearities
    - Function F(x,y) depends on chamber geometry
    - Measurement of betatron phase advance for different bunches in a train ?
    - xBSM
    - BSM (visible light)
    - Scraper measurement of tails