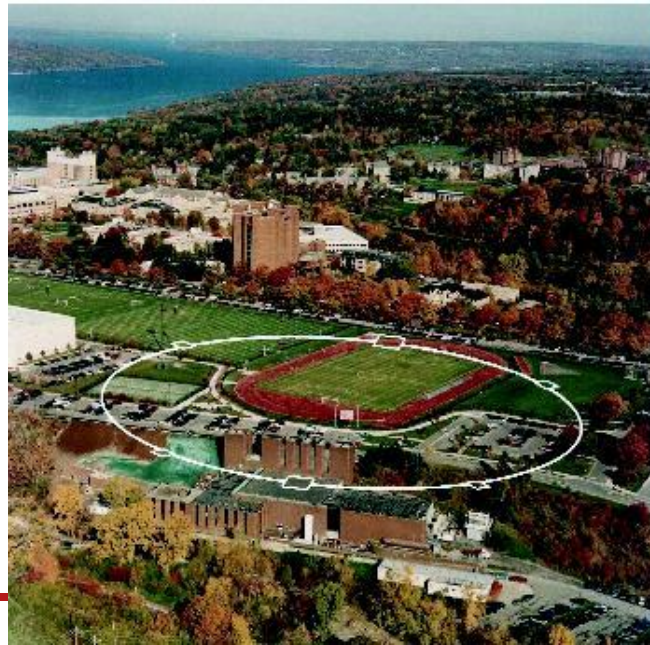




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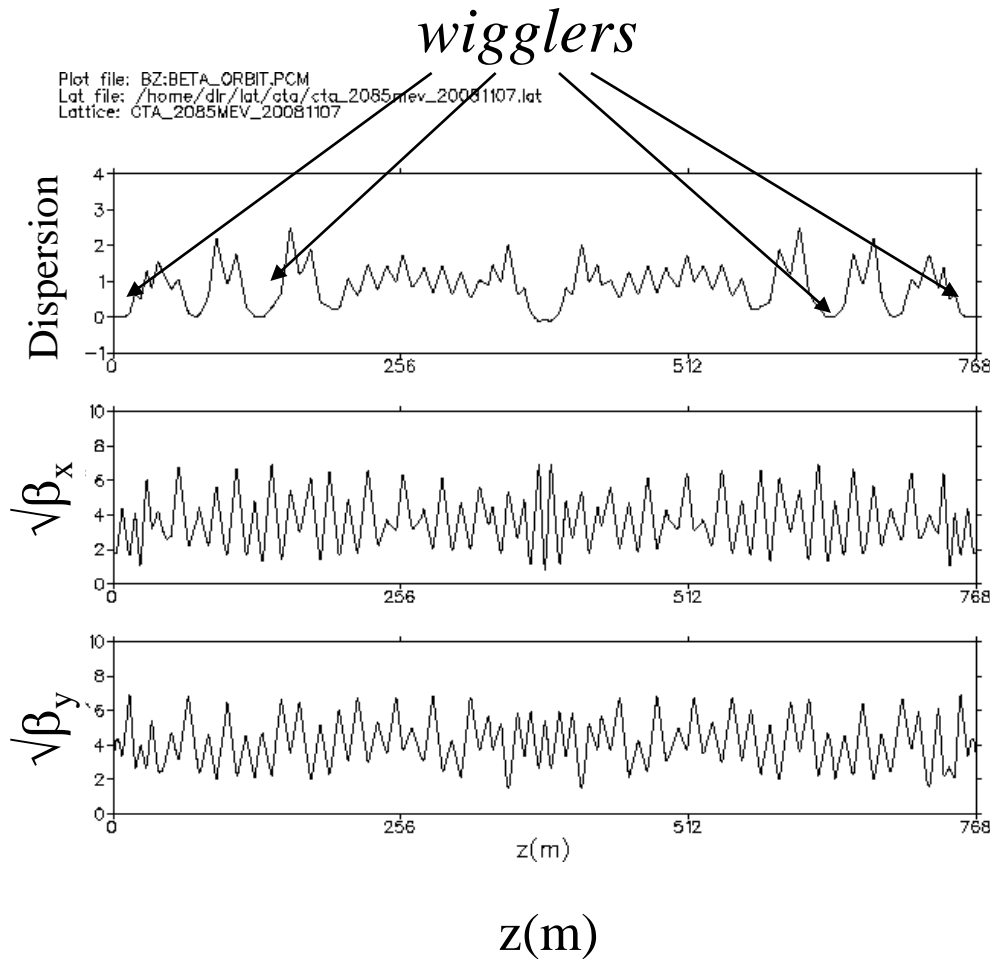
Low-Emittance Tuning at CESR-TA

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for the CESR-TA Collaboration*





- **Many facilities and users demand low emittance:**
 - Electron Cloud studies at CESR-TA
 - Lepton colliders
 - ILC damping rings
 - Light sources
- **Goals of Emittance Tuning at CESR-TA:**
 1. Develop a 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 $\varepsilon_y < 10\text{pm-rad}$



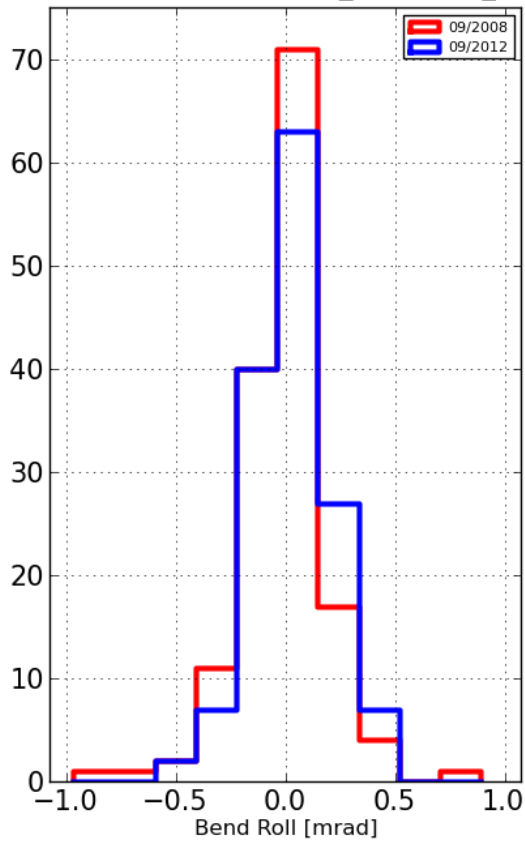
Parameter	
Circumference [m]	768.4
Energy[GeV]	2.1 (1.8-5.3)
Lattice type	FODO
Symmetry	\approx mirror
Horizontal steerings	55
Vertical steerings	58
Skew quadrupoles	27
Horizontal emittance [nm]	3.0
Damping wigglers [m]	12*
Wiggler B_{\max} [T]	1.9
Beam detectors	100
BPM diff resolution [μm]	10

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

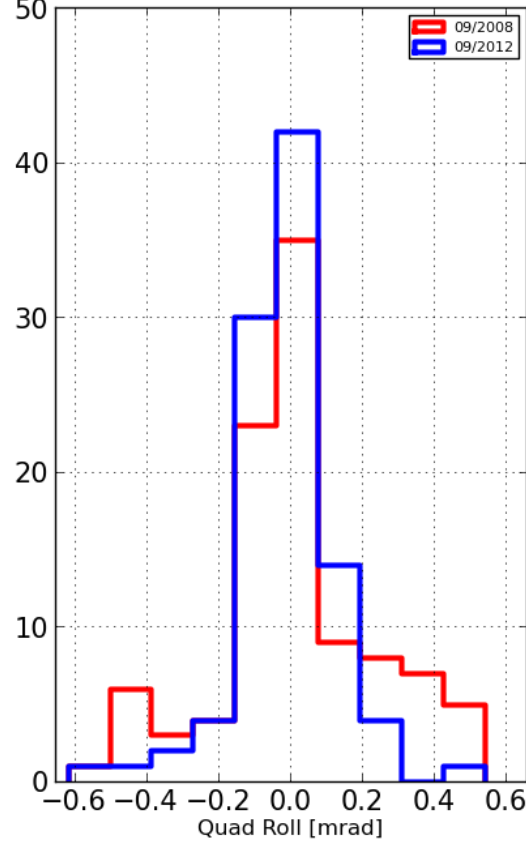


Starting Point: Survey and Alignment

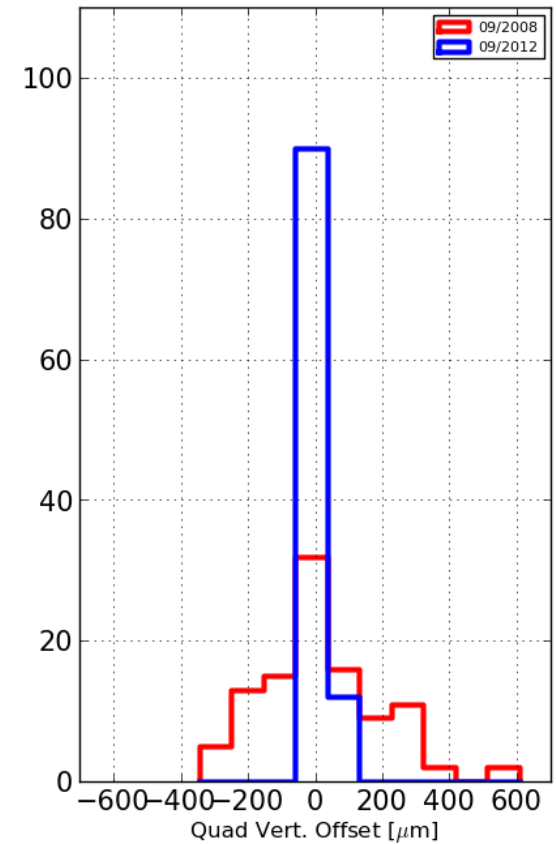
Bend Rolls [mrad]



Quad Rolls [mrad]



Quad Vert. Offset [μm]



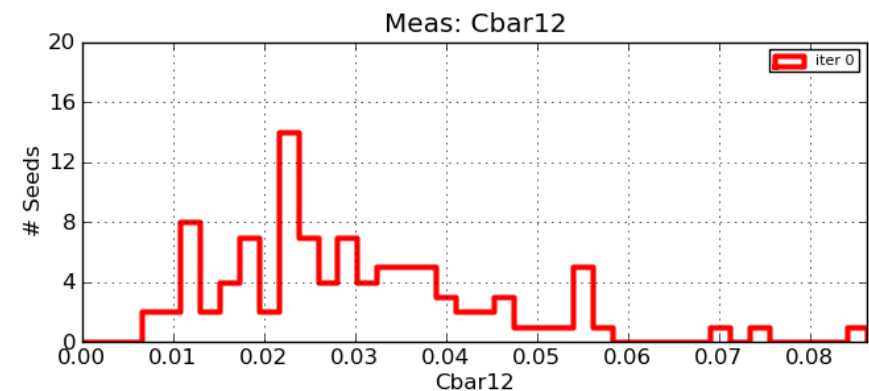
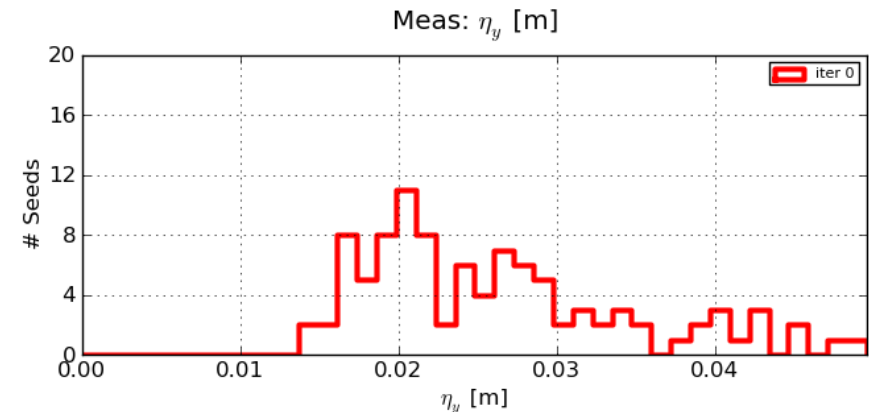
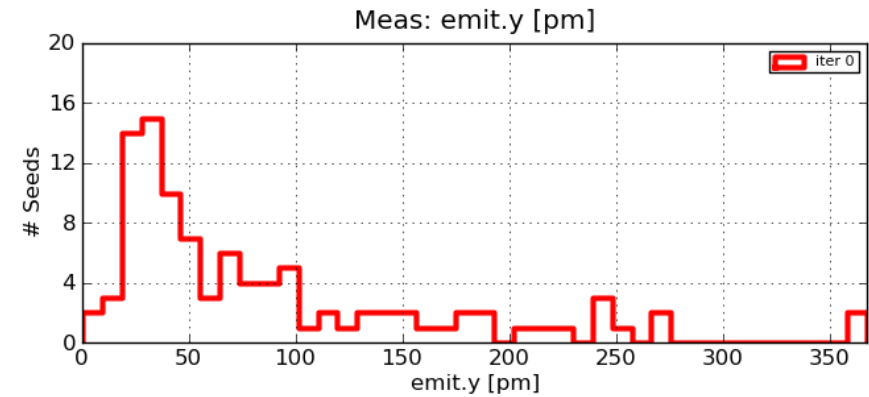
	Bend Rolls	Quad Rolls	Quad Vert. Offset
09/2008 RMS	206 μrad	227 μrad	193 μm
09/2012 RMS	177 μrad	148 μrad	25 μm



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

Mean $\epsilon_y = 100$ pm-rad
95%CL $\epsilon_y = 250$ pm-rad

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





- **Orbit Response Matrix (ORM)**
 - **Advantages:**
 - **Thorough** – measure change in machine conditions due to kicks throughout the ring
 - **Very successful** in reducing emittance at other storage rings
 - **Disadvantages:**
 - Data acquisition is slow
 - At CESR/TA, ~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!



- Most optics measurements at CESR utilize **resonant excitation** of 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

Precision BPMs are required in order to provide accurate data for corrections

1. Calibrate BPM button-to-button gain errors

- Fit BPM button gains using turn-by-turn trajectory data
- **Duration:** 30 seconds to acquire data; < 5 minutes to process and 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 settings on a quadrupole
- Fit 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 μ m**

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 **5mrad**



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

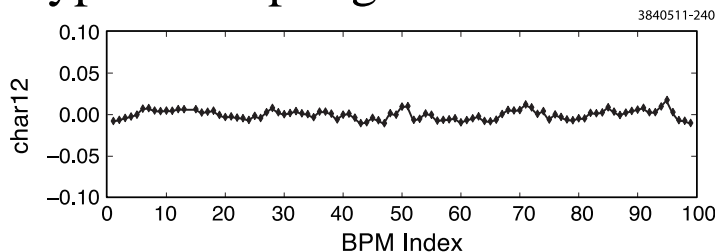
1. Measure closed orbit

- Correct with all horizontal and vertical steerings
- Typical correction levels: $\Delta x, \Delta y \sim 300\mu\text{m}$ (RMS)
- Takes about **30 seconds** to measure, analyze, load corrections, and re-measure orbit

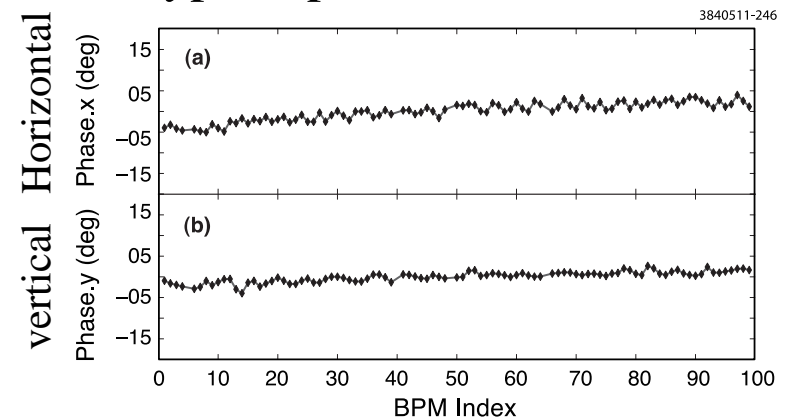
2. Measure betatron phase advance and transverse coupling

- 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) $< 2^\circ \rightarrow$ 3% beta beat
 - $C_{bar12} < 0.005 = 0.5\%$ x-y coupling
- One iteration takes about **one minute**

Typical coupling after correction:

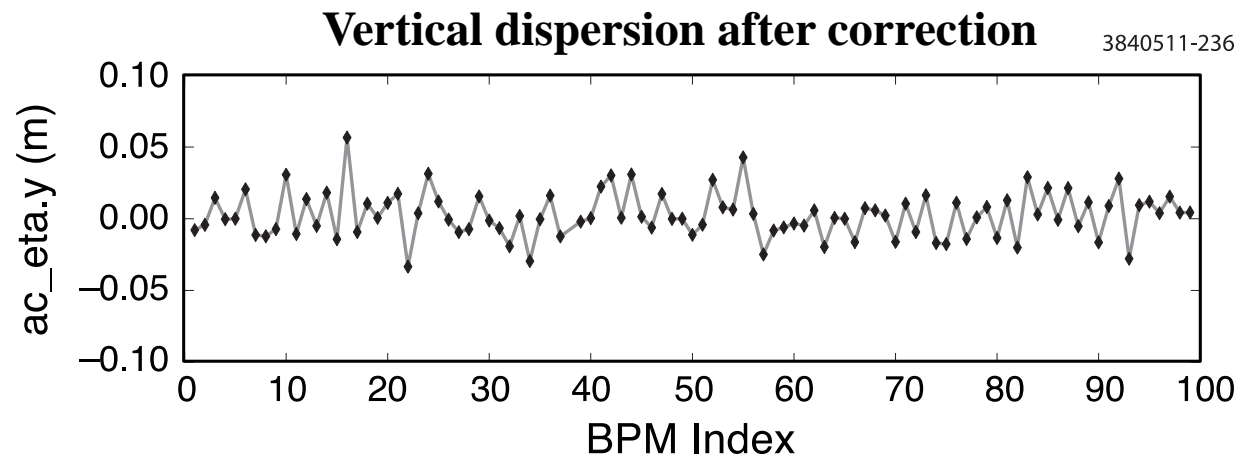


Typical phase after correction:



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 $\eta_y \sim 12\text{mm}$
 - Limited by BPM calibrations



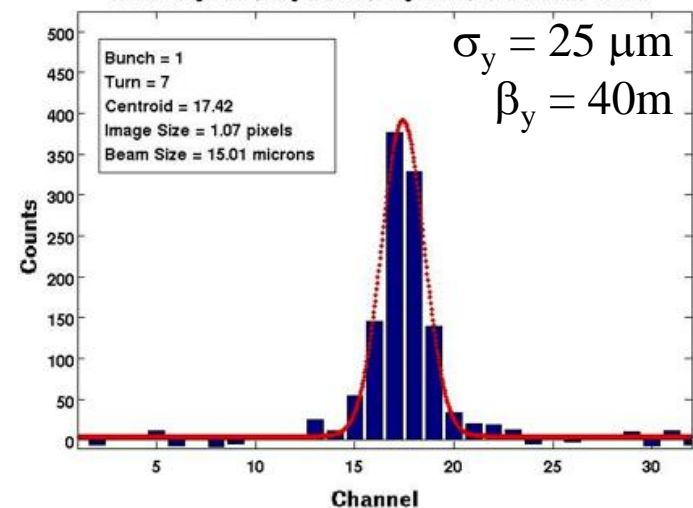
- Turnaround time: **~5 minutes** per correction iteration:
 1. Correct orbit
 2. Correct phase + coupling
 3. Correct orbit + coupling + dispersion

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 $\geq 4\text{ns}$ -spaced bunches
- **Under development:**
 - PMT with turn-by-turn response, using π -polarization measurement

Vertical beam size after correction using xBSM pinhole optic

xBSM Image Data, Single Bunch, Single Turn, 0.5 mA Bunch Current

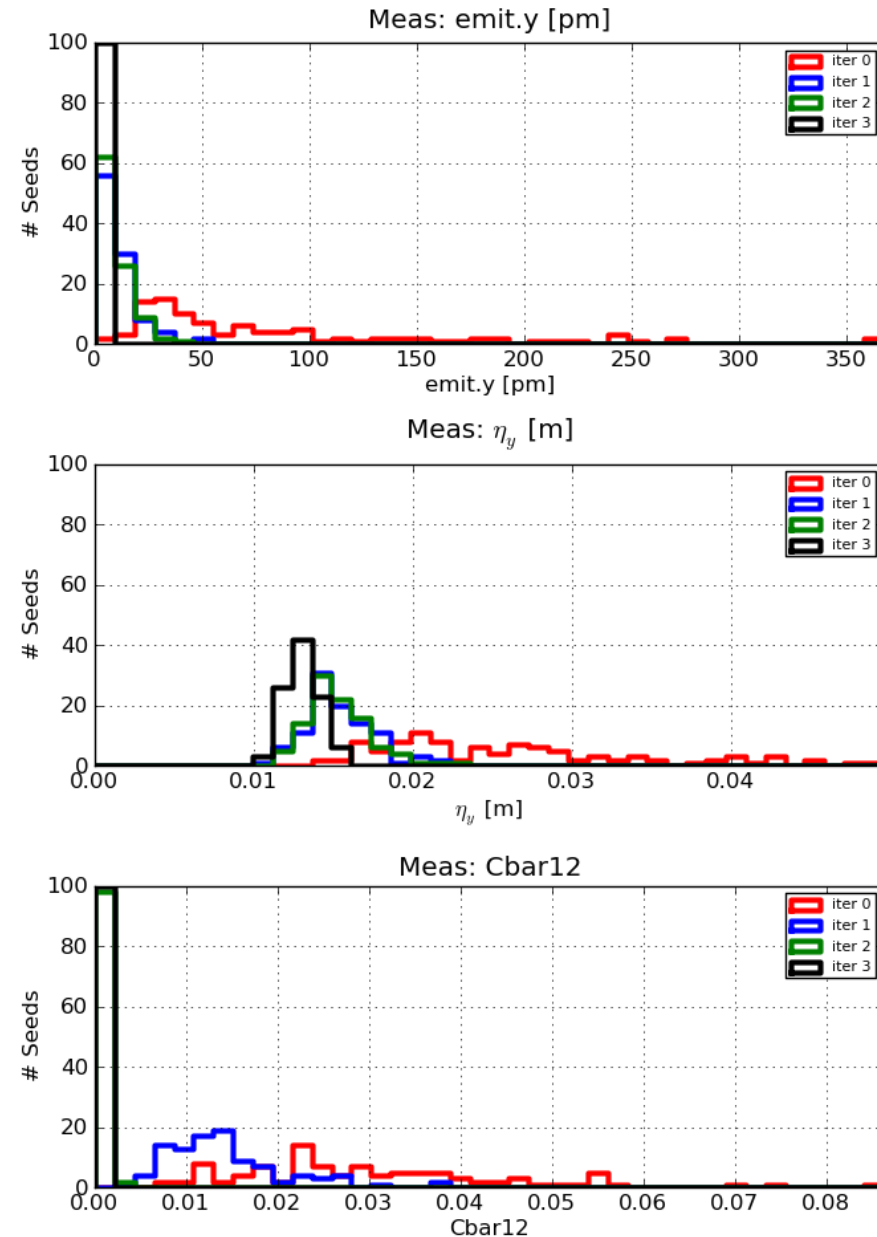


After corrections, typically measure $\varepsilon_y \sim 10\text{-}15\text{pm}$ with xBSM

At $0.5\text{mA} = 0.8 \times 10^{10}$ positrons



- Includes BPM errors and realistic TBT data processing with resonant excitation
- RMS vertical dispersion and Cbar12 in simulation are consistent with measurements from CESR
 - We conclude that the coupling and dispersion corrections are working as expected
- If optics errors are the primary contribution to vertical emittance, then $\epsilon_y \sim 1.5/2.6\text{pm}$ (mean/95%CL for 100 error distributions)





- Simulations suggest there are other contributions to ε_y , which dominate over contributions from coupling and dispersion
- From beam-based observations, high level of self-excitation
- Potential sources of emittance dilution are under investigation
 - Magnet power supply stability
 - RF power supply stability
 - Long-lived electron cloud trapping in wigglers, quadrupoles, ...
 - Reflections from feedback striplines, electrostatic separators
- **Developing Monte Carlo bunch tracking simulations**
 - Determine the effects of power supply stability or other modulating effects (ground motion, line voltage, ...)



- CESR TA vertical emittance target: $\varepsilon_y \leq 10\text{pm}$
 - Achieved $\varepsilon_y \sim 10\text{-}15\text{pm}$
- Demonstrated efficacy of optics corrections using resonant excitation data
 - Measured coupling, dispersion are consistent with simulations
 - Sources of emittance dilution are under investigation
- Further improvements to LET setup under development:
 - Vertical beam size using π -polarization with PMT array
 - Simultaneous triggering for xBSM, PMT array, and BPMs



Backup Slides



- Correctors available during optimization:
 - 55 horizontal steerings
 - Windings on dipole magnets
 - 58 vertical steerings
 - Windings on sextupole magnets in high- β_y regions
 - 100 normal quadrupoles
 - Independently powered
 - 27 skew quadrupoles
 - 15 dedicated skew quadrupoles
 - 12 skew quadrupole trims on sextupoles near arc wigglers
 - Allows for dispersion correction through arc wigglers
 - Conversely, also able to intentionally generate vertical emittance

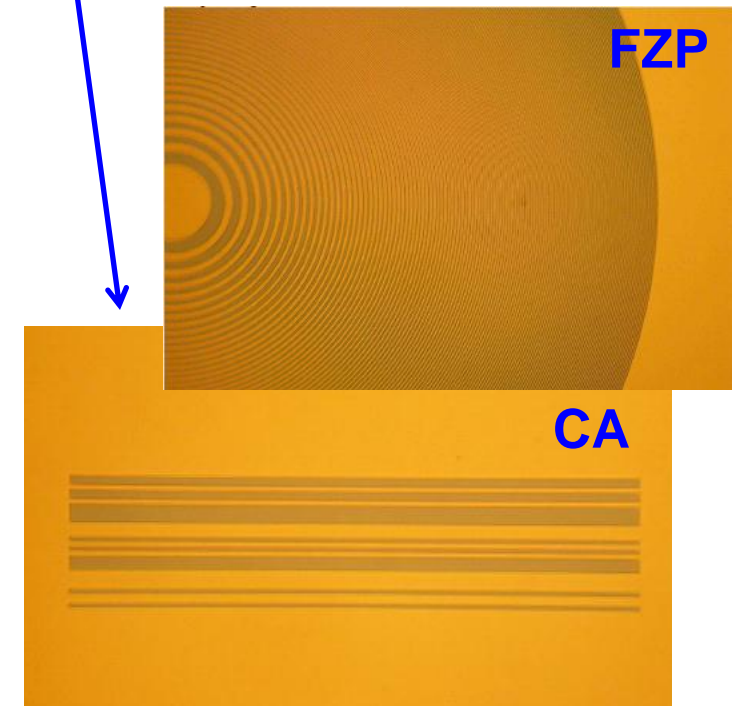
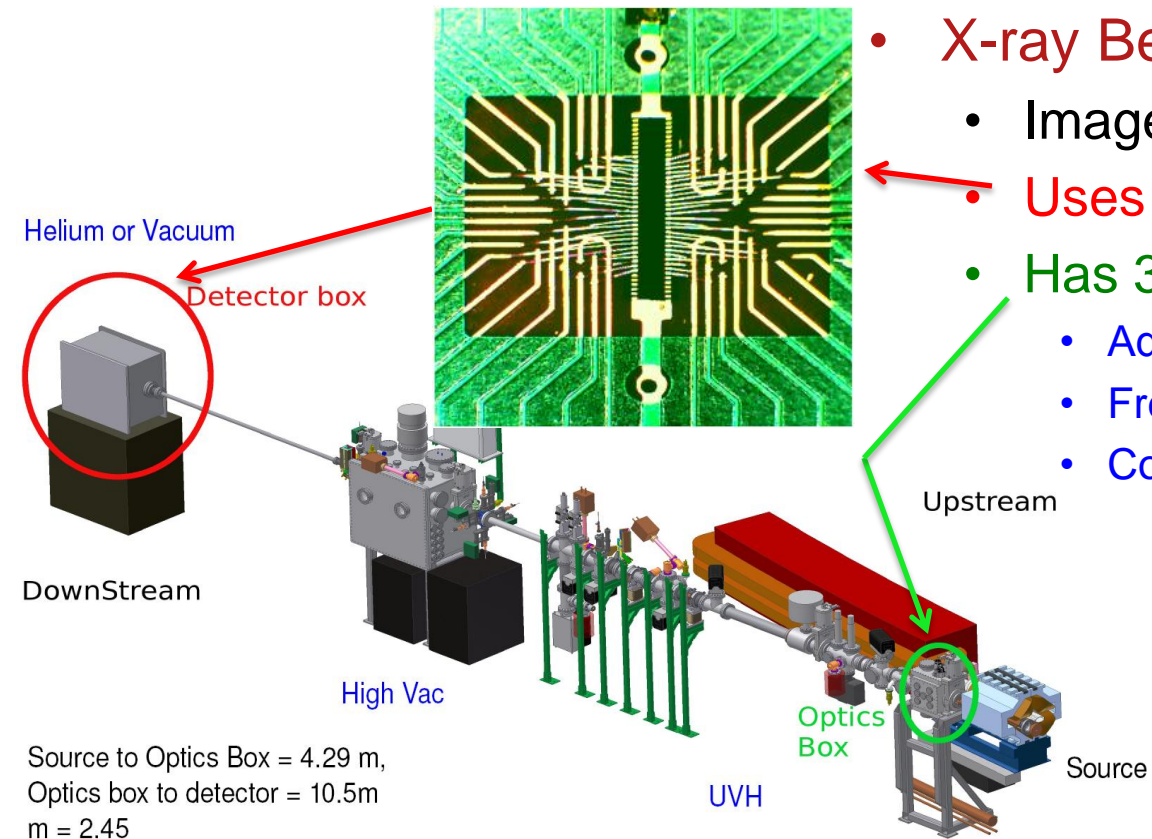


0. Time in individual BPM buttons

- Timings may drift by ~10's of ps during a shift
- Re-time before every correction iteration
 - minimal timing step is **10ps**
 - $\Delta\text{Signal} |_{\text{peak}}(t_0 \pm 10\text{ps}) \sim 5 \times 10^{-4} = 0.05\%$
- One time-in iteration takes about **one minute**

X-ray Beam Size Monitor

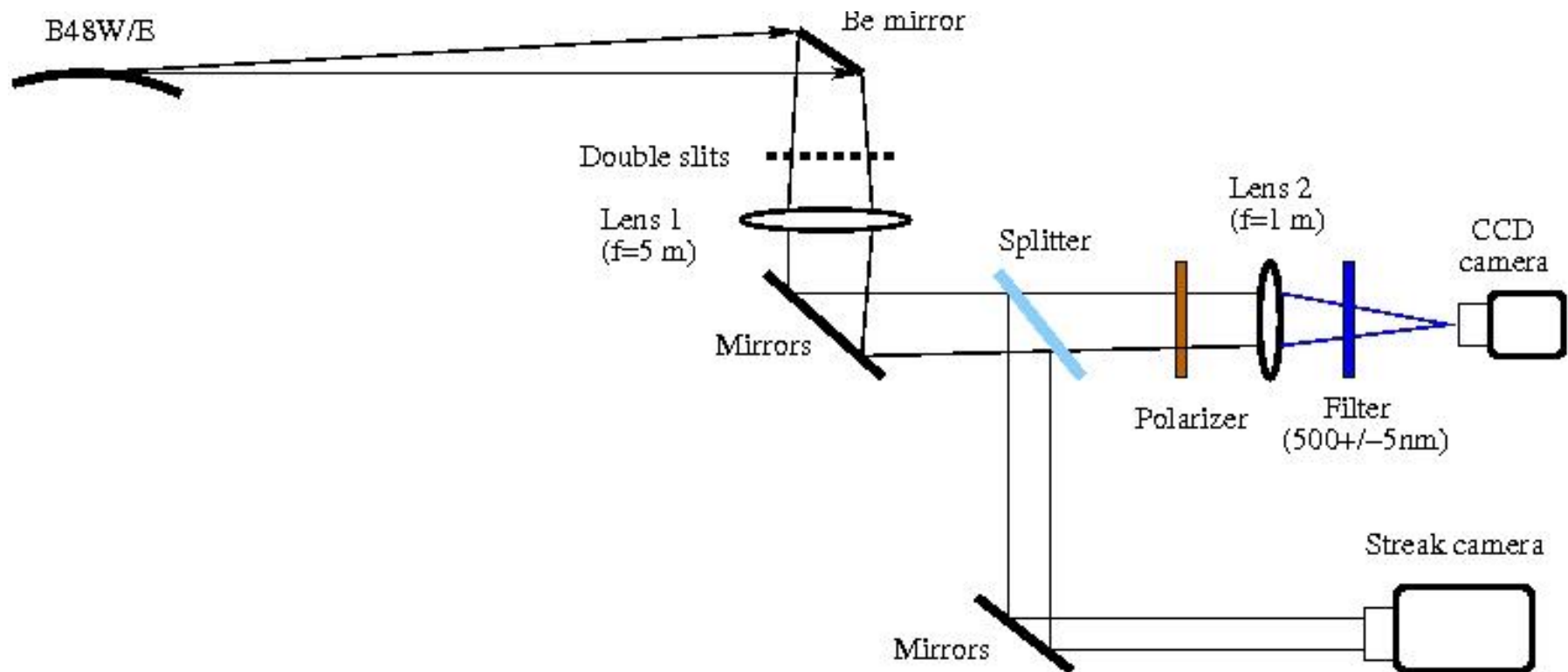
- X-ray Beam Size Monitor (xBSM)
 - Images X-rays from bending magnet
 - Uses 1D 32-chan vertical diode array
 - Has 3 choices for Optics Element
 - Adjustable Slit (“Pinhole” optics)
 - Fresnel Zone Plate (FZP)
 - Coded Aperture (CA)

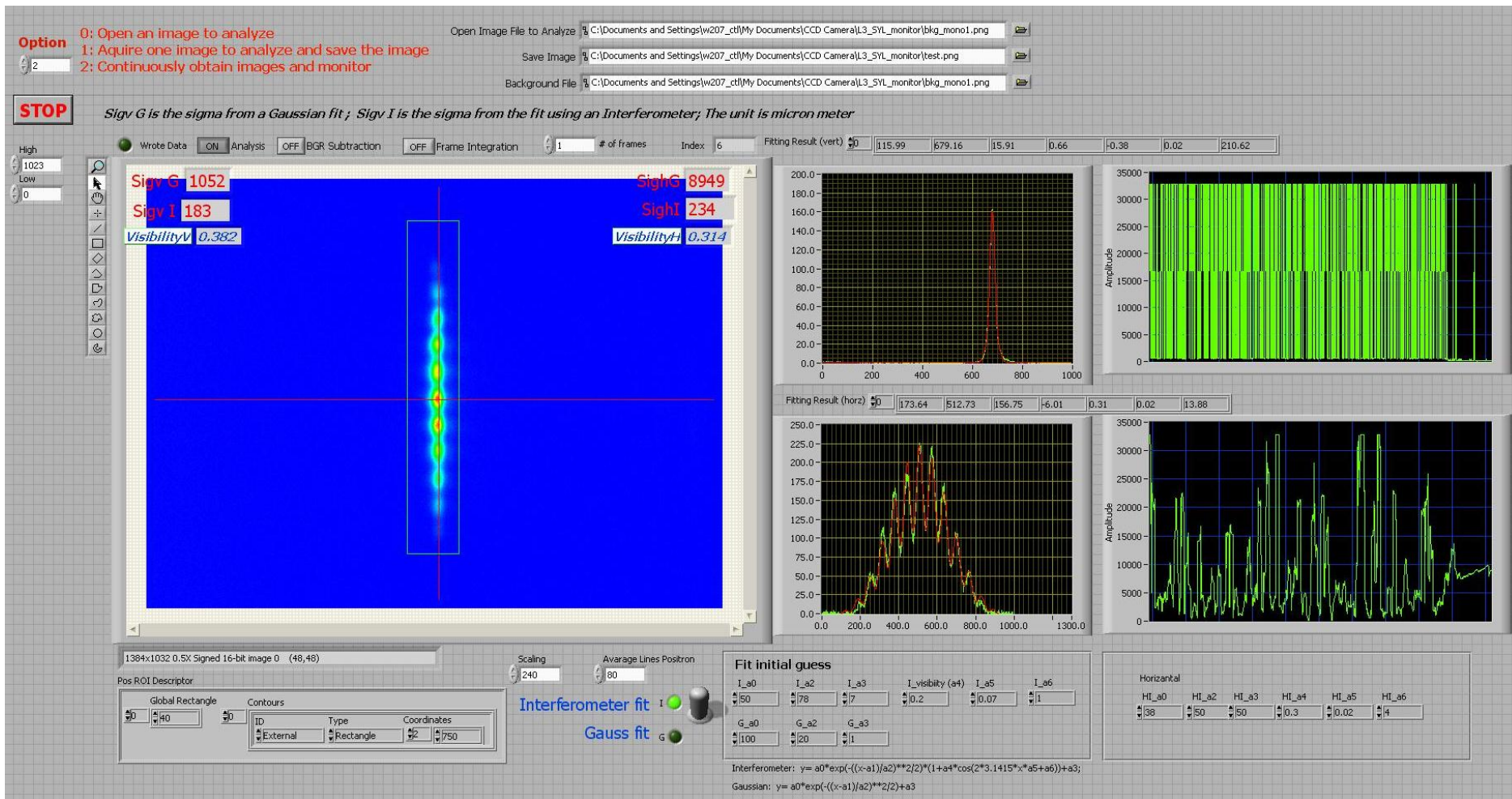


• Functions

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

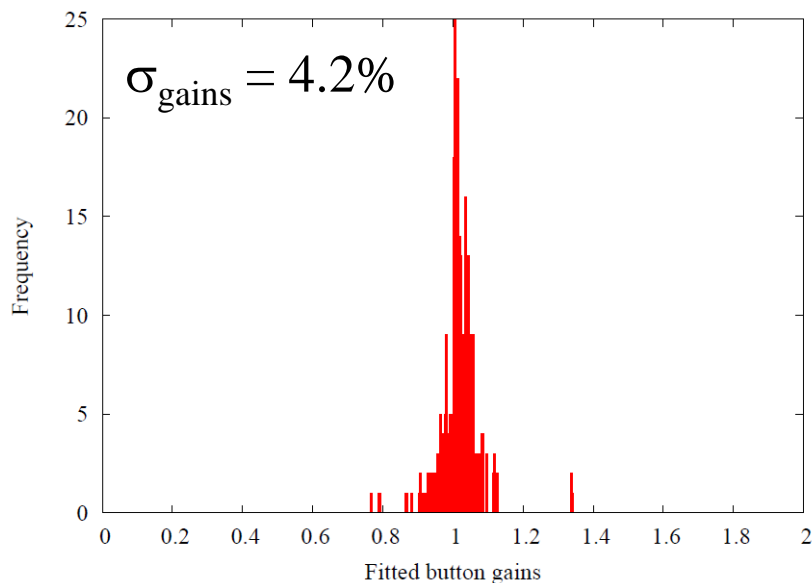
L3 setup includes beam splitter to allow simultaneous horizontal and longitudinal beam size measurements



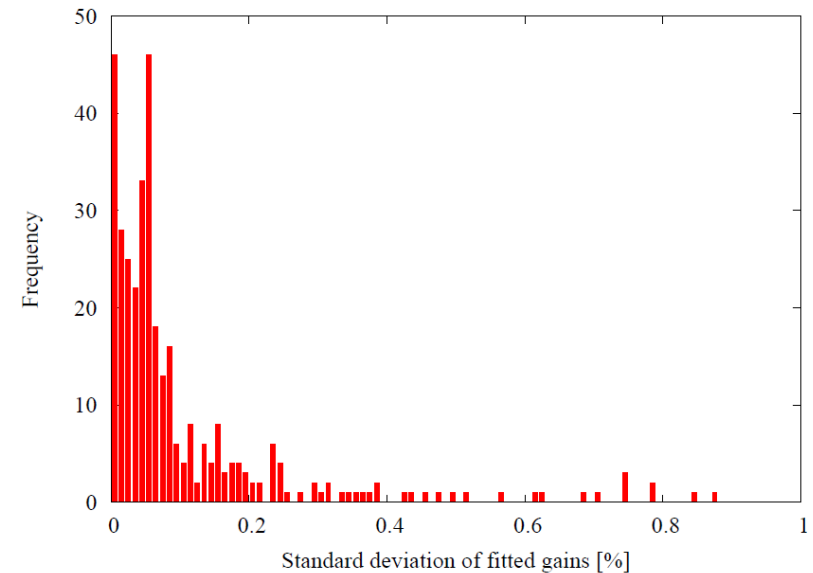


Horizontal beam size measured with visual-spectrum interferometer ($\lambda = 500\text{nm}$)

- 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**

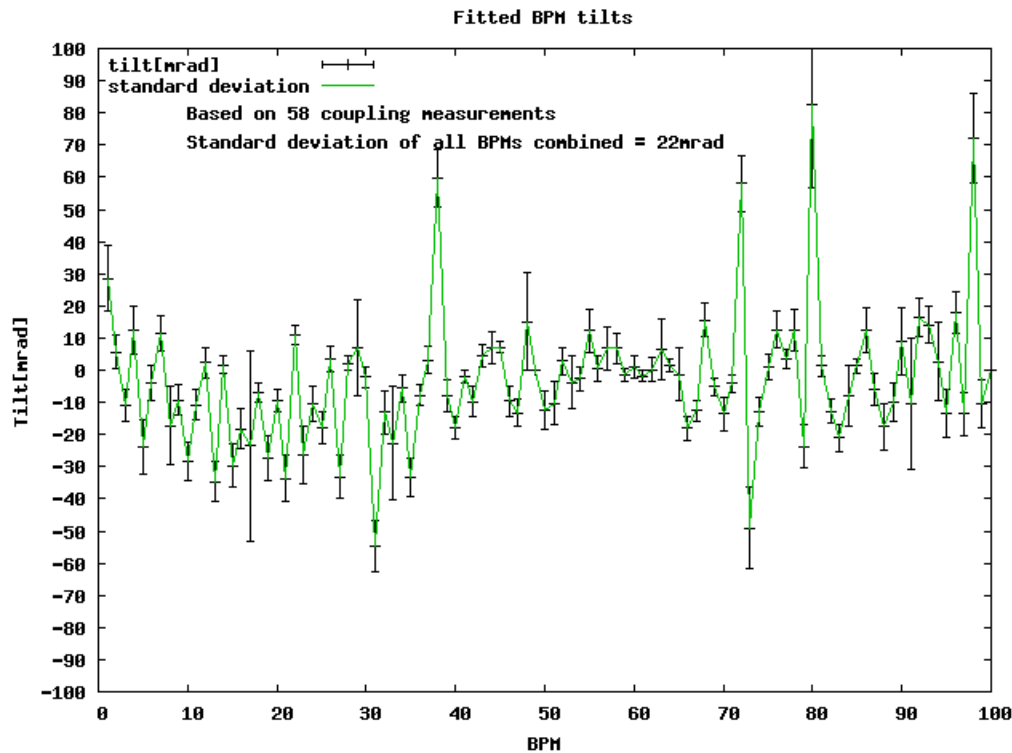


Standard deviations from the mean of **seven consecutive data sets**

- 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 $d\mathbf{y}'$ at the quadrupole
 - Fit the difference of **betatron phase measurements** with a kick $d\mathbf{k}$ at the quadrupole
 3. Quadrupole offset is then
$$y_{\text{offset}} = (1/L_{\text{quad}}) (dy'/dk) + y_0 \quad (y_0 = \text{nominal closed orbit})$$
- Iterate until convergence
 - Quadrupole / BPM centers then known to **< 300 microns**
- Takes about **2 hours** to center all 100 quadrupoles

- **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

- 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

