CesrTA Low-Emittance Tuning Update

September 29, 2011

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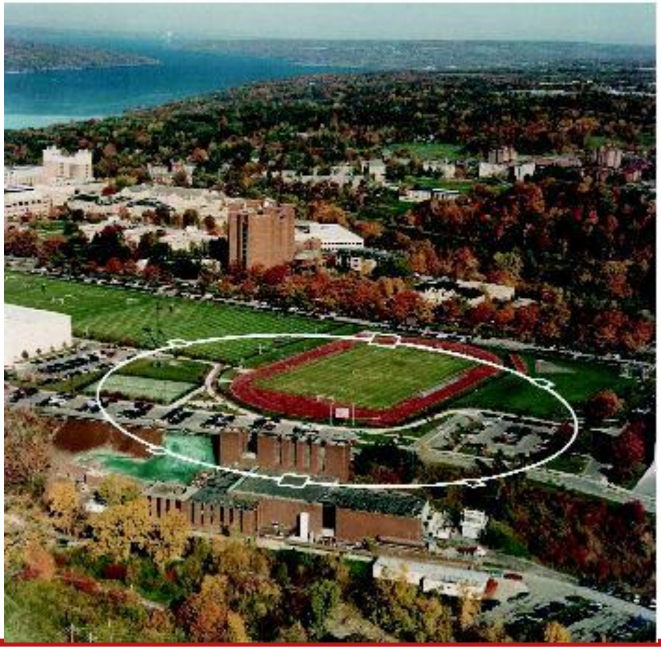
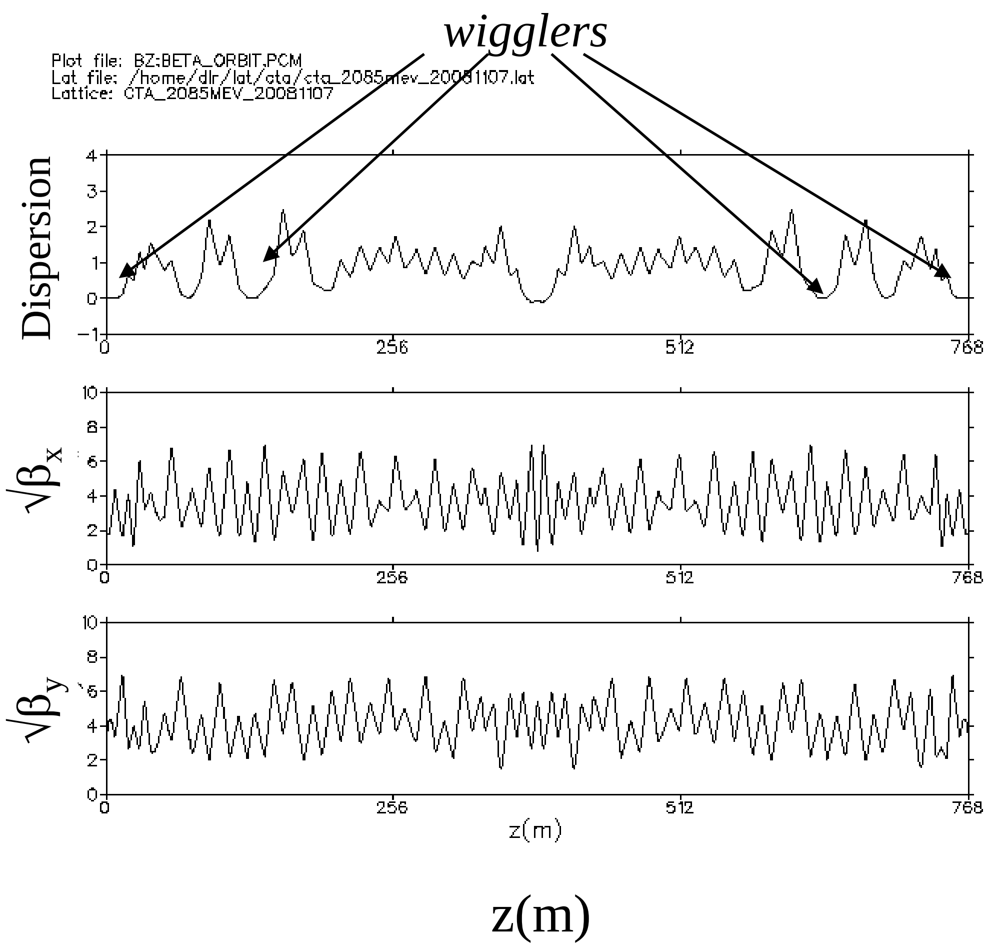


Overview

- CesrTA & Capabilities
- Emittance correction procedure
  - Survey and alignment
  - BPM calibration methods
  - Emittance correction
- Results from recent CesrTA runs

CesrTA - Parameters



Parameter	
Circumference [m]	768.4
Energy[GeV]	2.1 (1.8-5.3)
Lattice type	FODO
Symmetry	≈ mirror
Horizontal steerings	55
Vertical steerings	58
Skew quadrupoles	27
Horizontal emittance [nm]	2.6
Damping wigglers [m]	12*
Wiggler B_{max} [T]	1.9
Beam detectors	100
BPM diff resolution [μm]	10

*Wigglers account for 90% of synchrotron radiation at 2.1GeV

Capabilities: Resonant Measurements

- BPM system:
  - Capable of multibunch, turn-by-turn readout
    - Measure positions by peak detection for an arbitrary bunch pattern (down to 4ns bunch spacing) on every turn
    - Collect up to ~250k turns of beam position data
      - Turns depth is buffer-limited; dependent on number of bunches recorded
  - Most of the analysis used in emittance correction is derived from TBT data
    - Beta functions, betatron phase, coupling, dispersion
    - Advantages: fast, minimally-invasive, no hysteresis
- Typical resonant excitation data acquisition outline:
  1. Initial setup: lock tune trackers: ~1 minute
  2. Record TBT data: ~30s
     - 40,000 turns used for most common measurements
  3. Analyze data to extract betatron phase + coupling, or dispersion: ~10s

Betatron Phase and Coupling

- At each BPM button, measure the signal intensity on a sequence of turns
  - Typically **N = 40k turns** of data are recorded
  - Horizontal and vertical measurements are done simultaneously
    - Initially, tunes must not be near resonances, to prevent cross-talk between h/v modes
- BPM modules compute **FFT amplitude** of horizontal motion (Similar equations for vertical mode) at **button j** is a sum over **turns i**:

$$\mathbf{A_{j,sin,h} = 2/N\ S_i\ sin[\theta_{t,h}(i)]\ a_j(i)} \quad \text{(in-phase)}$$

$$\mathbf{A_{j,cos,h} = 2/N\ S_i\ cos[\theta_{t,h}(i)]\ a_j(i)} \quad \text{(out-of-phase)}$$

$\theta_{t,h}(i)$ = phase of tune tracker drive signal (phase-locked to horiz. tune) on turn i

$a_j(i)$ = signal on turn i at button j

Define:

$A_{x/y,sin/cos,h/v}$ = x/y components, via standard BPM "Δ/Σ"

$A_{x/y,h/v}$ = Total FFT amplitude of x/y signal at the horiz/vert mode

Coupling: Definition

Reminder– Cornell uses Cbar to describe coupling for 4x4 transport:

$$\begin{pmatrix} \mathbf{M} & \mathbf{m} \\ \mathbf{n} & \mathbf{N} \end{pmatrix} = \mathbf{V}\mathbf{U}\mathbf{V}^{-1} = \begin{pmatrix} \gamma\mathbf{I} & -\mathbf{C} \\ \mathbf{C}^{+} & \gamma\mathbf{I} \end{pmatrix}\begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix}\begin{pmatrix} \gamma\mathbf{I} & \mathbf{C} \\ -\mathbf{C}^{+} & \gamma\mathbf{I} \end{pmatrix}$$

Cbar = C matrix in normalized coordinates

Betatron Phase and Coupling

- Betatron phase and couplings (Cbar) are defined by:

$$\phi_{x,h} = \tan^{-1} (A_{x,\sin,h}/A_{x,\cos,h})$$

$$\bar{C}_{12} = \sqrt{(b_h/b_v)}\, A_{y,h} / A_{x,h} \sin(\phi_{y,h} - \phi_{x,h}) \qquad \text{from horiz. mode}$$

$$= \sqrt{(b_v/b_h)}\, A_{x,v} / A_{y,v} \sin(\phi_{x,v} - \phi_{y,v}) \qquad \text{from vert. mode}$$

$$\bar{C}_{22} = -\sqrt{(b_h/b_v)}\, A_{y,h} / A_{x,h} \cos(\phi_{y,h} - \phi_{x,h}) \qquad \text{from horiz. mode}$$

$$\bar{C}_{11} = -\sqrt{(b_v/b_h)}\, A_{x,v} / A_{y,v} \cos(\phi_{x,v} - \phi_{y,v}) \qquad \text{from vert. mode}$$

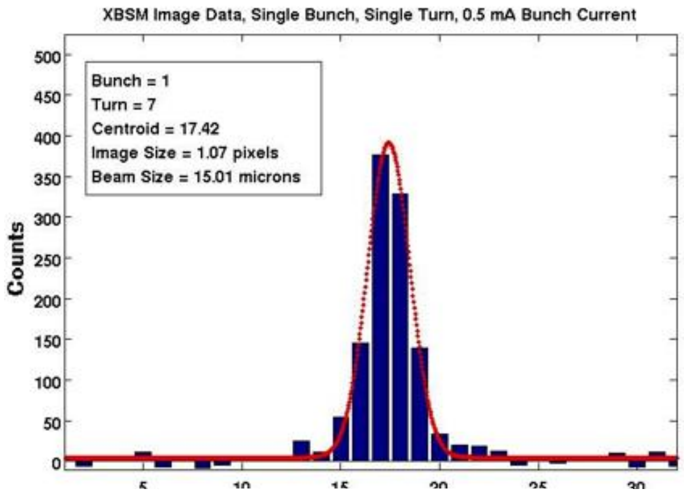
- **Cbar12** is "**out-of-phase**" component of coupling matrix
  - Independent of physical BPM tilts
- **Cbar 22** and **Cbar11** are "**in-phase**" components
  - Dependent on BPM tilts
- **Similarly**, when resonantly exciting beam **longitudinally** and measuring beam position **at the synch tune**, one obtains the **dispersion** ("AC dispersion" technique)

Further Capabilities

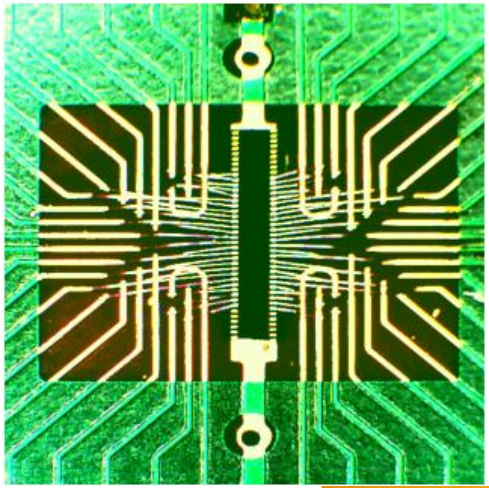
- Skew quad trims on sextupoles
  - Rewired several unused vertical steering trims on sextupoles near arc wiggler straights to generate skew-quad-like fields
  - Expands the total number of skew quadrupoles from 15 to 27
  - Allows for dispersion correction through arc wigglers
    - Conversely, also able to intentionally generate vertical emittance by coupling horizontal dispersion into the vertical mode in arc wigglers
- X-ray Beam Size Monitor (xBSM)
  - 1D vertical diode array
  - Capable of measuring TBT bunch size for ≥4ns-spaced bunches
  - Primary tool for measuring success of vertical emittance corrections

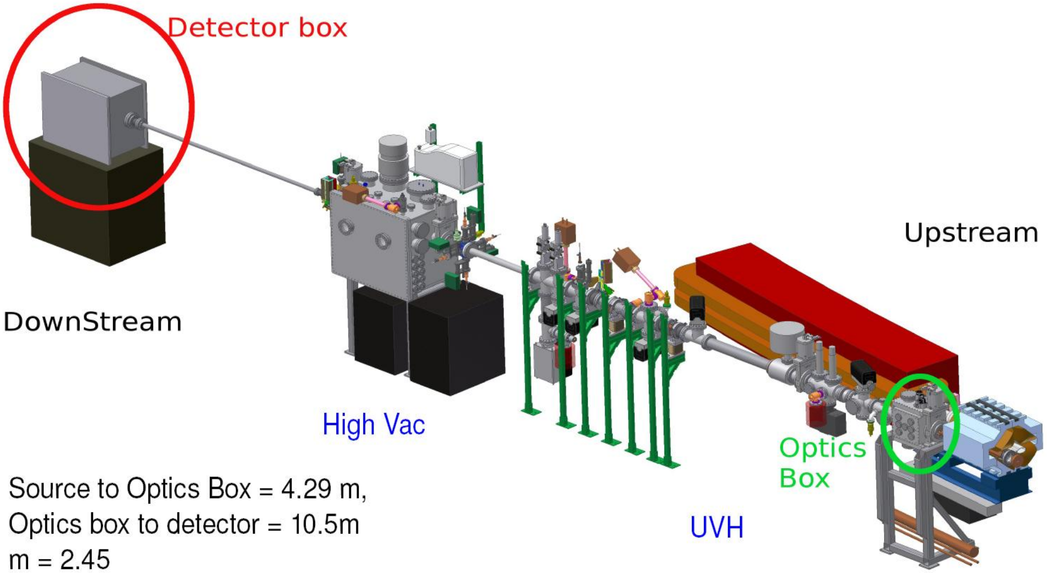
X-ray Beam Size Monitor

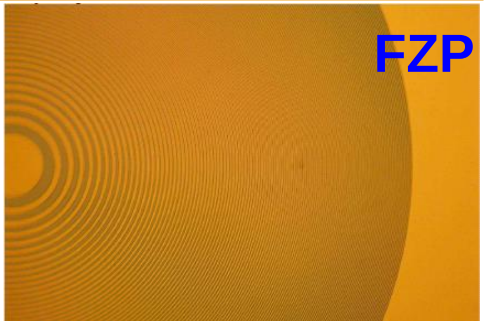
Image using pinhole optic



xBSM diode array







Source to Optics Box = 4.29 m,
Optics box to detector = 10.5m
m = 2.45

Emittance Correction Procedure

1. Long-term (~few times a year):
   - Survey and alignment
2. Medium-term (at start of CesrTA runs):
   1. Calibrate BPM button-to-button gains
   2. Calibrate BPM tilts
   3. Calibrate BPM / quad center offsets
3. Short-term (daily or more, during CesrTA runs):
   1. Re-time BPMs (before every measurement)
   2. Measure and correct orbit
   3. Measure and correct betatron phase and coupling
   4. Measure: orbit, betatron phase/coupling, and dispersion; correct simultaneously

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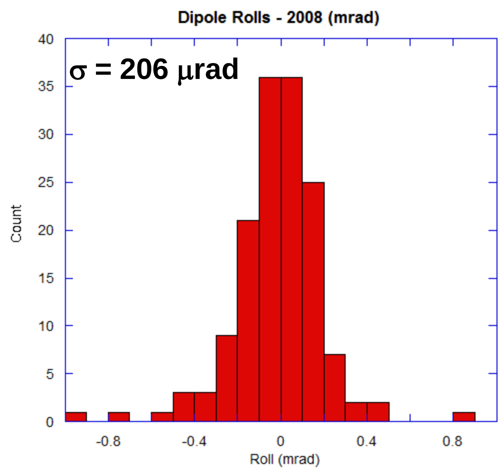
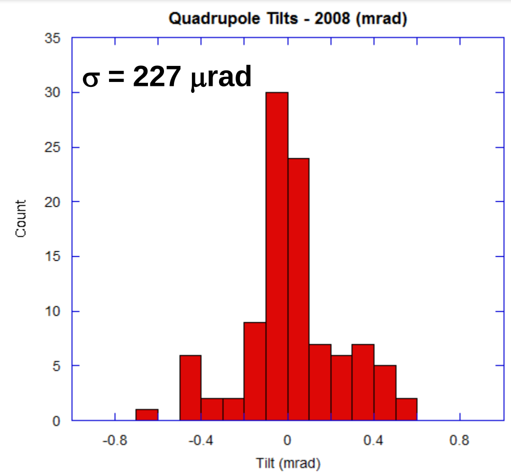
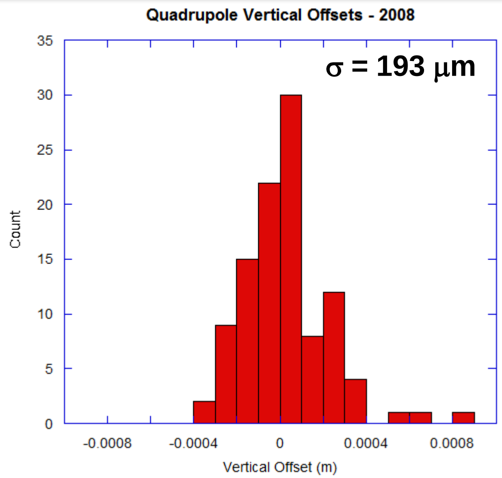
Survey and Alignment

Dipole Rolls | Quad Tilts | Quad Vertical Offsets

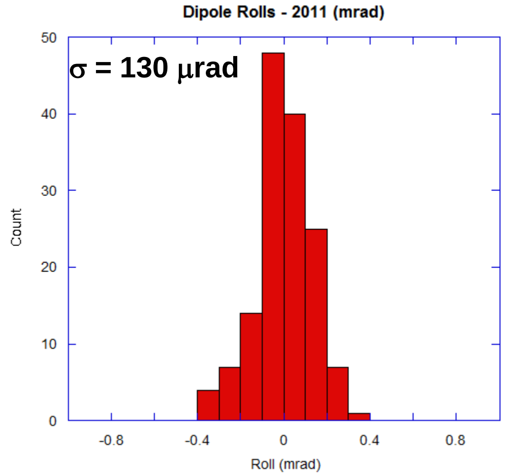
2008

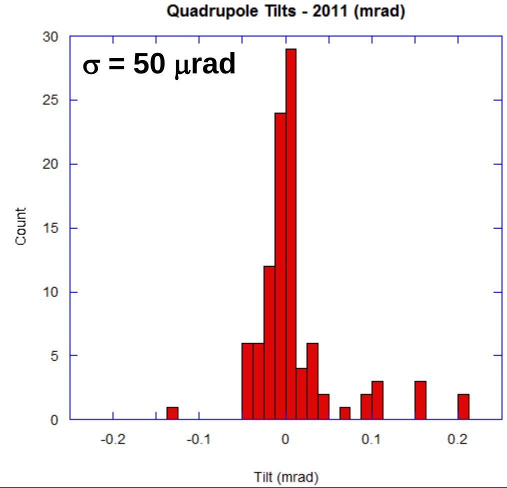


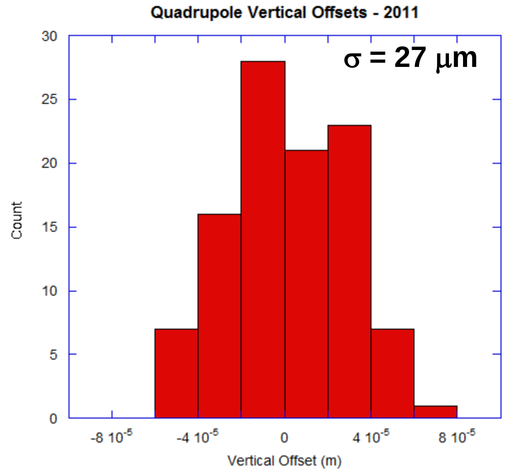




2011







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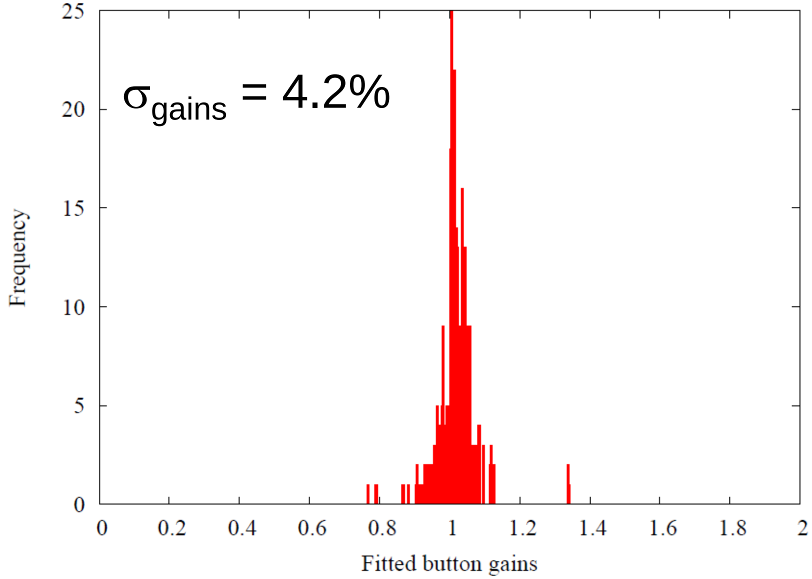
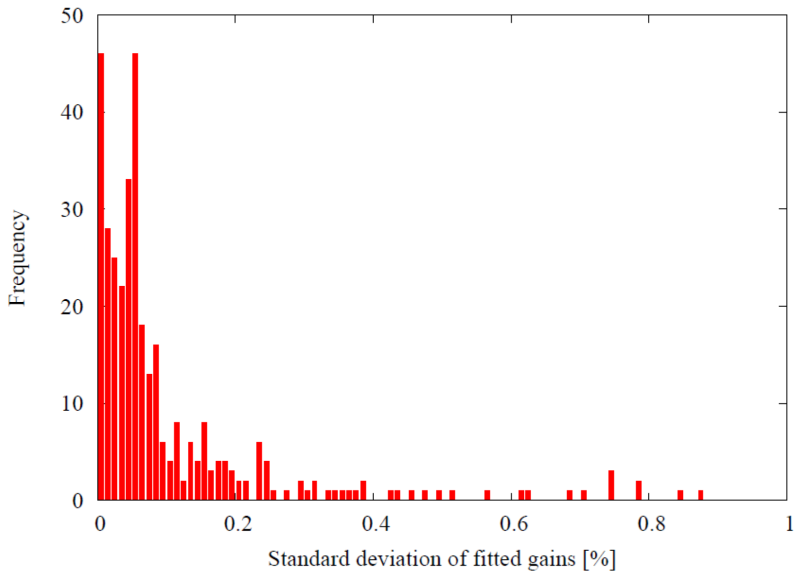
BPM Gain Calibrations

- Recalibrate BPM gains at the start of CesrTA runs
- Method:
  1. **Resonantly excite beam in horizontal and vertical**
  2. **Collect TBT data for 1024 turns at all BPMs**
  3. **Gain map analysis of TBT data assumes a second-order expansion of small-orbit response of buttons–** *Phys. Rev. ST Accel. Beams* **13**, September 2010, 092802
- Time required: 30 seconds to acquire data, < 5 minutes to analyze and load



Distribution of Fitted Gains for **one data set**



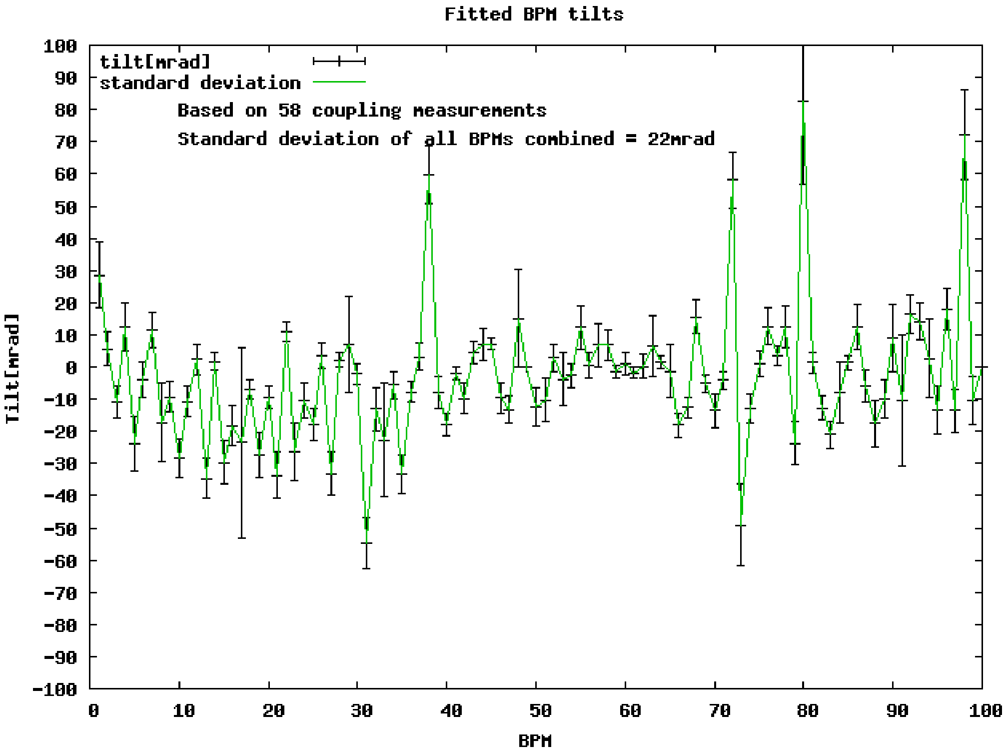
Standard deviations from the mean of **seven consecutive data sets**

BPM Tilt Calibrations

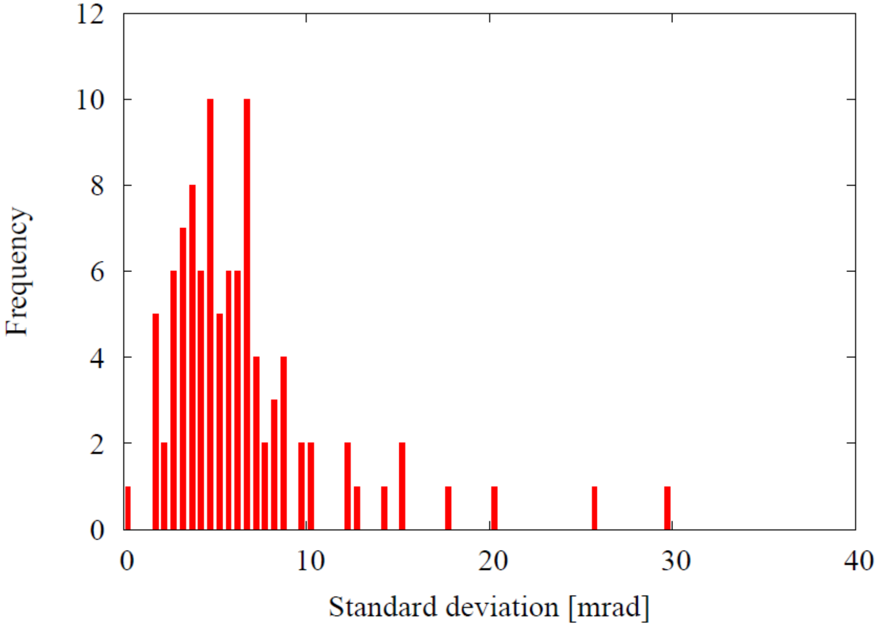
- Dispersion and BPM tilts:
  - A **10mrad** BPM tilt couples a 1m horizontal dispersion to an apparent (non-physical) **1cm** vertical dispersion
    - Limits the effectiveness of vertical dispersion correction at that BPM
  - Simulations suggest **1cm** RMS vertical dispersion will generate a residual vertical emittance of **~10pm**
- Tilt calibration procedure:
  1. Measure coupling (Cbar12) and correct using all skew quadrupoles
     - Recall: Cbar12 is insensitive to BPM tilts, as it is out-of-phase coupling
  2. Remeasure phase/coupling
     - Fit residual Cbar12 with model, using skew quadrupoles
     - The residuals of (measured – model) Cbar 22, 11 are related to BPM tilts

BPM Tilt Calibrations

- Fit residual Cbar22, Cbar 11 (in-phase betatron coupling) using BPM tilts
- Average fitted tilts plotted from 58 coupling measurements
- In the process of understanding these fits



RMS BPM tilt: **22mrad**



Standard Deviations of 58 fitted tilts at each BPM

BPM/Quad Offset Calibrations

- Vertical offsets between quadrupole and BPM centers will introduce vertical kicks, therefore vertical dispersion and vertical emittance
- Calibrate vertical BPM/quad offsets in the following way:
  1. Measure betatron phase twice, changing one quadrupole's strength in-between
  2. Determine Twiss parameters (β, phase ϕ, and tunes ν) and closed orbits from each of the two TBT data sets
     - Fit the difference of **closed orbit measurements** with a kick **dy'** at the quadrupole
     - Fit the difference of **betatron phase measurements** with a kick **dk** at the quadrupole
  3. Quadrupole offset is then

$$y_{offset} = (1/L_{quad})\,(dy'/dk) + y_0 \qquad (y_0 = \text{nominal closed orbit})$$

- Iterate until convergence
  - Quadrupole / BPM centers then known to **< 300 microns**
- Takes about **2 hours** to center all 100 quadrupoles

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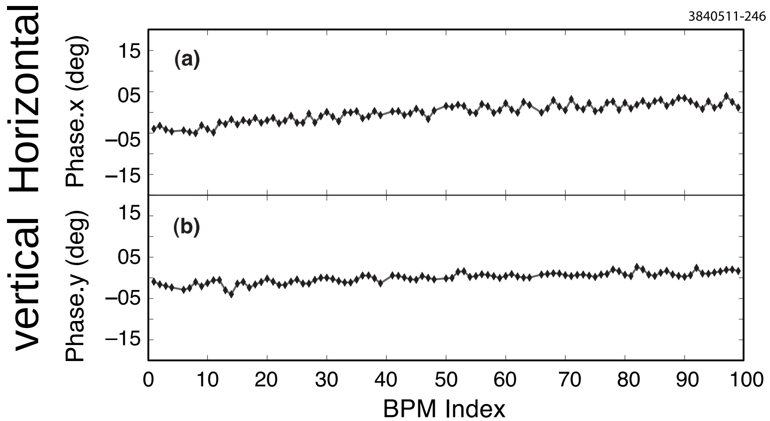
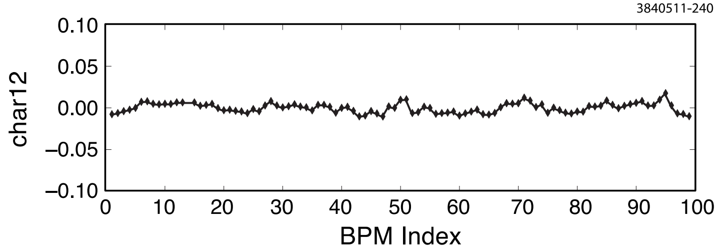
Emittance Correction I

1. Time in individual BPM buttons
   - Timing drifts by ~10's of picoseconds over the course of an hour
   - Re-time before every measurement
     - minimal timing step is **10ps**
     - **ΔSignal $|_{peak}$(t_0 $\pm$10ps) ~ 5x10^{-4}**
   - One iteration takes about **one minute**
2. Measure closed orbit and correct with all horizontal and vertical steerings
   - Takes about **30 seconds** to measure, analyze, load corrections, and re-measure orbit
3. Measure betatron amplitudes, phase advance and transverse coupling
   - Use all 100 quadrupoles and 27 skew quads to fit the machine model to the measurement, and load correction
   - Typical correction levels:
     - **$\Delta\phi$ (meas-design) < 2° → 3% beta beat**
     - **Cbar12 < 0.005**
   - One iteration takes about **one minute**

Phase after correction:



Coupling after correction:

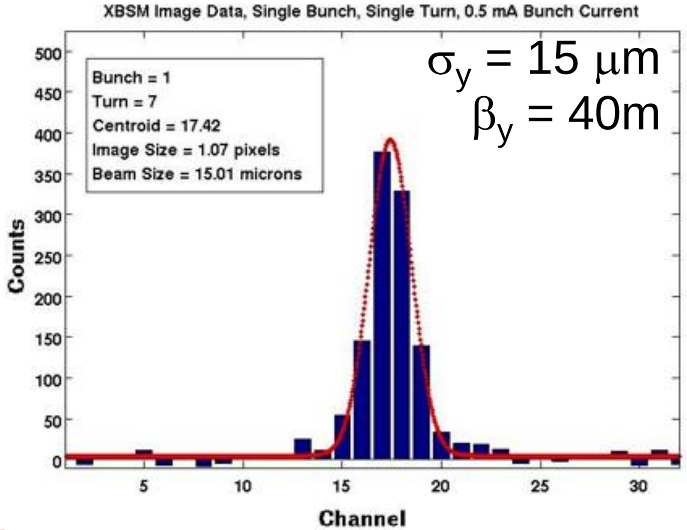


Emittance Correction II

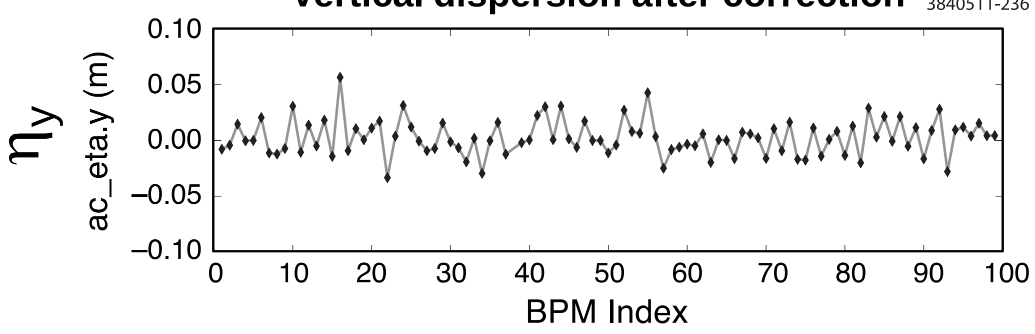
4. Re-measure closed orbit, phase and coupling, and dispersion
   - Simultaneously minimize a weighted sum of orbit, vertical dispersion, and coupling using vertical steerings and skew quads
     - Typical level of correction: measure η_y **~15mm**
     - Measure $\boldsymbol{\varepsilon_y}$ **< 10pm** with xBSM
       - At 0.5mA = 0.8×10^{10} positrons
       - Suggests η_y measurement is resolution-limited

- Turnaround time: **~5 minutes** per correction iteration:
  1. **Correct orbit**
  2. **Correct phase/coupling**
  3. **Correct orbit + coupling + dispersion**

Vertical beam size after correction using xBSM pinhole optic



Vertical dispersion after correction



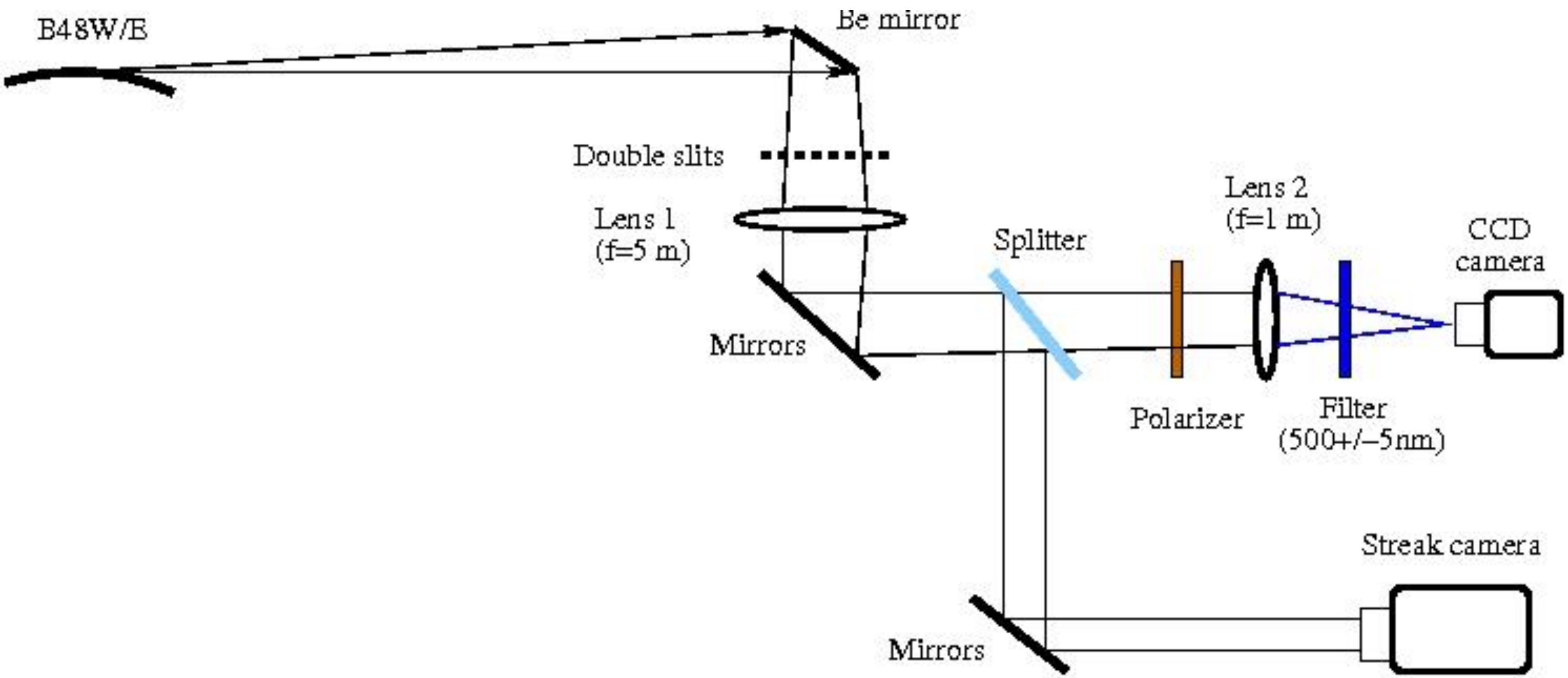
Further Improvements: In Progress

During June 2011 run, we began work on further improvements to LET setup:

- Conditions have been recovered at two new energies:
  - **1.8GeV** and **2.3GeV**, in addition to standard **2.085GeV**
- First tests of simultaneous beam size measurements in horizontal, vertical, and longitudinal
  - Horizontal interferometer setup; multi-turn integration
  - Longitudinal via streak camera
  - Vertical using xBSM
- xBSM data acquisition can now be automated
  - Acquires a 4096-turn snapshot every ~5 seconds, processing the first 100 turns on the fly
  - A more continuous data acquisition scheme is under development
- New digital tune tracker
  - Capable of phase-locking to any single bunch in the ring

vBSM + Streak Camera Setup

L3 setup includes beam splitter to allow simultaneous horizontal and longitudinal beam size measurements

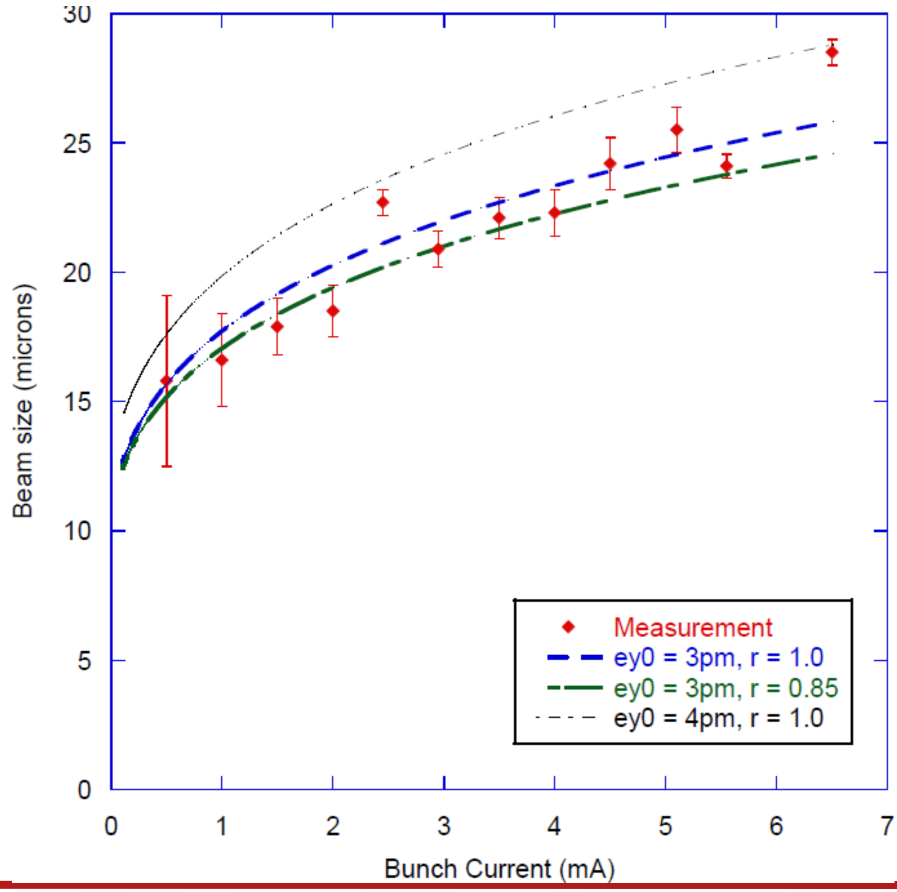


Initial IBS Studies

- **April 2011**, 2.085GeV, single bunch of positrons, fill to ~6.5mA (~1x10^{11} e^+)
- Use xBSM to record 100 consecutive turns of vertical beam size at several currents

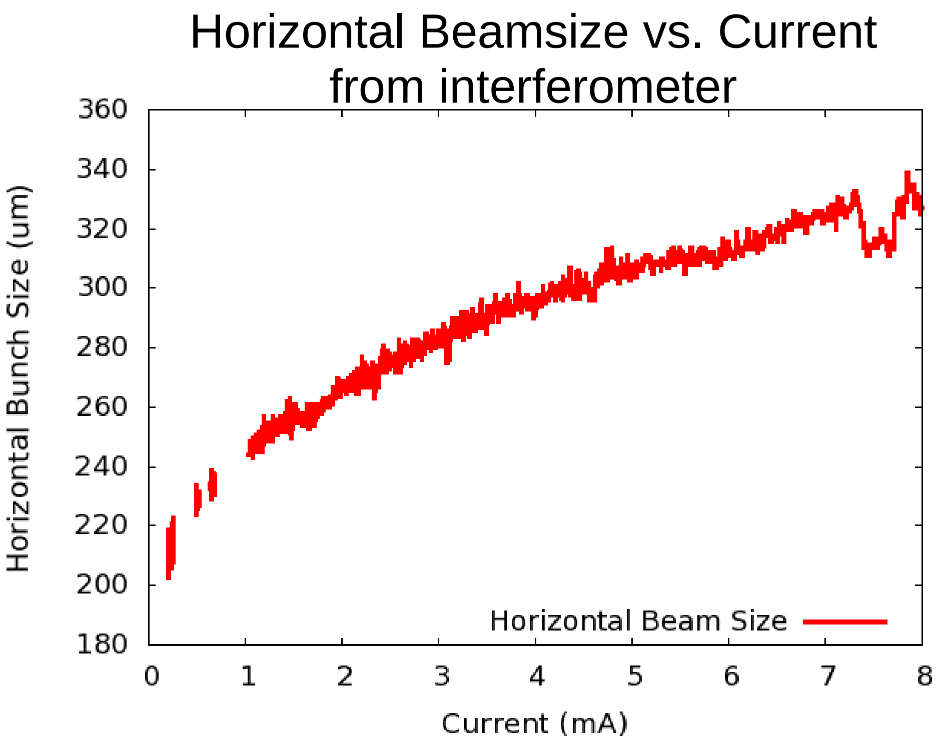
- Overlay on plot: simple IBS model, with the following inputs:
  - Ideal lattice (no misalignments)
  - Zero-current ε_y assumed to be 3-4pm
  - Parameter r is a "fudge factor" to allow comparison between ideal simulation and real-world machine
    - r ~ (ε_y from coupling) / (ε_y from η_y)
  - **Further analysis is necessary**

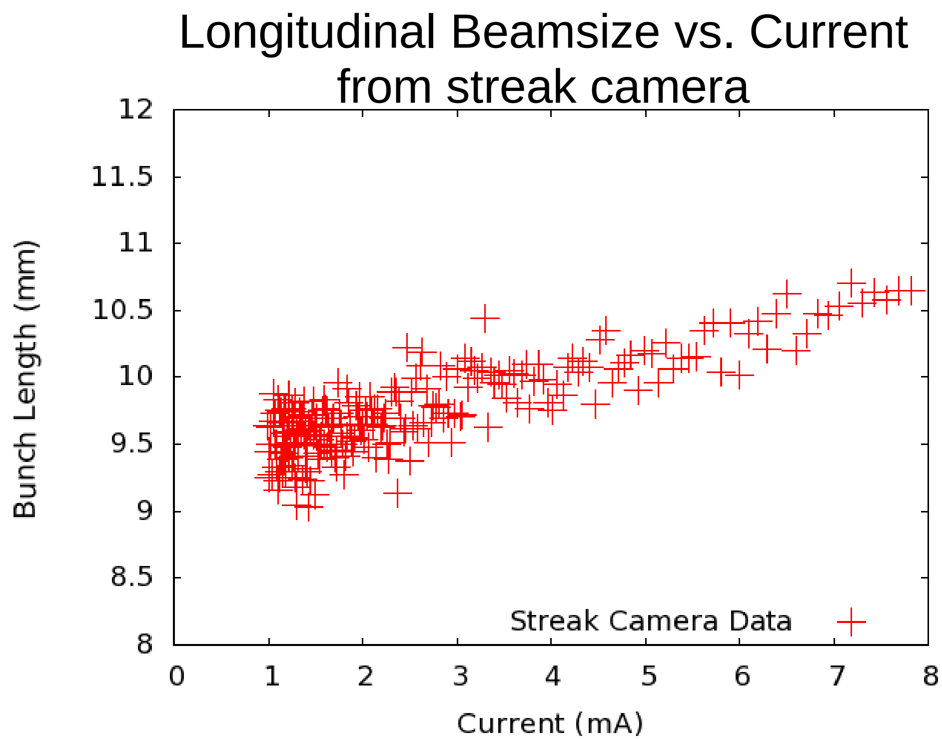
Vertical Bunch Size vs. Current
from xBSM, pinhole optic



Horizontal + Longitudinal IBS Measurements

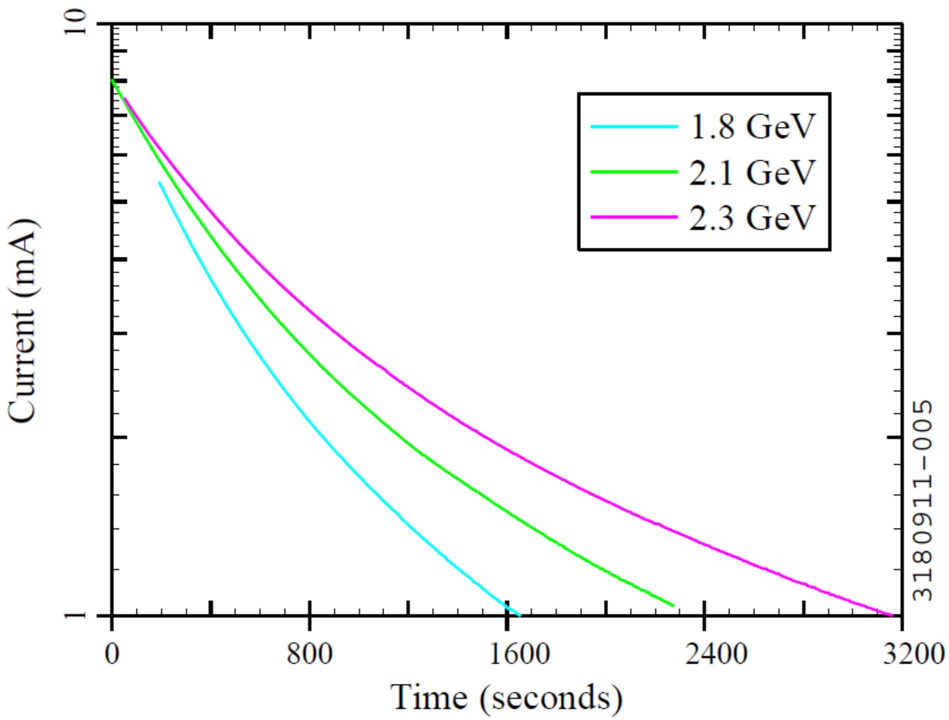
- First tests of simultaneous horizontal and longitudinal beam size measurements in **June 2011**

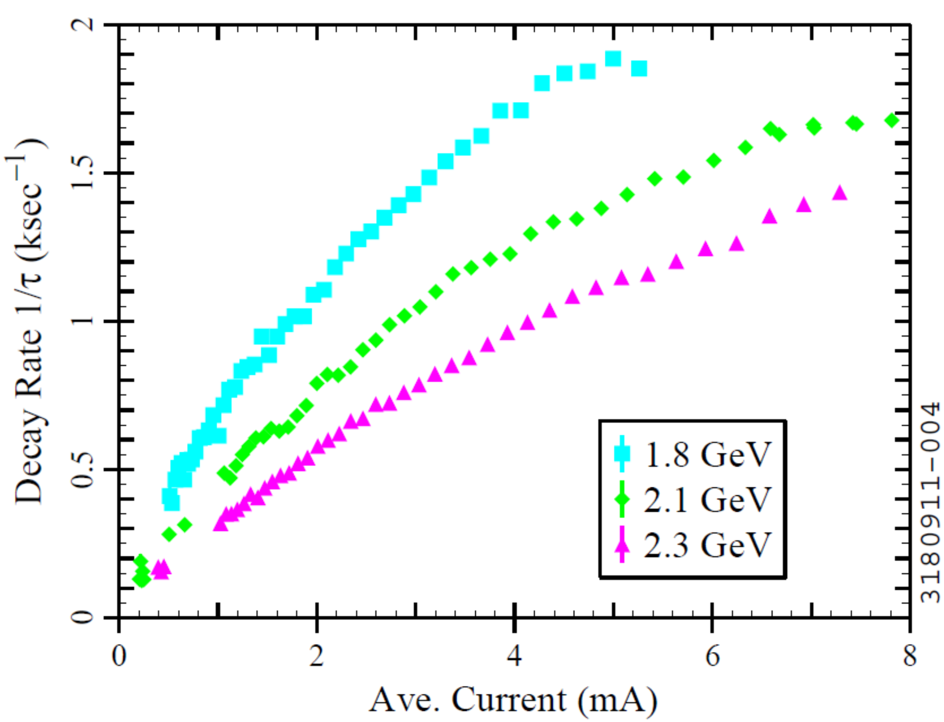




- **Note: precision calibrations have not been done on these instruments!**
- ***We intend to do more IBS studies in the upcoming December 2011 run***

Touschek Lifetime





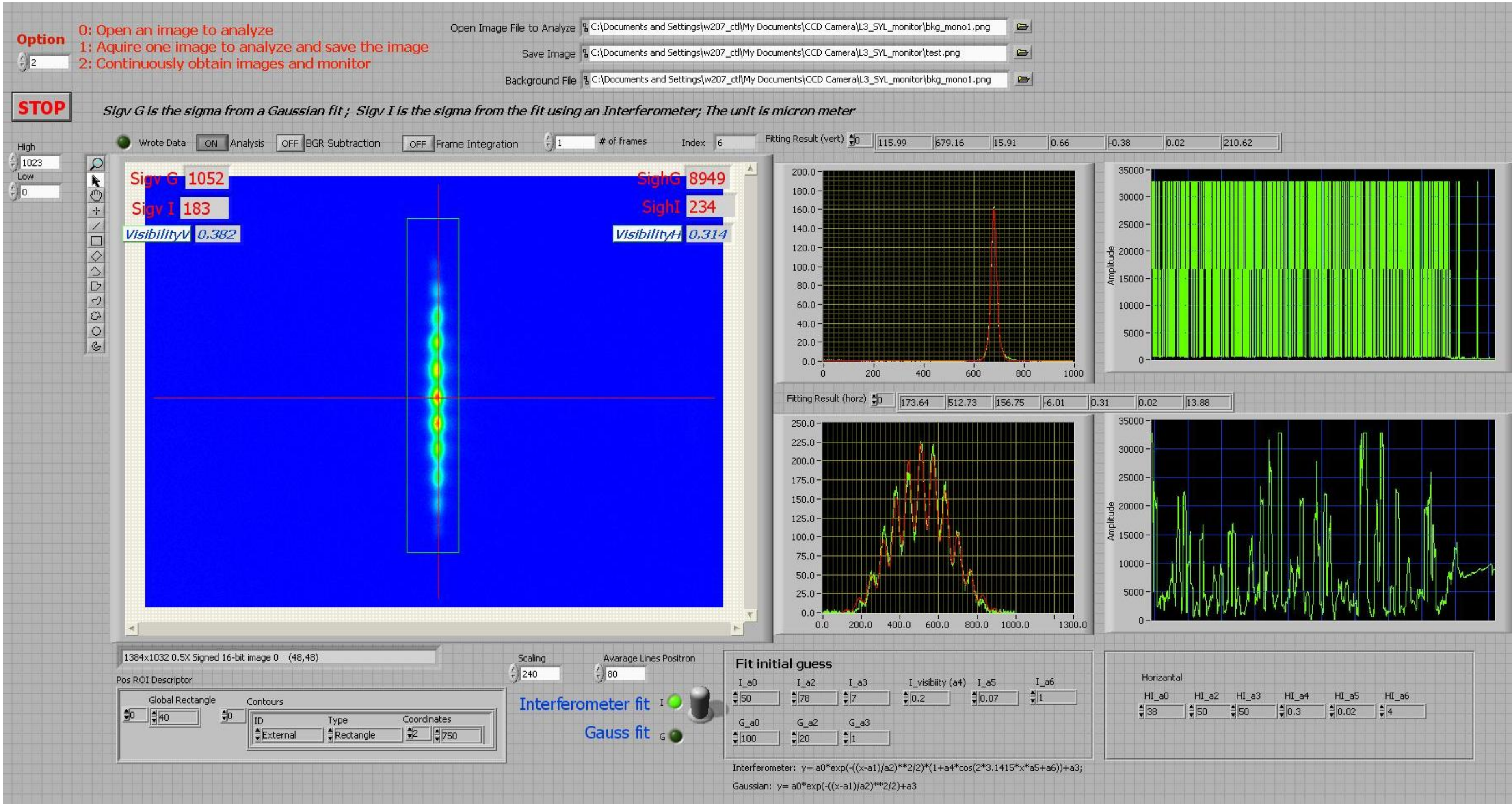
- Touschek lifetime data acquired at three energies:
  - 1.8GeV, 2.085GeV, 2.3GeV
- We are in early stages of understanding the results

Summary

- Survey and alignment has made significant progress
- We are in the process of understanding BPM tilt calibrations
- Demonstrated efficacy of optics corrections using resonant excitation data
  - Typical vertical emittance after correction is ε_y **< 10pm**
- Initial "proof-of-concept" IBS and Touschek measurements have been made
  - Further analysis is necessary
  - Will be studied further in December 2011 CesrTA run, with more tests of simultaneous horizontal, vertical, and longitudinal bunch size
  - *We encourage interested collaborators to participate!*

Backup Slides

Horizontal vBSM



Horizontal beam size measured with visual-spectrum interferometer (λ = 500nm)

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

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

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

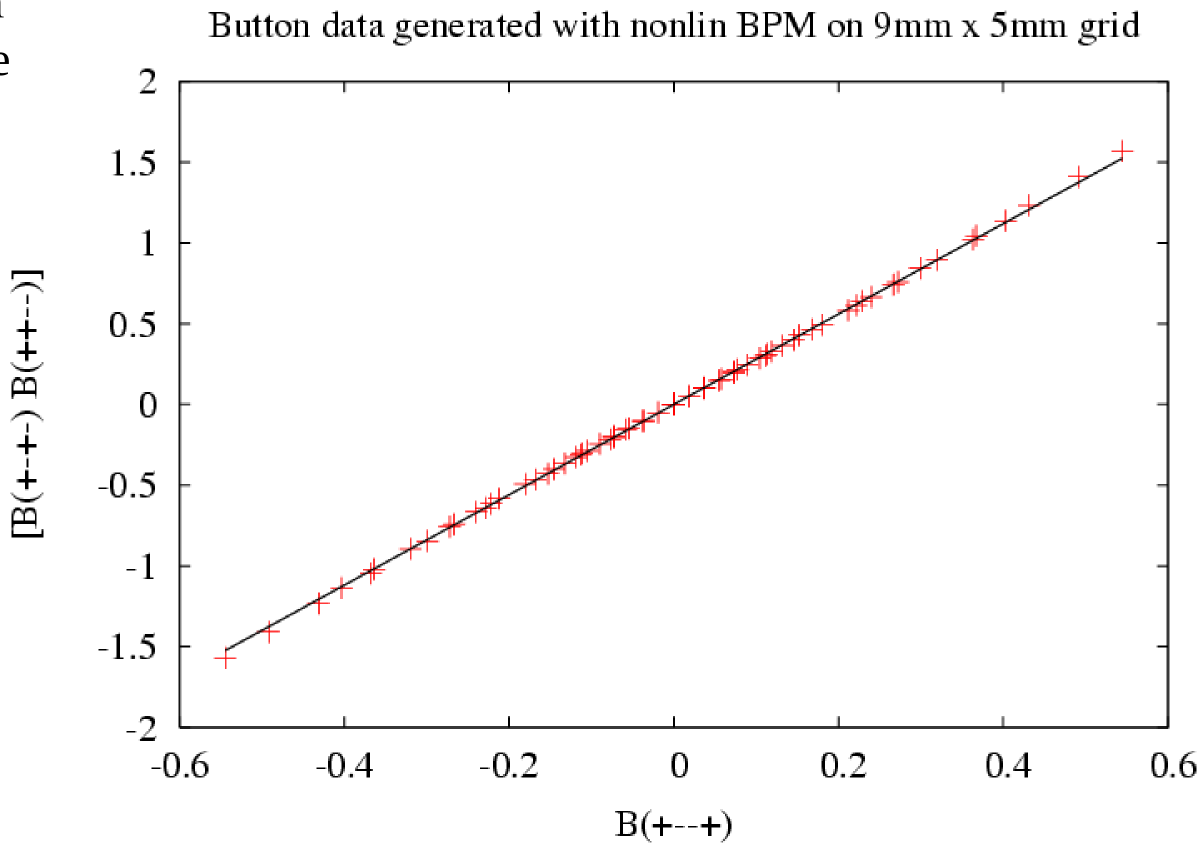
Gain characterization simulation

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

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.

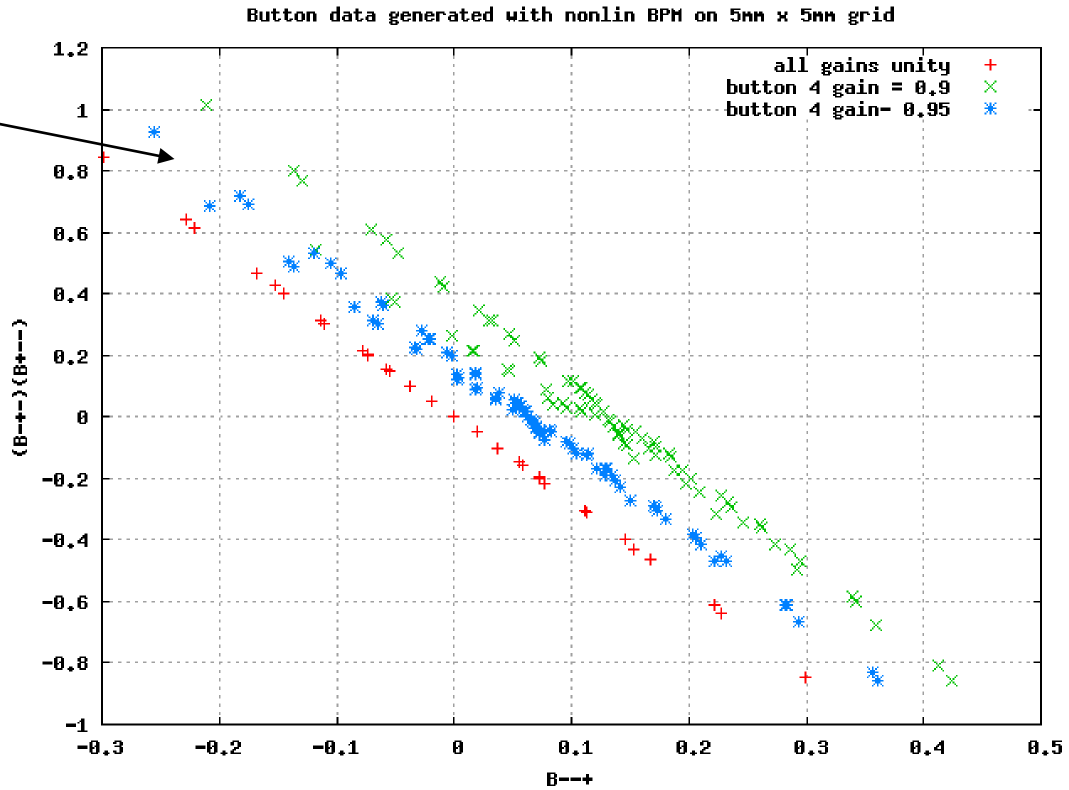


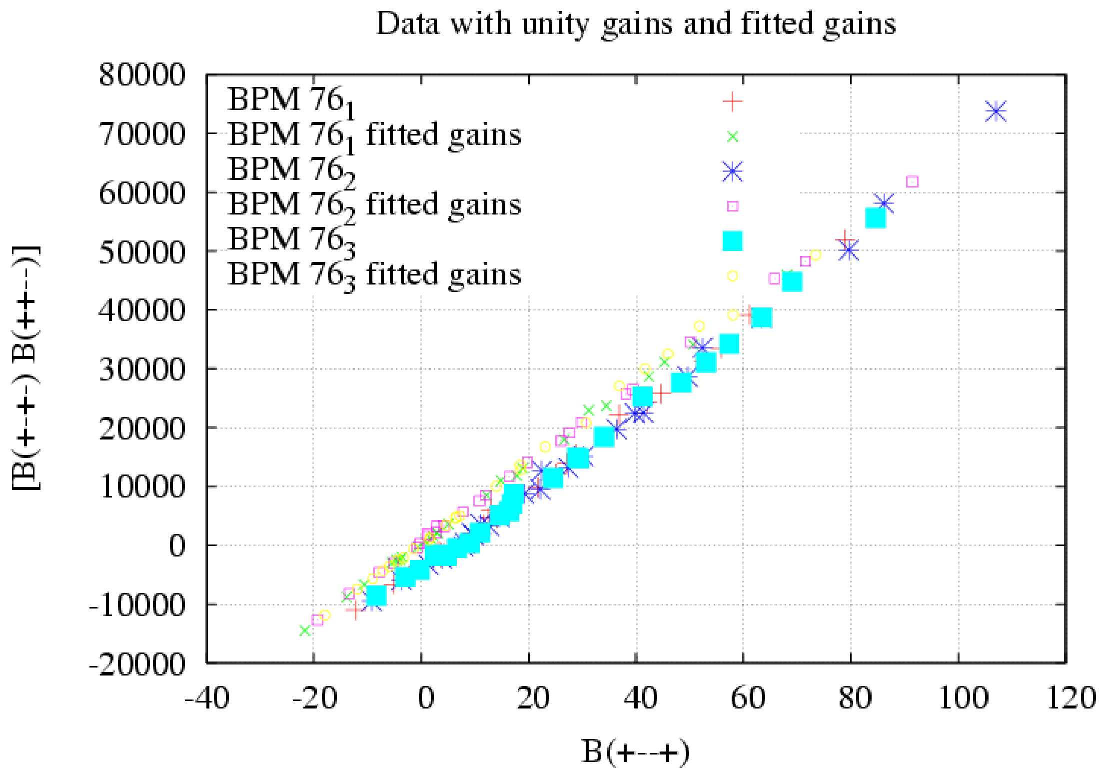
Gain characterization simulation

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

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

Fit typically reduces χ^2 by two orders of magnitude

Low emittance tuning - modeling

Introduce misalignments

Element	Misalignment
Quadrupole vertical offset [μm]	250
Quadrupole tilt [μrad]	300
Dipole roll [μrad]	300
Sextupole vertical offset [μm]	250
Wiggler tilt [μrad]	200

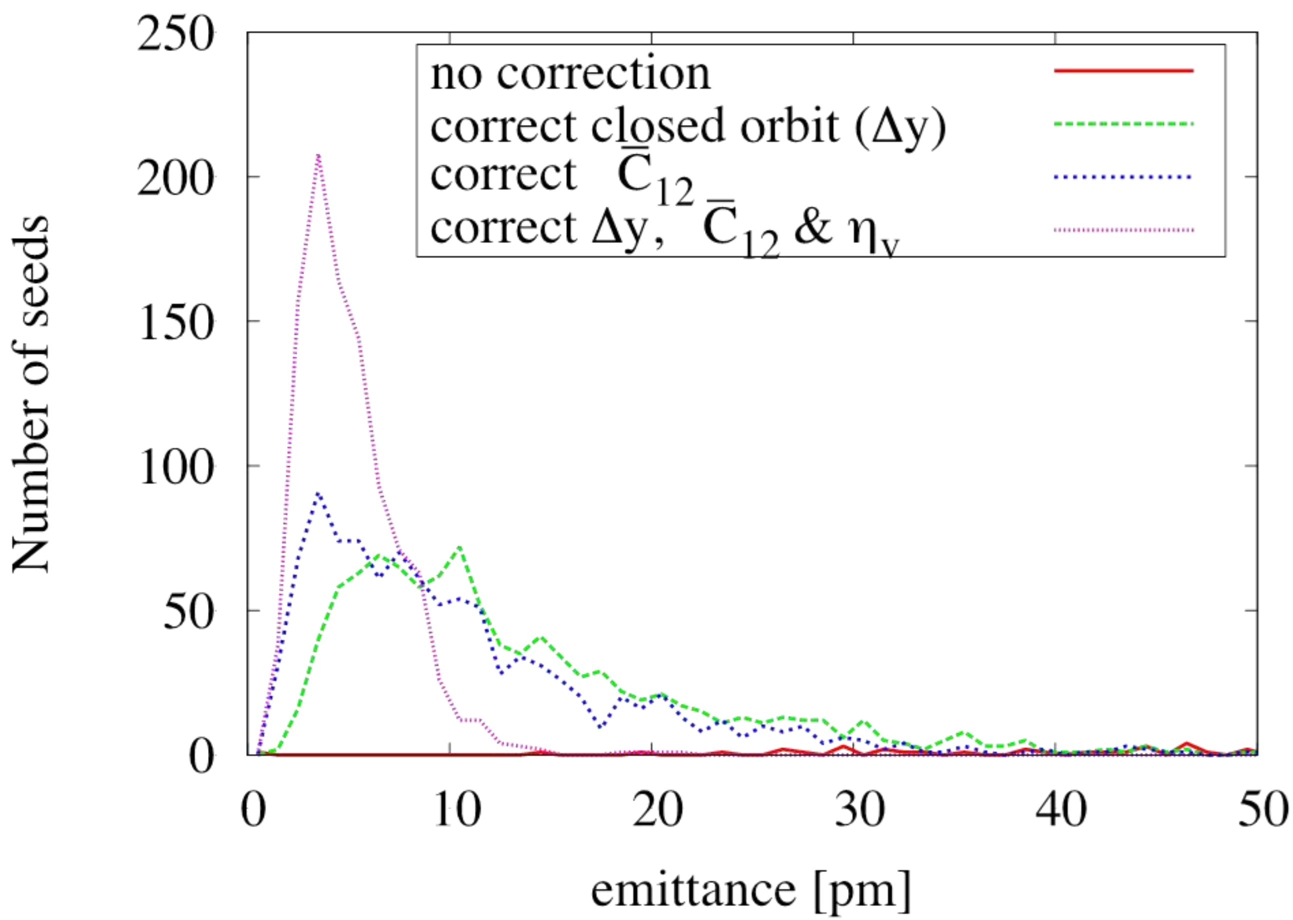
BPM parameters

BPM precision	
Absolute [μm]	200
Differential [μm]	10
Tilt [mrad]	22

Emittance Tuning Simulation

- Create 1000 models
- Apply tuning procedure

Emittance distribution after each step



LET Correction Simulations

- Software has been developed to simulate resonant excitation data, including:
  - Magnet misalignments and errors
  - BPM transverse misalignments, resolution, gain errors, tilts, timing errors, etc.
  - Tune trackers to drive beam
  - Resonantly excite the beam, damp until equilibrium, then record turn-by-turn positions (with BPM errors applied)
  - Process data as our control software does, emulating:
    - BPM gain maps
    - BPM tilt calibrations
    - Iterative LET correction procedure based successive measurements
- See Excel spreadsheet for example results

Low Emittance Tuning

The same simulation predicts 95% seeds are tuned to <2pm if BPM

- Offsets < 100μm
- Button to button gain variation < 1%
- Differential resolution < 4 μm (1 μm for ATF lattice)
- BPM tilt < 10mrad

- We have beam based techniques for calibrating gain variation based on turn by turn position data
- Determining tilt from coupling measurements
- We are exploring a tuning scheme that depends on measurements of the normal modes of the dispersion rather than the horizontal and vertical and that is inherently insensitive to BPM button gain variations and BPM tilts.

Hints of FII signal in bunch-by-bunch data.

$$y(s,z) \approx \hat{y}\frac{1}{4\sqrt{\pi}}\frac{1}{\eta^{1/4}}\exp\left(2\sqrt{\eta}\right)\sin\left(\omega_i z - \omega_\beta s + \theta - \phi\right)$$

Ion Frequency

- Calculated ion frequency between 5 and 10 Mhz.
- Analysis is FFT of 45 bunches at 1 BPM averaged over 4096 turns
- Data needs to be understood in context of trapping condition.