Low-Emittance Instrumentation in Use at CESRTA

Michael Billing
for the CESRTA Collaboration

LCWS12

October 25, 2012

Low Emittance Instrumentation

- Motivation for Instruments in CESRTA
- Alignment Tools
- Beam-Based Instruments
  - Digital Tune Tracker
  - BPM System
  - xBSM -Xray (Vertical) Beam Size Monitor
  - vBSM -Visible (Horizontal) Beam Size Monitor
- Process for Reduction of Vertical Emittance

Motivation

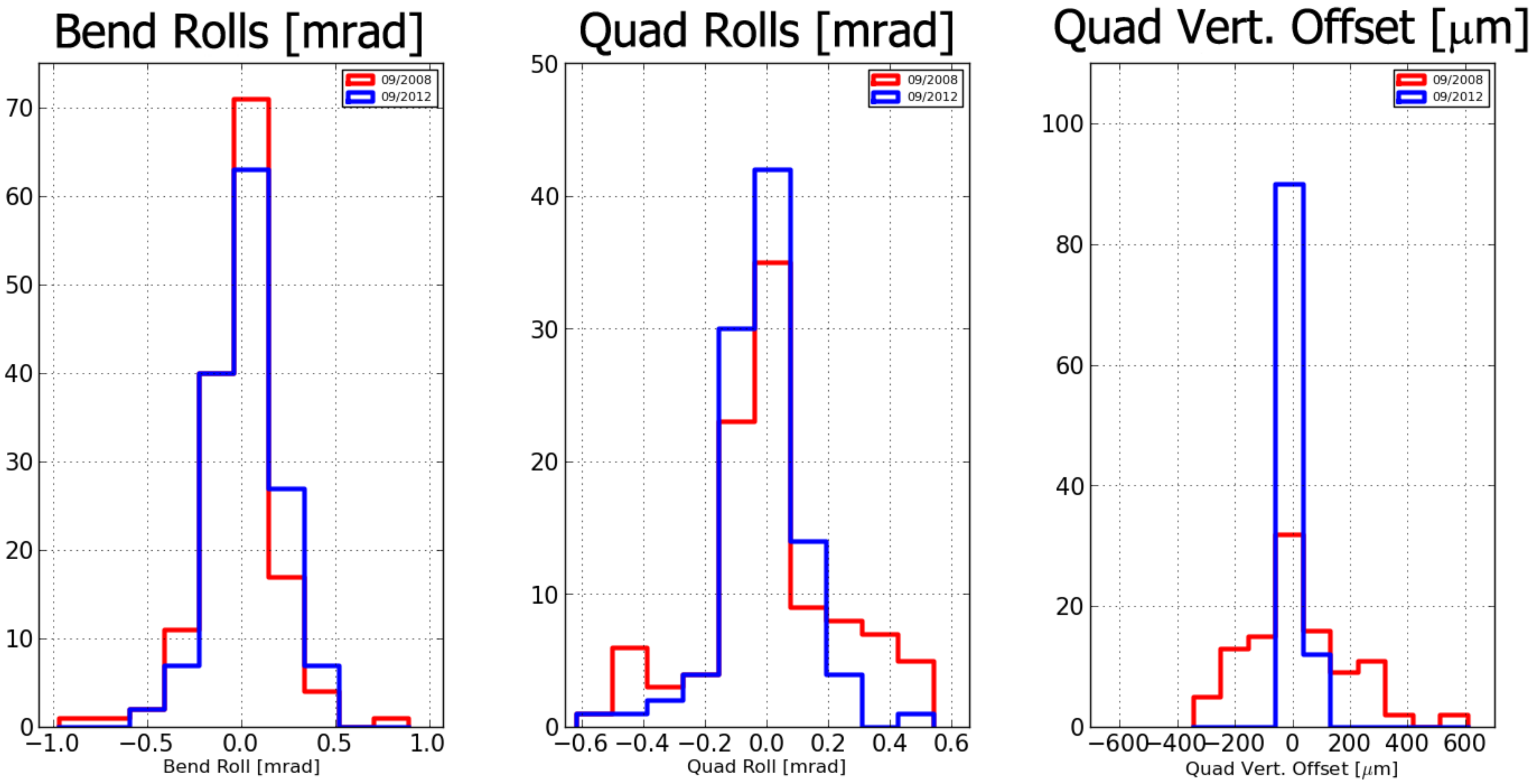
- Many Facilities and Users Demand Low Emittance:
  - Electron Cloud studies at CESRTA
  - Lepton colliders
  - Linear collider damping rings
  - Light sources
- Goals of Emittance Tuning at CESRTA:
  1. Develop framework for optics characterization which:
     1. has a fast turn-around time for full characterization
     2. scales well to large rings
     3. does not induce hysteresis in magnets
  2. Utilize optics characterization to correct ε_y **< 10pm-rad**
  3. Develop instrumentation to support these goals

CESR Alignment

- Survey Instrumentation at CESRTA
  - API Tracker III laser tracker with interferometer
  - Monument with1.5” spherically mounted reflectors
  - Leica DNA03 digital level & staffs
- Measurements
  - Survey network grid – allows observation of drift of monuments over time
- More Accurate Survey
  - Reduces size of correction
  - Sets baseline for limit to smallest emittance

Reflector mounts

Progress of CESR Survey and Alignment

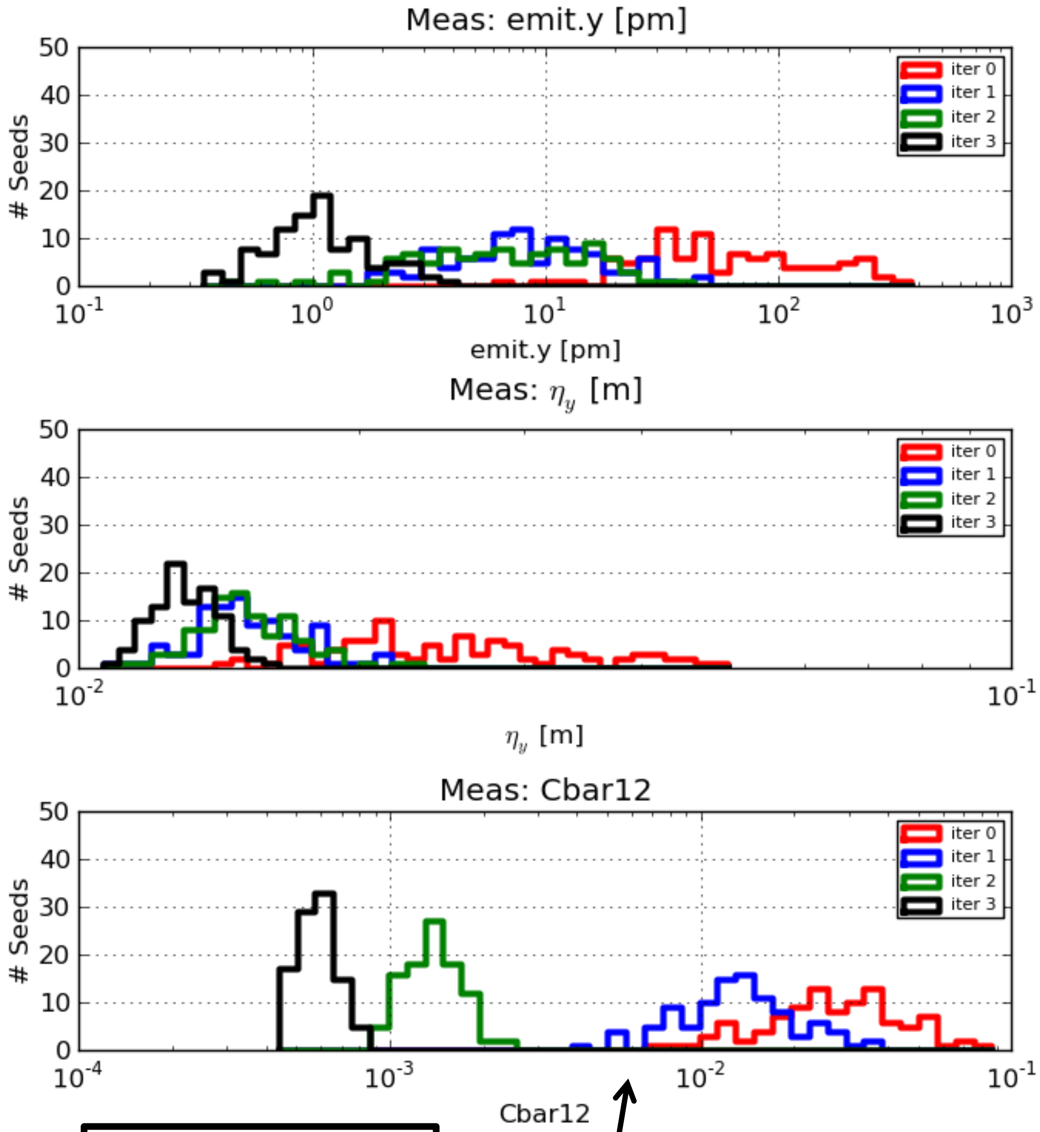


	Bend Rolls	Quad Rolls	Quad Vert. Offset
09/2008 RMS	206 μrad	227 μrad	193 μm
09/2012 RMS	177 μrad	148 μrad	25 μm

Study of Beam-based Emittance Correction

- Introduce misalignments in model lattice
  - Use RMS offsets, tilts from survey
- Repeat for 100 random distributions; record emittances

Mean ε_y = 100 pm-rad
95%CL ε_y = 250 pm-rad



To achieve CESRTA target emittance, we must employ beam-based correction techniques

3 iterations

The Path to Low Emittance

- Accelerator Component Survey:
  - Better element placement requires much less correction
  - Good placement (location & tilts) needed for
    - Bends, quadrupoles & to a lesser degree sextupoles
- Accurate Twiss, Couping & Vertical Dispersion Parameter Measurements:
  - Utilize excitation + BPMs & a good model for correction of
    - Orbit (H & V steerings)
    - Beta-functions (quadrupoles)
    - Linear coupling matrix elements (skew quadrupoles)
    - Vertical dispersion (skew quadrupoles & V steerings)
- Check Accuracy of Correction
  - Measure vertical (& horizontal) beam size
- Iterate These Steps

Beam-based Instrumentation

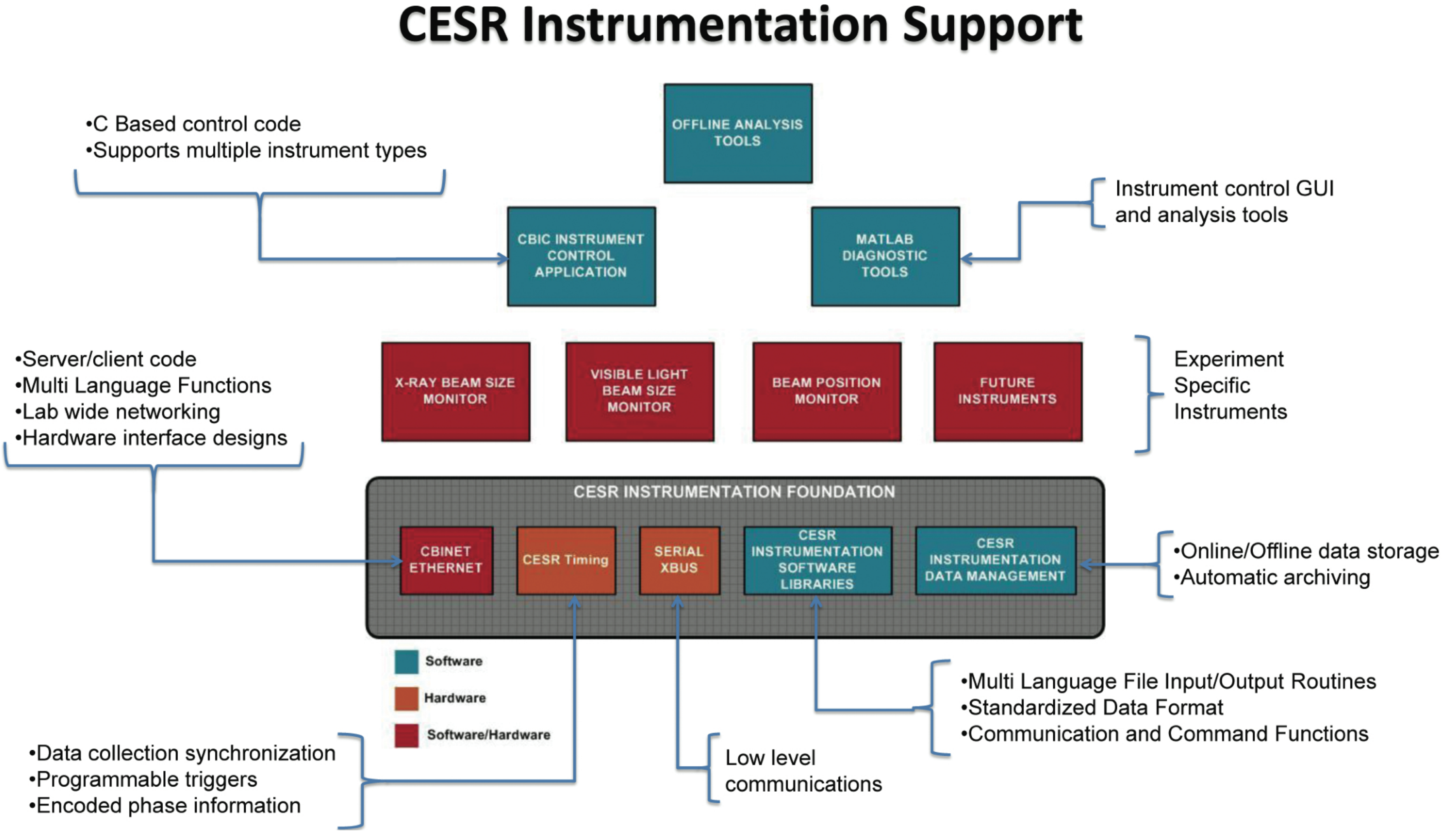
- General Requirements
- CESR General Interface for Advanced Instruments
- Instruments
  - Digital Tune Tracker
  - BPM System
  - xBSM -Xray (Vertical) Beam Size Monitor
  - vBSM -Visible (Horizontal) Beam Size Monitor

Requirements for Beam-based Instruments

- CESR's instruments must function in an experimental setting
- Instruments must function for both CESRTA and CESR, operating for CHESS X-ray lines
  - CESRTA
    - Need to be able to study effect of Electron Clouds within trains of positron or electron bunches
    - Able to measure each bunch within multi-bunch trains
    - Train spacing ≥ 4 nsec in arbitrary distribution
    - Able to synchronously measure 1) Beam Position, 2) Vertical & Horizontal Beam Sizes
  - CESR, operating for CHESS
    - Have electron & positron counter-rotating beams
    - Need to readout positions of bunches in both beams
  - These considerations have driven our solutions

Configuration for Advanced Instruments

- General data acquisition system software architecture for FPGA-based instruments



CESR Instrumentation Support

OFFLINE ANALYSIS TOOLS

CBIC INSTRUMENT CONTROL APPLICATION

MATLAB DIAGNOSTIC TOOLS

- C Based control code
- Supports multiple instrument types

Instrument control GUI and analysis tools

X-RAY BEAM SIZE MONITOR

VISIBLE LIGHT BEAM SIZE MONITOR

BEAM POSITION MONITOR

FUTURE INSTRUMENTS

Experiment Specific Instruments

- Server/client code
- Multi Language Functions
- Lab wide networking
- Hardware interface designs

CESR INSTRUMENTATION FOUNDATION

CBINET ETHERNET

CESR Timing

SERIAL XBUS

CESR INSTRUMENTATION SOFTWARE LIBRARIES

CESR INSTRUMENTATION DATA MANAGEMENT

- Online/Offline data storage
- Automatic archiving

🟦 Software
🟧 Hardware
🟥 Software/Hardware

- Multi Language File Input/Output Routines
- Standardized Data Format
- Communication and Command Functions

Low level communications

- Data collection synchronization
- Programmable triggers
- Encoded phase information

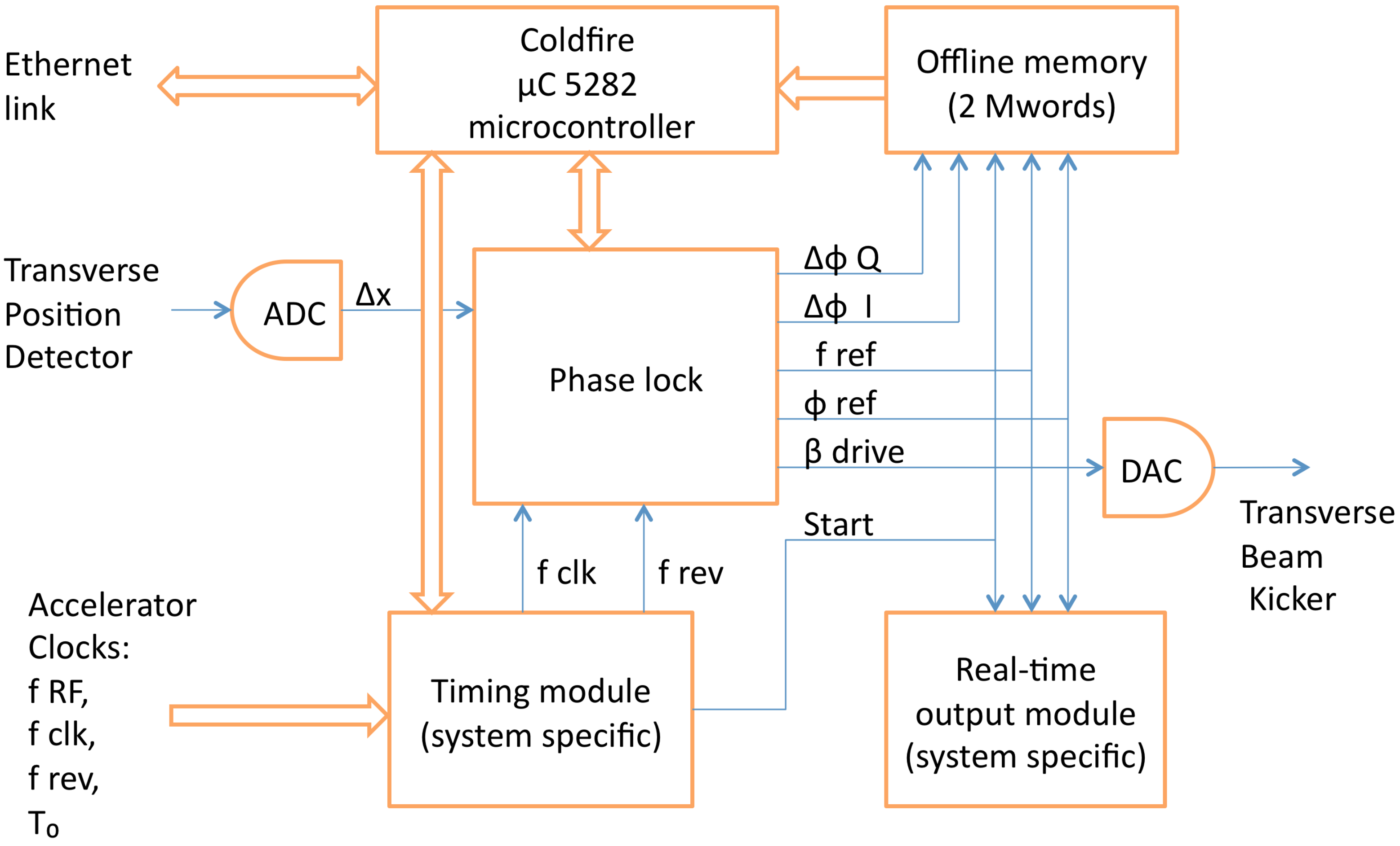
Digital Tune Tracker

- Purpose – Phase-Stable Beam Excitation
  - Locks to betatron and synchrotron tunes by resonantly exciting beam via either
    - Narrowband shaker magnet
    - Stripline or cavity kicker (H, V, L)
  - To provide phase information to BPM modules (encoded within the BPM clock), which in turn yield
    - Phase advance information around ring → beta functions
    - Betatron coupling information
    - Dispersion information
  - Can lock on any one bunch in the ring
  - Critical element for phase accuracy to follow any betatron or synchrotron tune drift during measurement

Digital Tune Tracker

- Functional block diagram

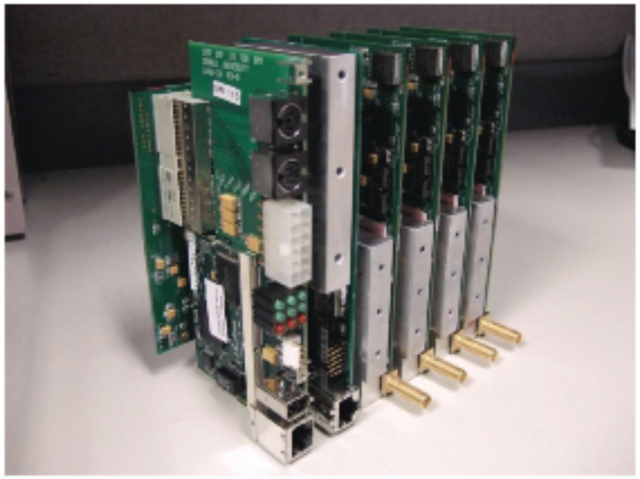
Digital tune tracker



CPBM System Specifications

BPM Development

Property	Specification
Front-end Bandwidth (4ns bunch trains)	500 MHz
Absolute Position Accuracy (long term)	100 μm
Single Shot Position Resolution	10 μm
Differential Position Accuracy	10 μm
Channel-to-Channel Sampling Time Accuracy	10 ps
BPM Tilt Errors (after correction)	10 mrad



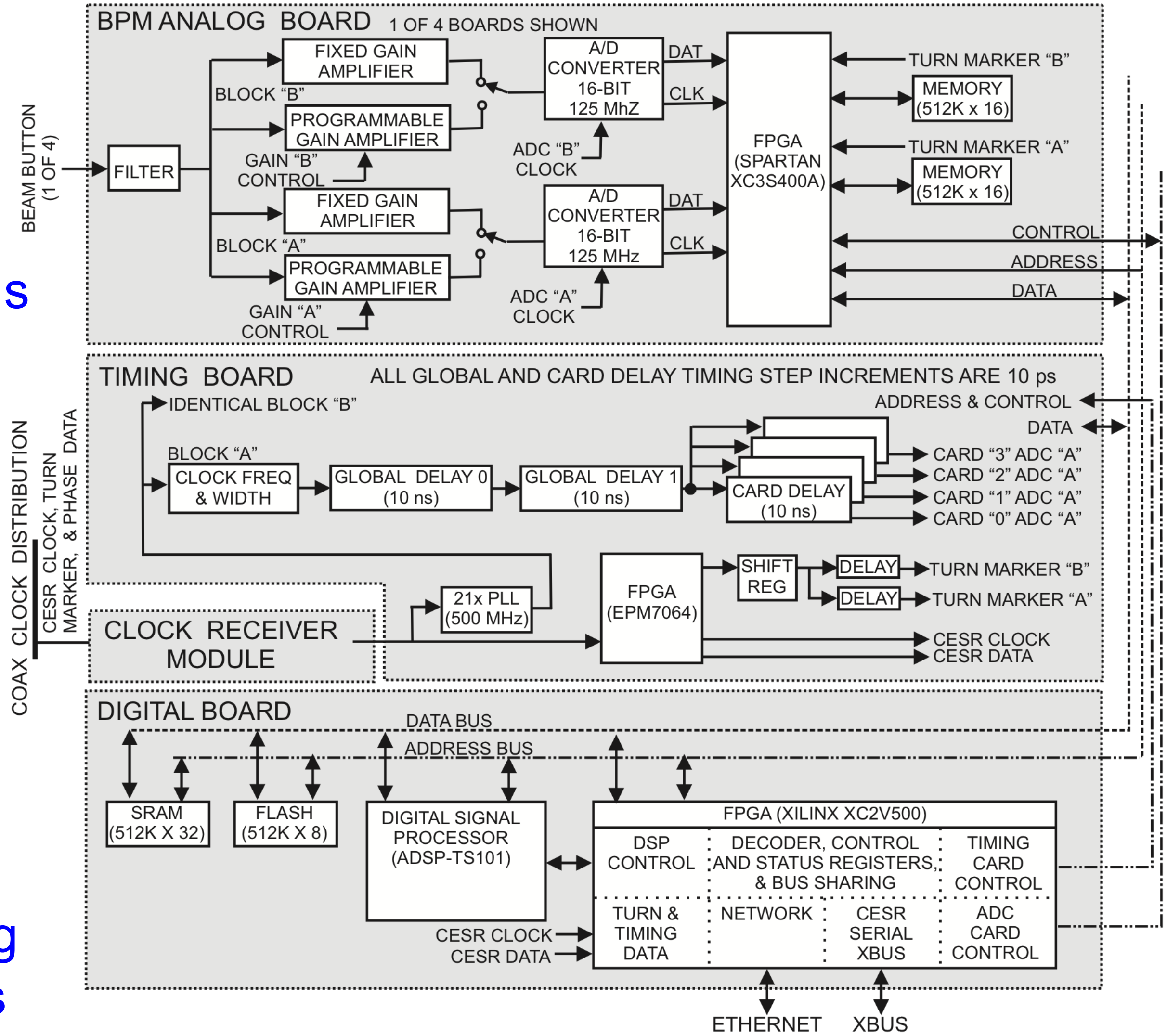
4 channels of 2 independently-timed digitizers (1 for each button)

Peak-detection of BPM signal
≥ 4ns-spaced bunches

Onboard FPGA for
- auto-timing control
- triggered-synchronous TBT trajectory acquisition for all bunches
- FFT of resonantly excited trajectories

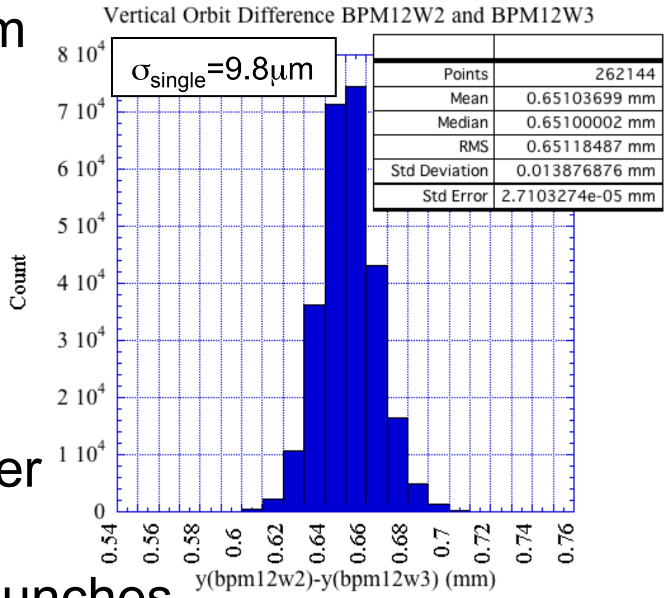
CBPM Module

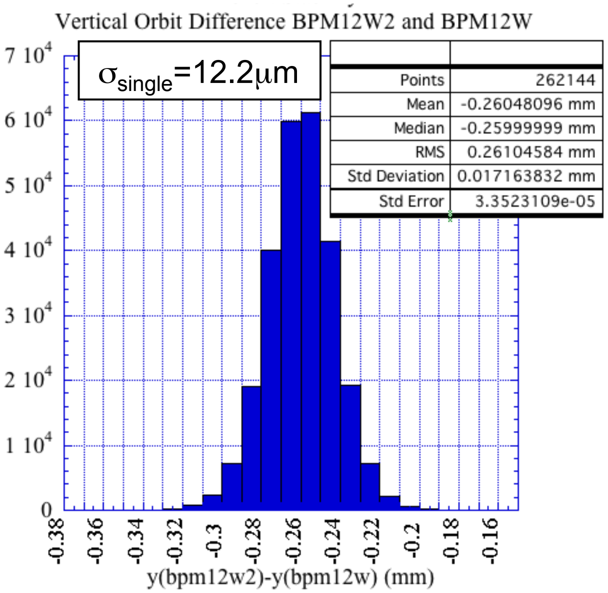
- Module Layout (BPM system uses ~110 modules)
  - 4 Analog boards, each containing
    - 2 16b-digitizers at 125 MHz
    - Precision fixed gain & ≥ 40 dB variable gain amp's
    - Independently timed for peak detection
  - Timing board
    - Clocking, delay & triggering
  - Digital board
    - FPGA (Xilinx) for control, processing & communications



CPBM Module Characterization

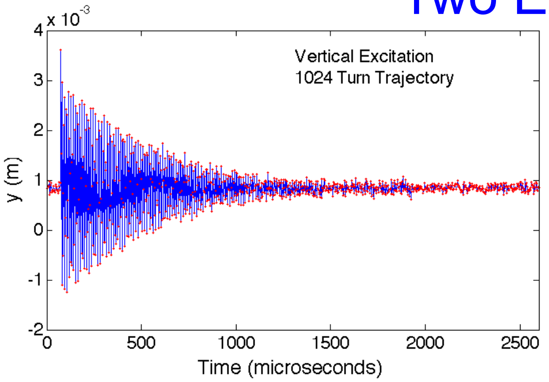
- Qualification Test: Triplet BPM Position Measurement
  - Resolution: ~10 μm
    - dominated by timing drift
    - auto-timing can be invoked



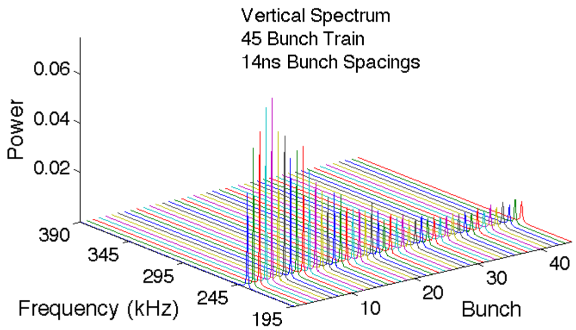


- Multi-bunch TBT
  - Synchronous trigger for all modules for any sequence of bunches
  - ADC memory depth
    - >300k bunch-turns
- Timing Diagnostics
  - Displacing sampling trigger to zero-crossing of signal -> timing variation check

Two Examples



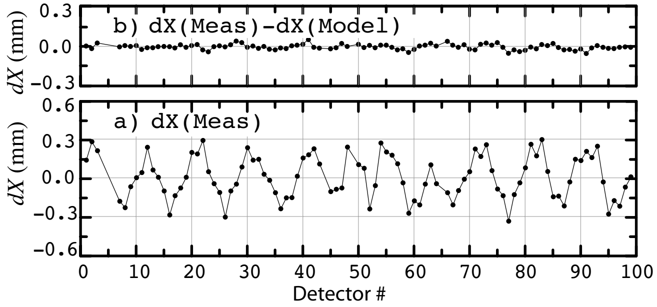
Single bunch TBT trajectory



FFT of 45-bunch train trajectories

CBPM Measurements

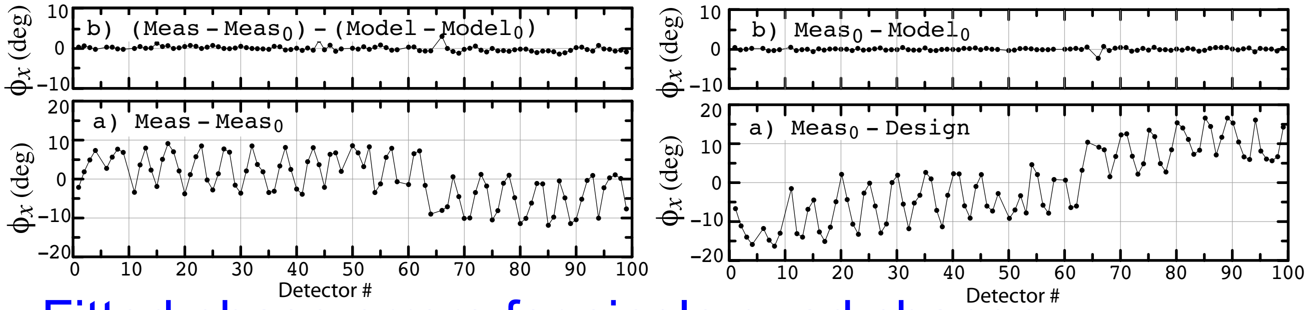
- Orbit



Fitted orbit error for single corrector change

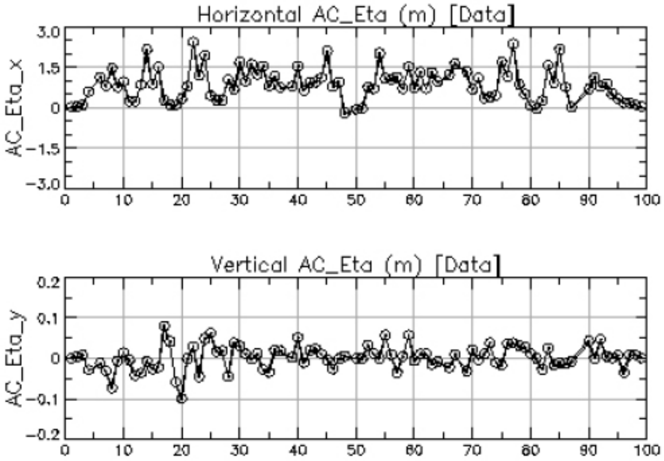
- Betatron ϕ

  & Coupling
  - See explanation below



Fitted phase errors for single quad change

- Dispersion
  - Conventional & AC



AC Eta: Dispersion using phase-locked shaking of the CESR RF Phase

CBPM Calculation of Betatron Phase & Coupling

1) Excite beam with Tune Tracker – encode its phase within the BPM clock

2) 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
  - Tunes must not be near resonances, to prevent cross-talk between H/V modes

3) BPM modules compute **FFT amplitude** of horizontal motion (Similar equations for vertical mode) at **button j** is a sum over **turns i**:

$$A_{j,\,\sin,\,h} = \frac{2}{N}\sum_{i}^{N} \sin\left[\theta_{t,\,h}(i)\right] a_j(i) \quad \text{(in-phase)}$$

$$A_{j,\,\cos,\,h} = \frac{2}{N}\sum_{i}^{N} \cos\left[\theta_{t,\,h}(i)\right] a_j(i) \quad \text{(out-of-phase)}$$

$\theta_{t,h}(i)$ = 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

Phys. Rev. ST Accel. Beams ***3***, September 2000, 092801

Aside: Coupling Definition

- Two eigen modes for x-y coupled motion
  - “Diagonalize” motion into 2 eigen modes
  - Coupling can be represented as 2 components:
    - Slow wave – propagates as $\phi_v - \phi_h$
    - Fast wave – propagates as $\phi_v + \phi_h$

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 = above C matrix, but in amplitude normalized coordinates

When we excite the beam with two tune trackers, we drive each of these eigen modes.

Betatron Phase & Coupling Measurement

From measurements, we obtain –

Betatron phases and couplings (Cbar) defined by:

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

$$\bar{C}_{12} = \sqrt{\beta_h/\beta_v}\;\left\{A_{y,h}/A_{x,h}\right\}\;\sin\left(\phi_{y,h}-\phi_{x,h}\right)$$ from **horiz.** mode

$$= \sqrt{\beta_v/\beta_h}\;\left\{A_{x,v}/A_{y,v}\right\}\;\sin\left(\phi_{x,v}-\phi_{y,v}\right)$$ from **vert.** mode

$$\bar{C}_{22} = \sqrt{\beta_h/\beta_v}\;\left\{A_{y,h}/A_{x,h}\right\}\;\cos\left(\phi_{y,h}-\phi_{x,h}\right)$$ from **horiz.** mode

$$\bar{C}_{11} = \sqrt{\beta_v/\beta_h}\;\left\{A_{x,v}/A_{y,v}\right\}\;\cos\left(\phi_{x,v}-\phi_{y,v}\right)$$ from **vert.** mode

Cbar 12 is “**out-of-phase**” component of coupling matrix

- Insensitive to rotation of x-y coordinates - Independent of physical BPM tilts

Cbar 22 and **Cbar 11** are “**in-phase**” components

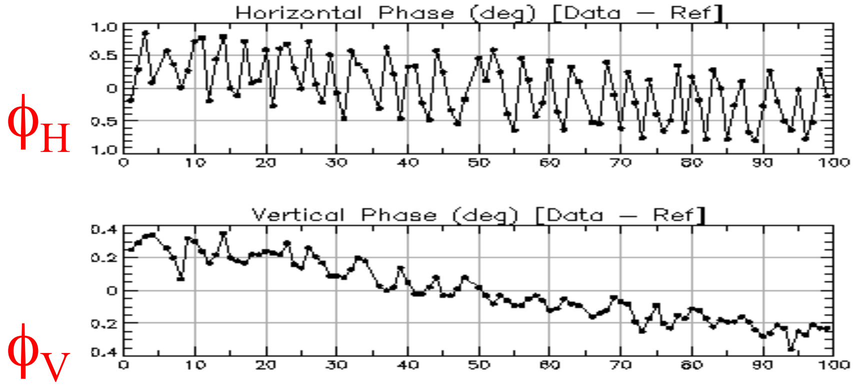
- Sensitive to rotation of x-y coordinates - Dependent on BPM tilts

Similarly, when resonantly exciting beam **longitudinally** and measuring beam position **at the synch tune**, one obtains the **dispersion** (“AC dispersion” technique)

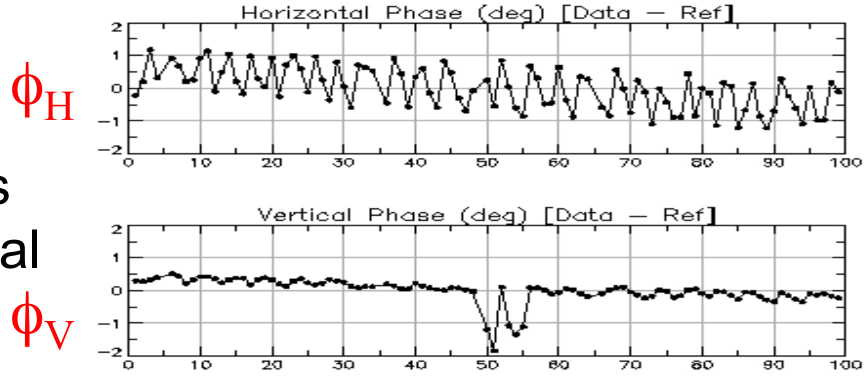
Multi-bunch: CBPM & Digital Tune Tracker

- Bunch-by-bunch Phase Measurement for 30 Bunch Train
  - See phase advances errors for each bunch
  - (Coincidently observe a spurious signal arising from EC)

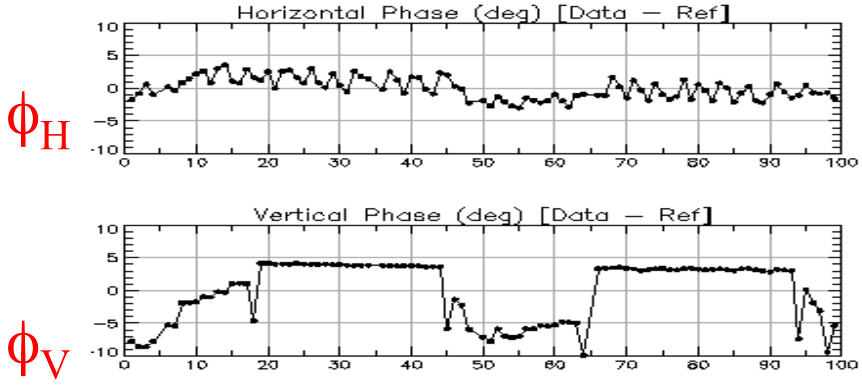
Bunch 12 phase, showing phase shift along train



Bunch 15 phase, showing a spurious electron cloud signal

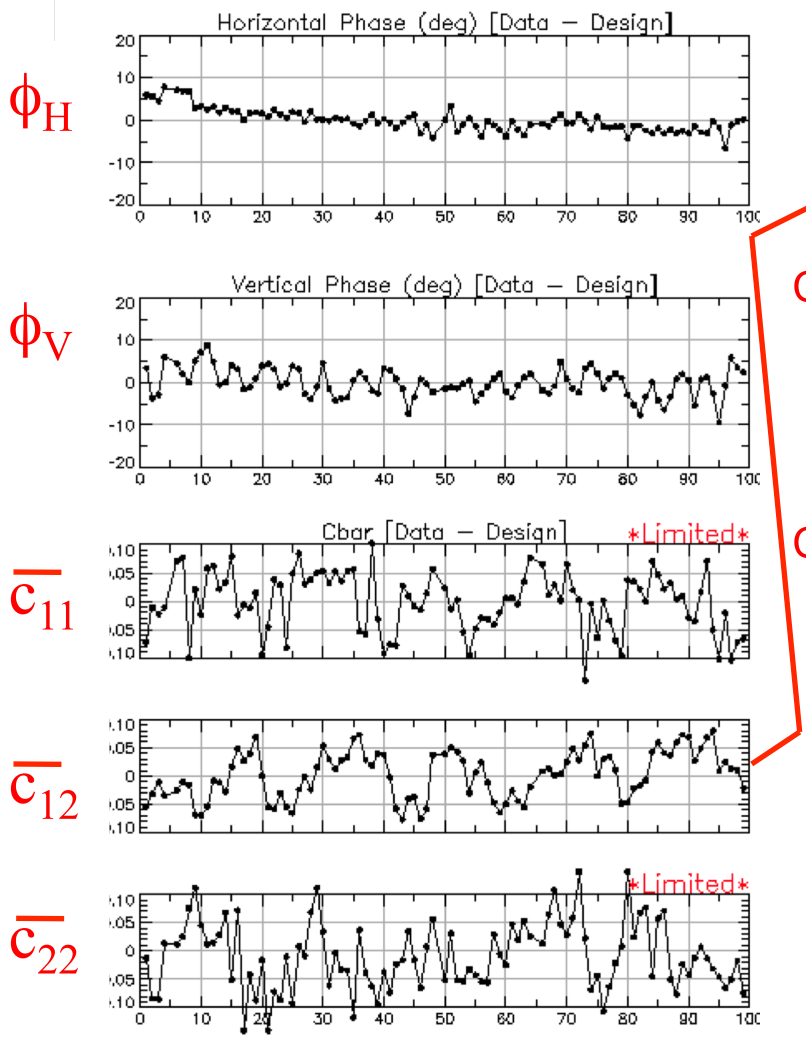


Bunch 25 phase, showing expanding electron cloud.

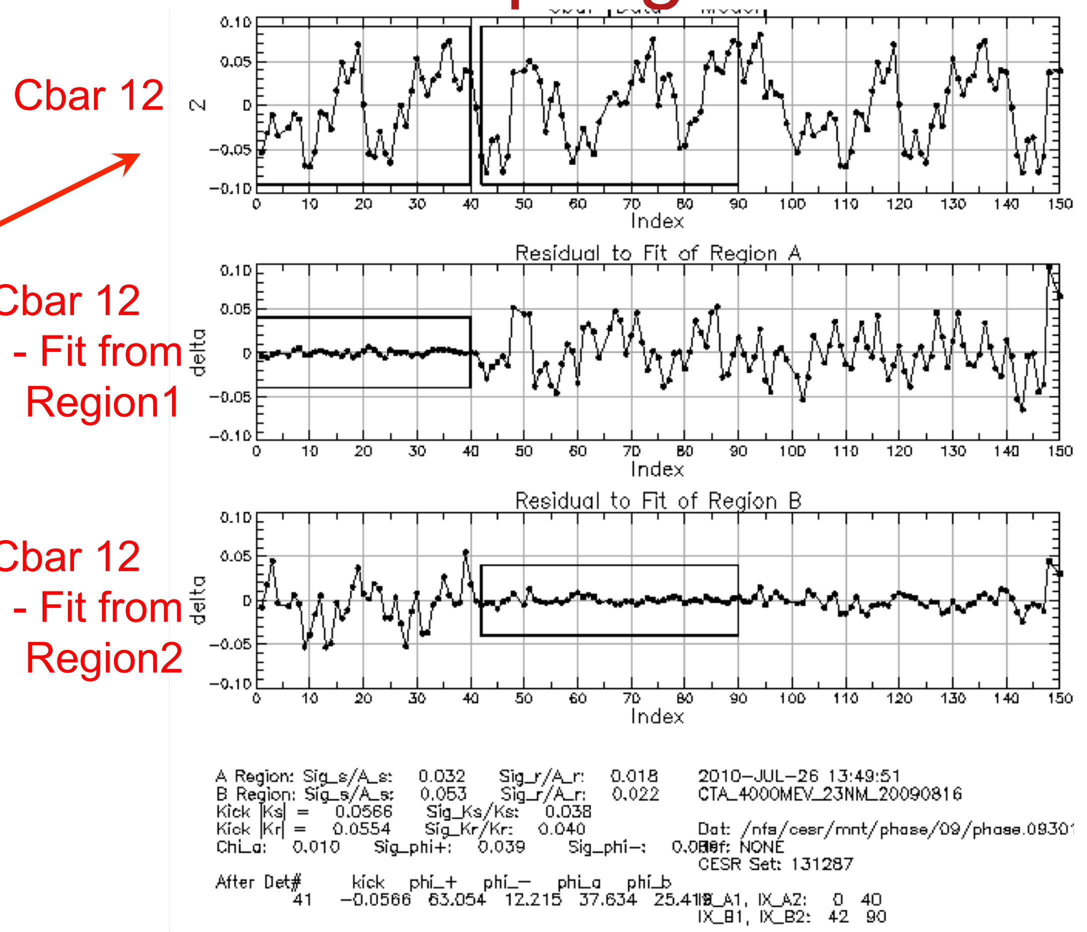


Using CBPM & Digital Tune Tracker Results

- Example: Finding Source of Coupling Error



Phase & Coupling Measurements



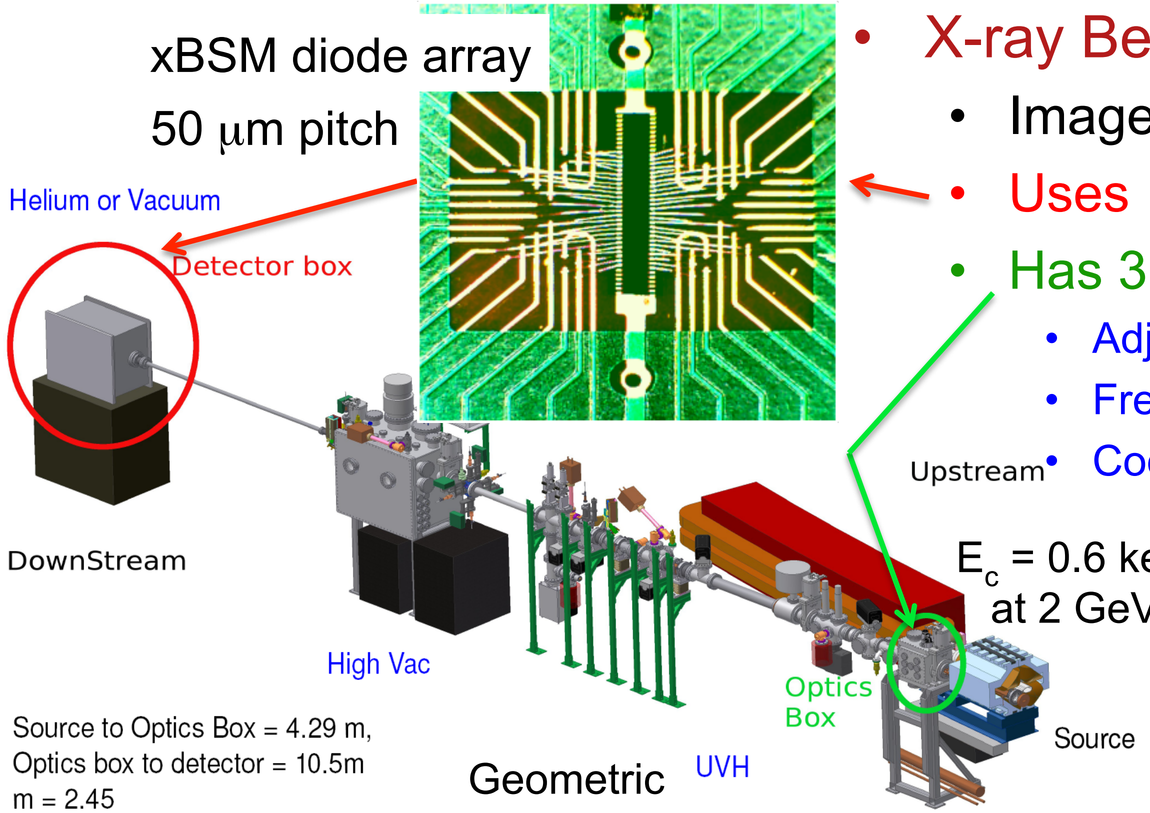
```
A Region: Sig_s/A_s:    0.032     Sig_r/A_r:    0.018      2010-JUL-26 13:49:51
B Region: Sig_s/A_s:    0.053     Sig_r/A_r:    0.022      CTA_4000MEV_23NM_20090816
Kick |Ks| =     0.0566     Sig_Ks/Ks:    0.038
Kick |Kr| =    0.0554     Sig_Kr/Kr:    0.040                Dat: /nfs/cesr/mnt/phase/09/phase.09301
Chi_a:    0.010     Sig_phi+:    0.039       Sig_phi-:    0.0Ref: NONE
                                                           CESR Set: 131287
After Det#       kick    phi_+    phi_-    phi_a    phi_b
        41    -0.0566   63.054   12.215   37.634   25.41IX_A1, IX_A2:    0   40
                                                           IX_B1, IX_B2:   42   90
```

Select 2 regions: Fit freely propagating Cbar
Gives phase location of single error.

(Bottom 2 plots show measurement - fits)

X-ray Vertical Beam Size Monitor

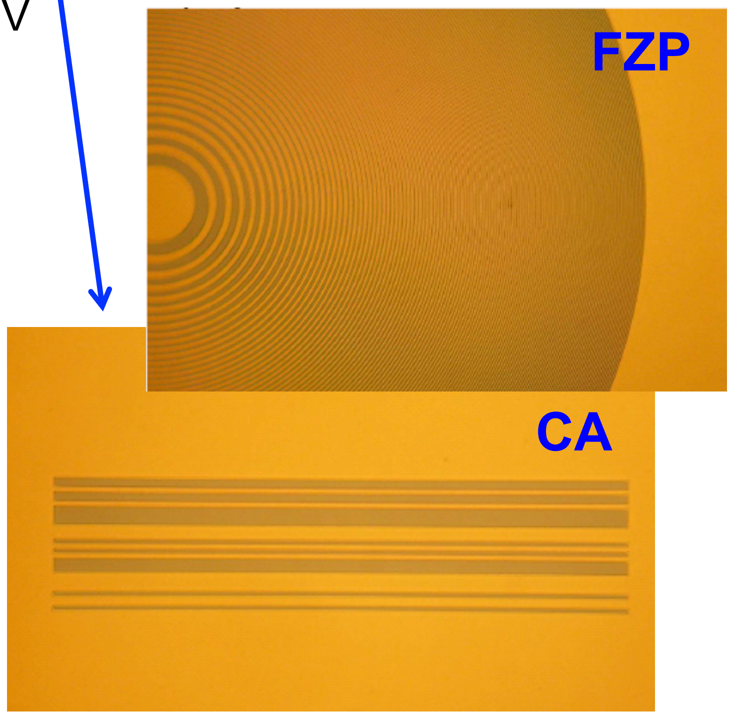
- X-ray Beam Size Monitor (xBSM)
  - Images X-rays from bending magnet
  - Uses 1D 32-chan vertical diode array
  - Has 3 choices for Optics Element
    - Adjustable Slit ("Pinhole" optics)
    - Fresnel Zone Plate (FZP)
    - Coded Aperture (CA)



E_c = 0.6 keV at 2 GeV

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

Geometric Magnification ~2.5

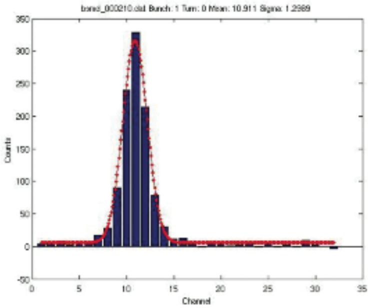


- Functions
  - Capable of measuring TBT bunch size for ≥ 4ns-spaced bunches
  - 40 dB gain adjustment
  - Primary tool for confirming vertical emittance corrections

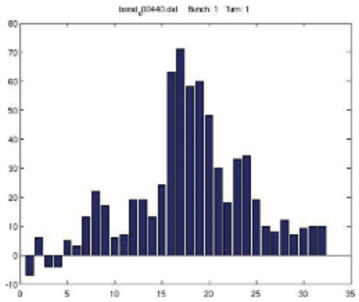
xBSM Measurements

- Observe signal with single bunches with different x-ray optics

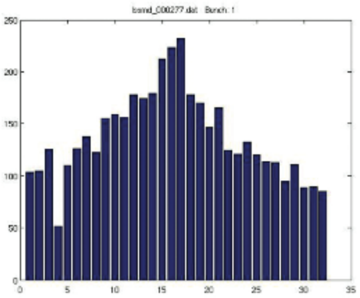
Slit

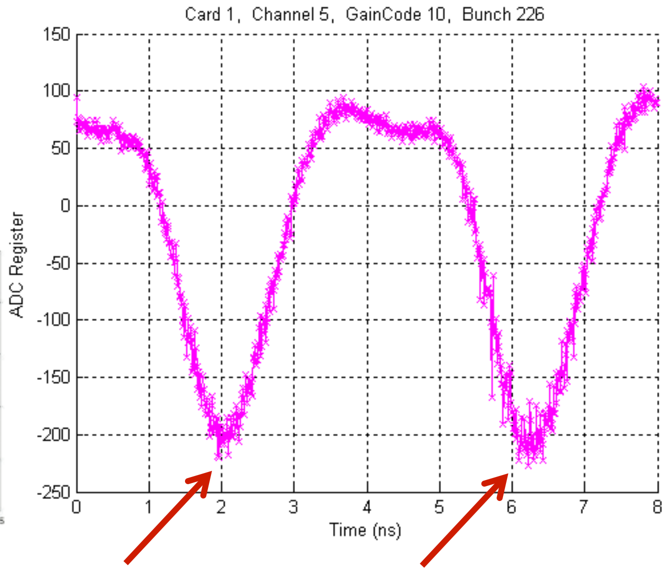


Coded Aperture



Fresnel ZP



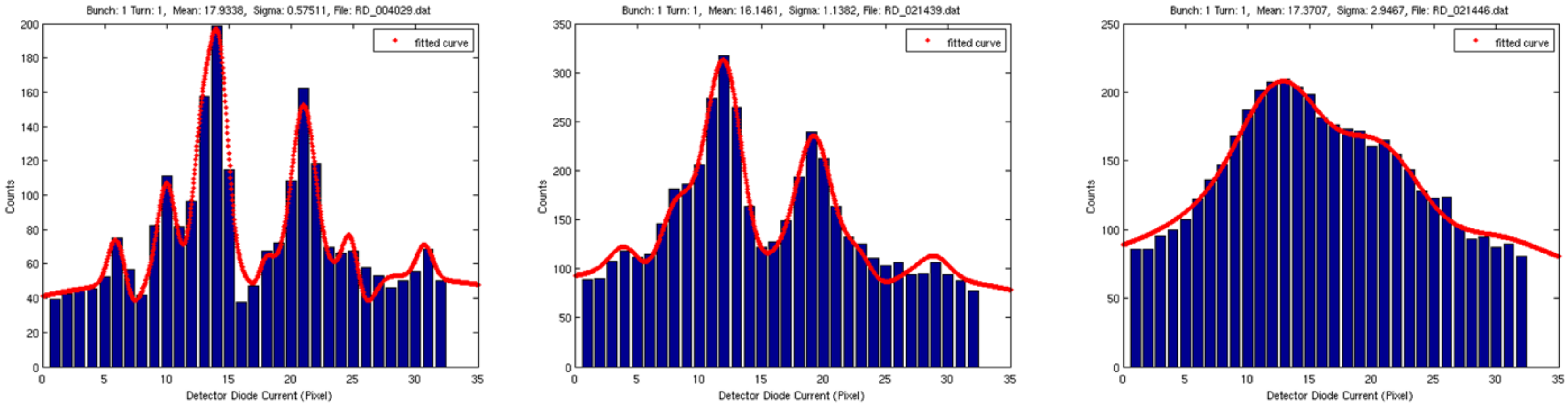


Sample Point
Bunch 1

Sample Point
Bunch 2

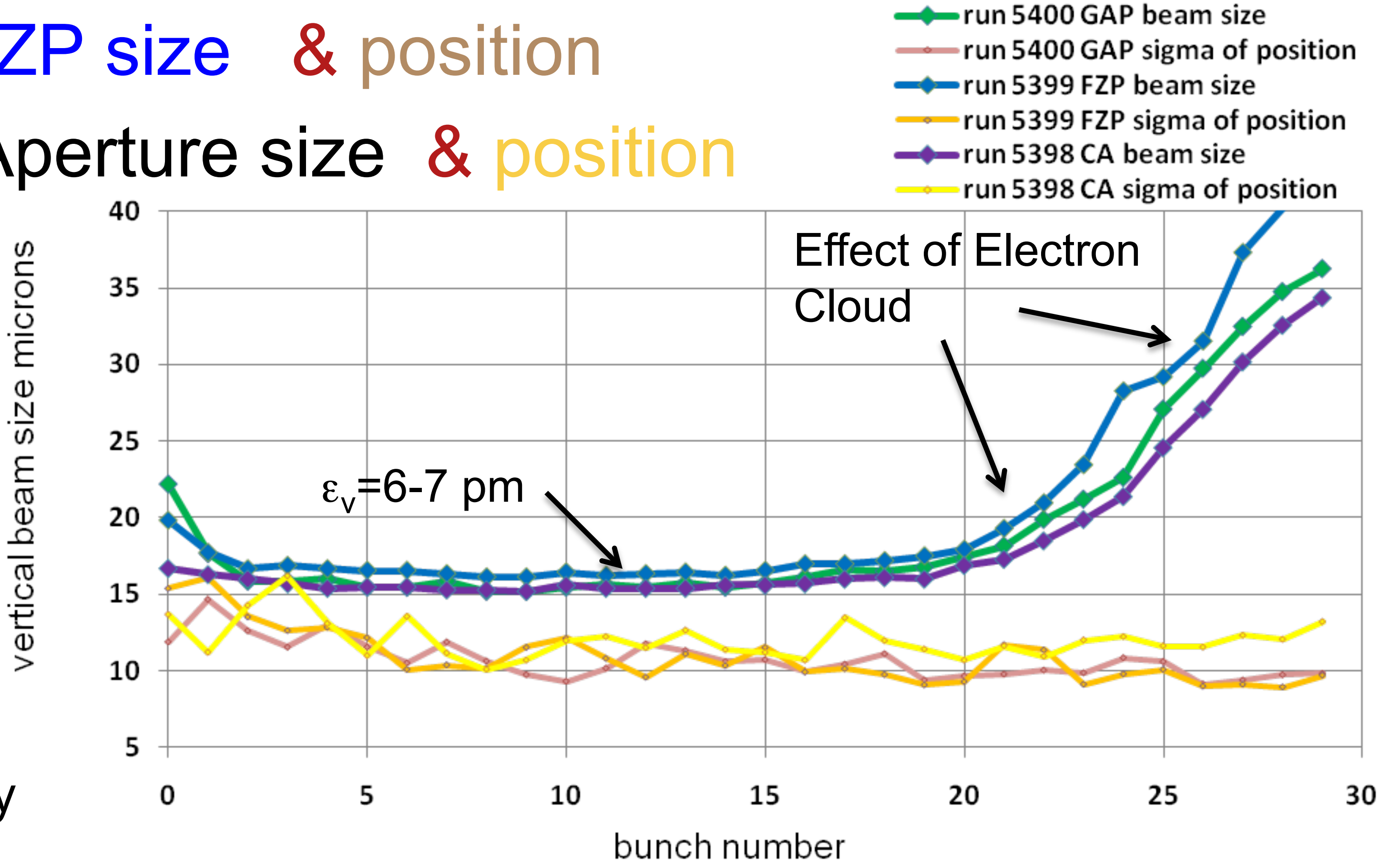
Single Pass-Single Bunch Distributions
with Fitting Function

Coded Aperture Fits for Different Beam Sizes



xBSM Measurements

- Systematic studies of multi-bunch performance with different x-ray optics (30 bunch train)
  - Slit (Gap) size & position
  - Fresnel ZP size & position
  - Coded Aperture size & position



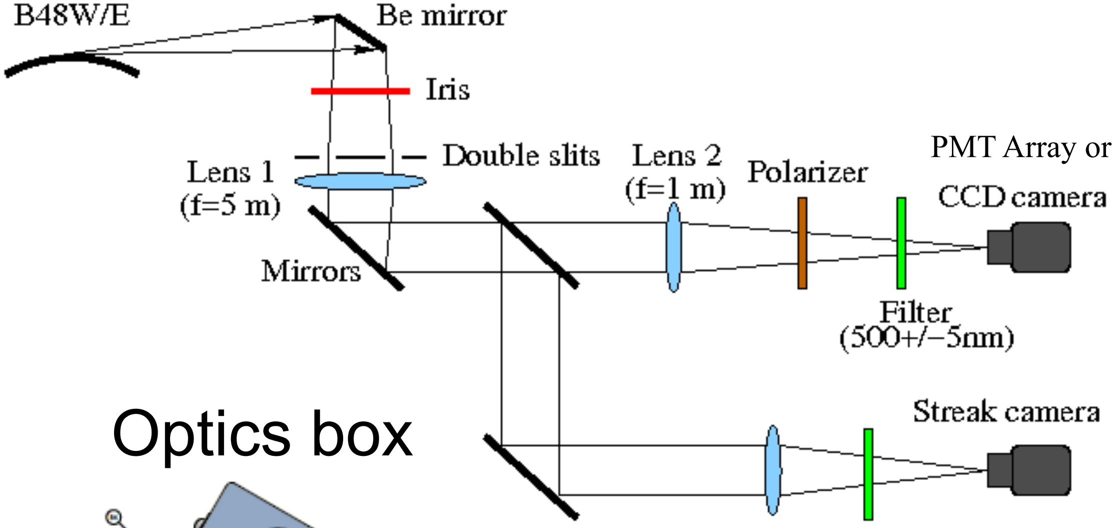
Effect of Electron Cloud

ε_v=6-7 pm

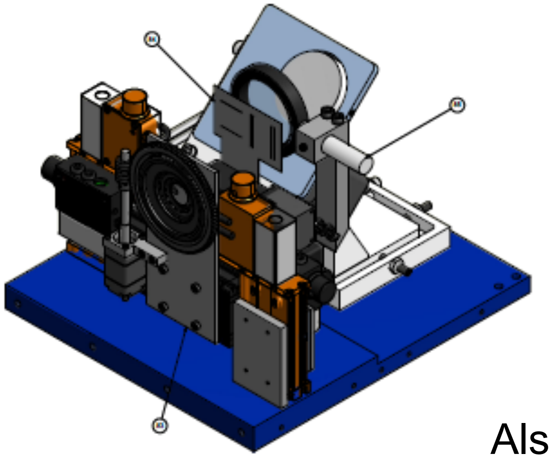
Data for each optic taken simultaneously

Horizontal Visible Light Beam Size Monitor

Visible-light Beam Size Monitor (vBSM)

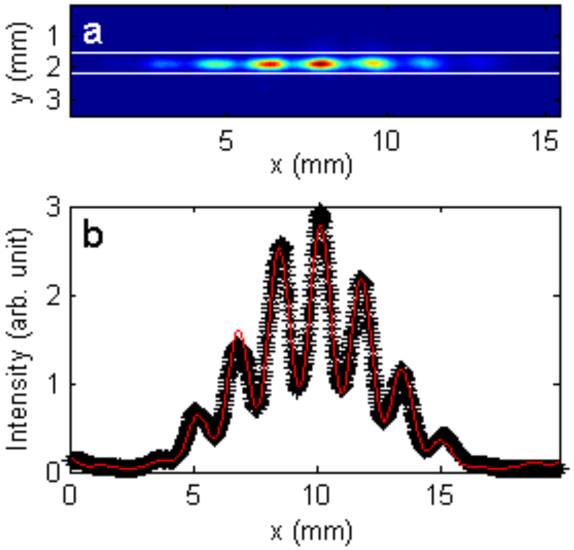


Optics box

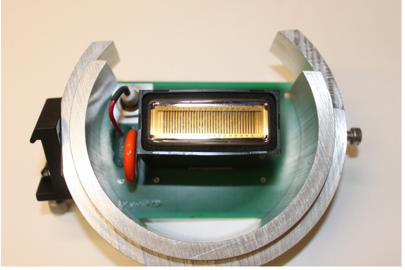


Also Studying
Measurement of Bunch-Bunch
V Beam Size Using π Polarization

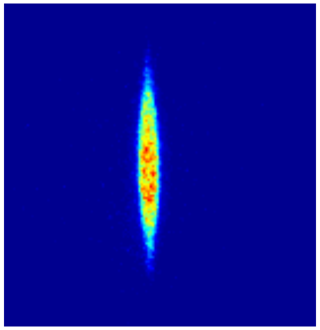
Horizontal beam size using
double slit interferometer



Photomultiplier Array for
Bunch-Bunch Beam Size



Streak Camera Image for
Bunch Length Measurement



Other Optics Characterization Method

- Orbit Response Matrix (ORM)
  - Advantages:
    - **Thorough** – measure change in machine conditions due to perturbations for elements throughout the ring
    - **Very successful** in reducing emittance at other storage rings
  - Disadvantages:
    - Data acquisition is slow
      - At CesrTA, **~2.5hrs** to collect one data set
      - For low-emittance rings with small Touschek lifetime, many top-ups are necessary
    - Acquisition **time scales linearly** with number of **elements** in ring
    - Varying all corrector magnets introduces **hysteresis**

➡ **Does not meet our requirements!**

CESR's Optics Characterization Method

- Most optics measurements at CESR utilize **resonant excitation** of betatron or synchrotron motion for the bunch
- Typical resonant excitation data acquisition:
  1. Resonantly drive the bunch with Digital Tune Trackers
     - Phase-lock and resonantly excite any single bunch in the ring
     - Initial setup: ~1 minute
  2. Record and read out TBT data
     - $2^{15} = 32{,}768$ turns used for most common measurements
     - Acquisition time: ~10 seconds
  3. Post-process data to extract optics information: < 5 seconds
- **Betatron phase, coupling, and dispersion** all measured with resonant excitation techniques
- **Meets all requirements:**
  1. Fast measurements, therefore fast turn-around between corrections
  2. Scales well to large rings
  3. No magnet hysteresis

BPM Calibrations

Precision BPMs required for accurate data for corrections

1. **Calibrate BPM button-to-button gain errors**
   - Fit gains for 2nd order expansion of BPM button using turn-by-turn trajectory data (*Phys Rev ST Accel Beams, 13, Sept. 2010, 092802)*
   - **Duration**: 30 seconds to acquire data; < 5 minutes to process & load corrections
   - **Result:** BPM button-to-button gains known to within **0.5 %**
2. **Calibrate BPM-to-quadrupole offsets**
   - Collect betatron phase data for two different settings on a quadrupole
   - Fit the phase difference to determine actual change in quad strength
   - Fit orbit difference to determine kick
   - **Duration**: 2 hours to measure and calibrate all BPM-to-quad offsets
   - **Result:** BPM-to-quadrupole offsets known to within **300 μm**
3. **Calibrate BPM tilts**
   - In-phase components of Cbar coupling matrix are related to BPM tilts
   - Fit many betatron coupling measurements to determine tilts
   - **Duration**: 30 seconds / coupling measurement; 5 minutes for analysis
   - **Result:** BPM tilts known to within **5 mrad**

Emittance Correction Procedure

1. **Orbit**
    1. **Measure** horizontal and vertical orbit
    2. **Correct** orbit to reference orbit
2. **Betatron phase and coupling**
    1. **Measure** betatron phase and coupling (Cbar12)
    2. **Correct** betatron phase to design, Cbar12 to zero
3. **Dispersion**
    1. **Measure** orbit, phase and coupling (Cbar12), AC dispersion
    2. **Correct** vertical orbit, Cbar12, vertical dispersion

Emittance Correction I

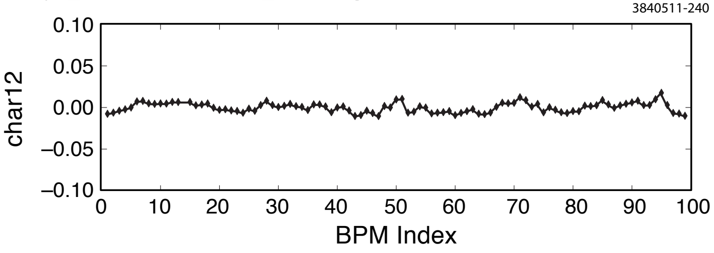
1. Measure closed orbit

- Correct with all horizontal and vertical steerings
- Typical correction levels: **Δx, Δy ~ 300μm** (RMS)
- Takes about **30 seconds** to measure, analyze, load corrections, and re-measure orbit

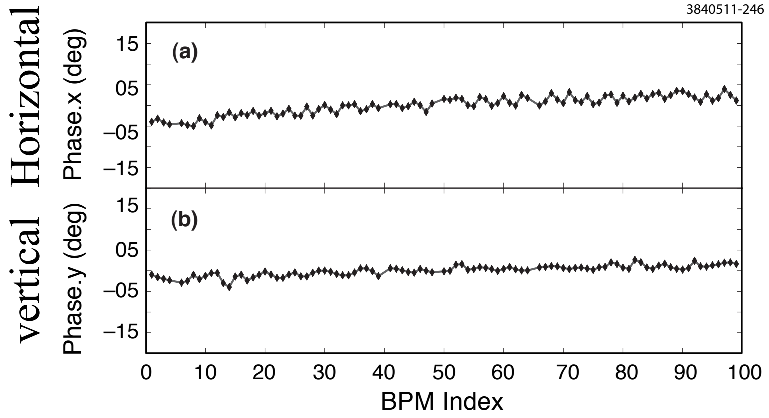
2. Measure betatron phase advance and transverse coupling

- 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 = 0.5% x-y coupling**
- One iteration takes about **one minute**

Typical coupling after correction:



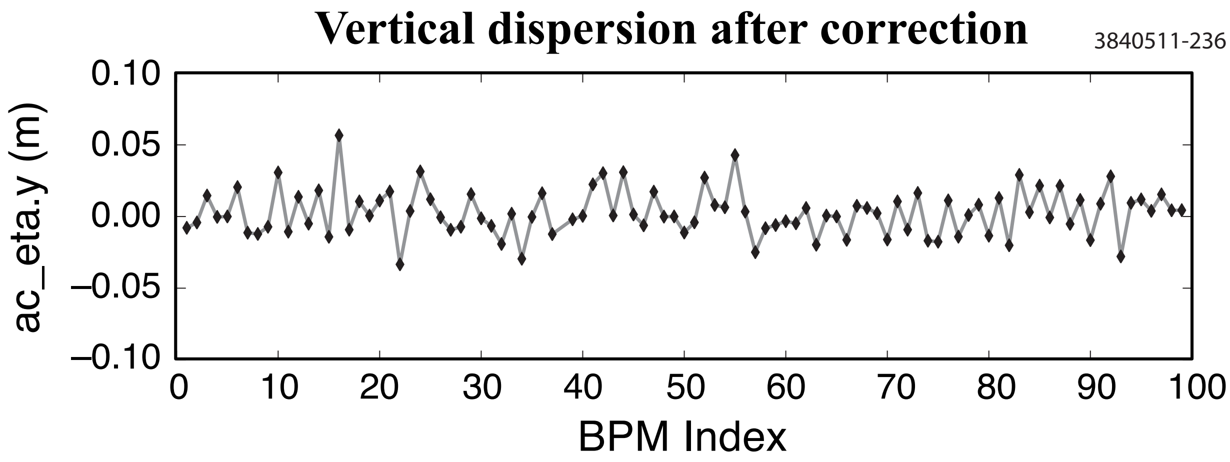
Typical phase after correction:



Emittance Correction II

3. Re-measure closed orbit, phase and coupling; measure 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 **~12mm**
  - Limited by BPM calibrations



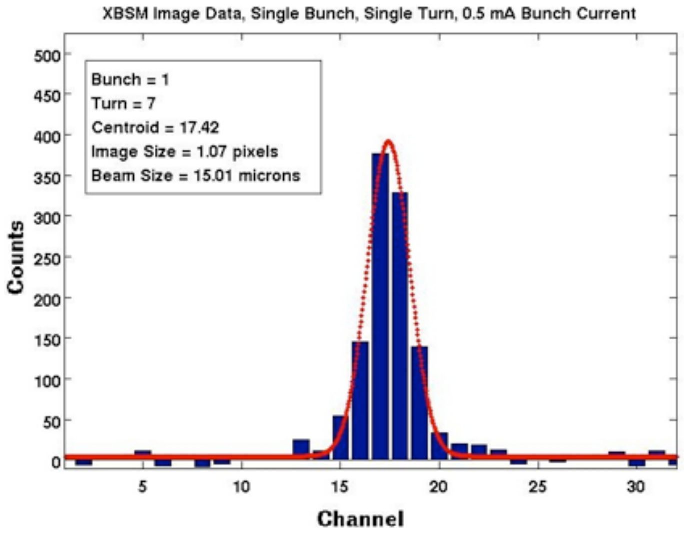
- Turnaround time: **~5 minutes** per correction iteration:
  1. **Correct orbit**
  2. **Correct phase + coupling**
  3. **Correct orbit + coupling + dispersion**

Vertical Beam Size Measurement

Beam size is the primary diagnostic for determining the success of emittance corrections

- X-ray Beam Size Monitor (xBSM)
  - 1D vertical diode array
  - Capable of measuring bunch-by-bunch, TBT bunch size for ≥4ns-spaced bunches
- Under final testing:
  - PMT with turn-by-turn response, using π-polarization measurement

Vertical beam size after correction using xBSM pinhole optic



After corrections, typically measure ε_y **< 10-15pm** with **xBSM**

At 0.5mA = 0.8x10^{10} positrons

Conclusions

- Achieving Low Emittance Requires Beam-based Techniques
- CESRTA Has Created a Suite of Instruments
  - Tune tracker, b-b: BPM system, xBSM & vBSM
- Also Developed Accompanying Analysis Tools
  - Correction: orbit, beta-functions, coupling, vertical dispersion
- Tested Procedure to Routinely Produce Low Emittance Beams
  - Tested in many different CESR optics
  - Working on ε_y below 10 pm

Acknowlegements

- Special Thanks to Few Individuals, Who Had Made Significant Contributions to This Talk
  - Nate Rider
  - Jim Shanks
  - John Sikora