Low Emittance Instrumentation in CESRTA

October 5, 2011

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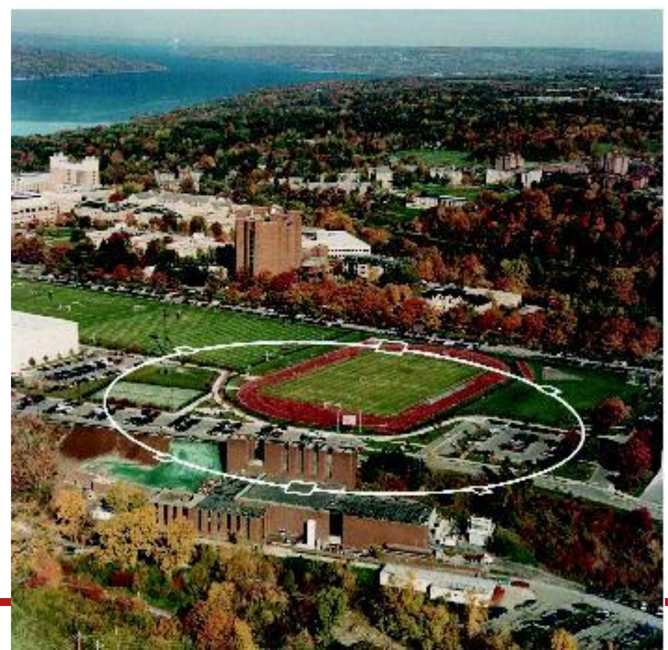
for CESRTA Collaboration



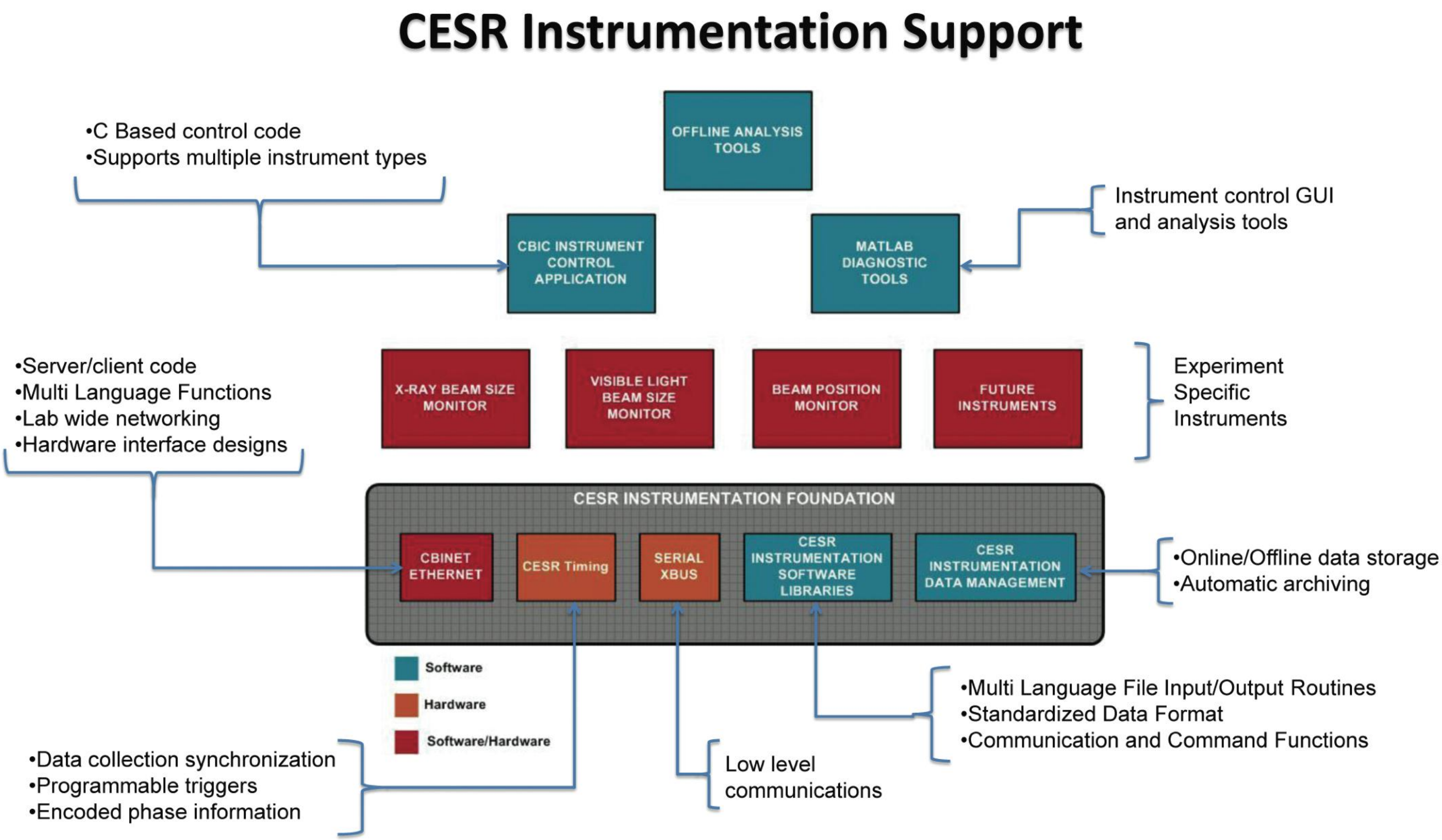
Overview

- General Requirements
- General Interface for Advanced Instruments
- BPM System
- Digital Tune Tracker
- xBSM -Xray (Vertical) Beam Size Monitor
- vBSM -Visible (Horizontal) Beam Size Monitor
- Planning: ODR test with CERN

General Requirements

- 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
  - 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

• General system for FPGA-based instruments



CPBM System Specs

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

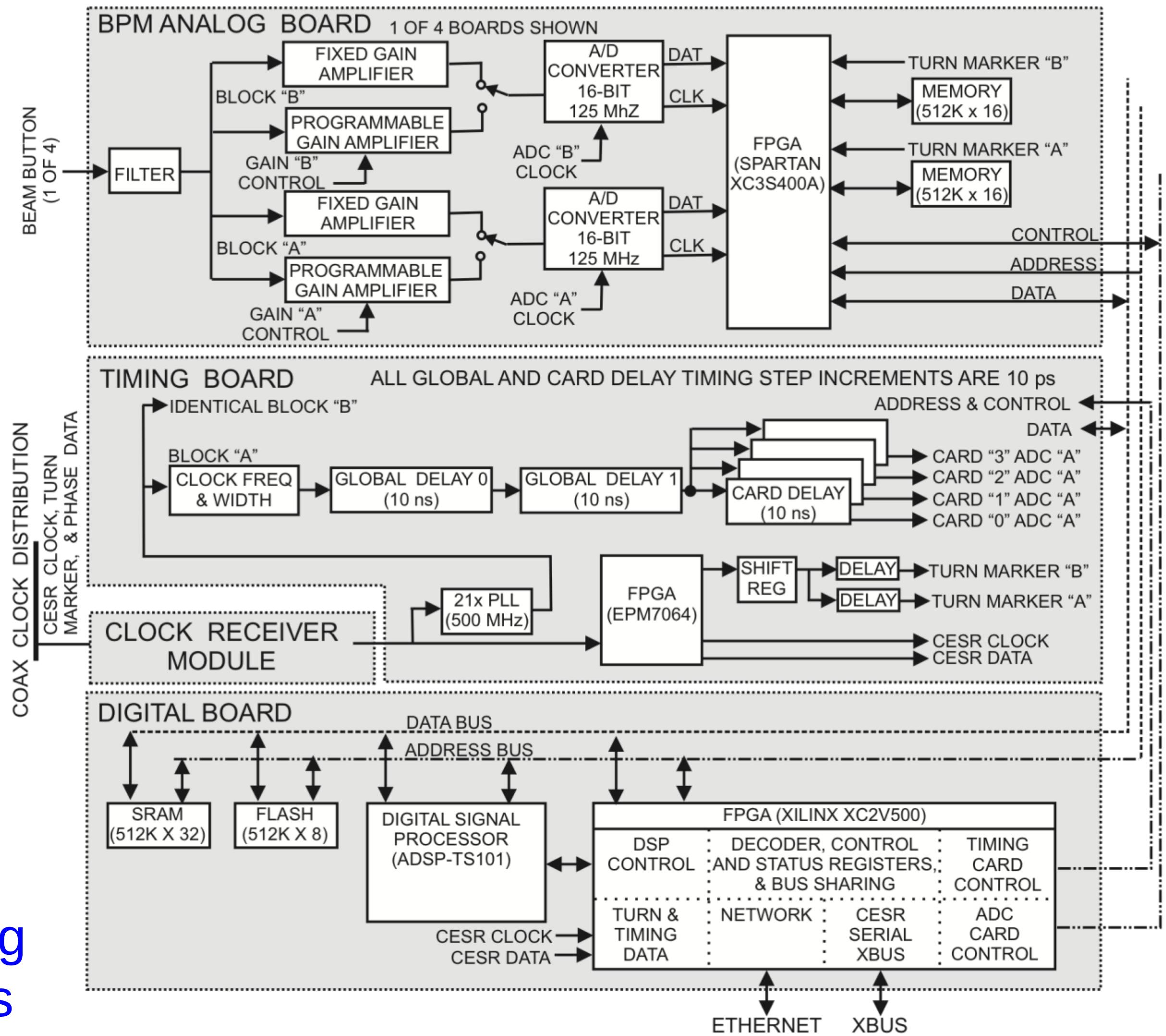
4 channels of 2 independently-timed digitizers (1 for each button)

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

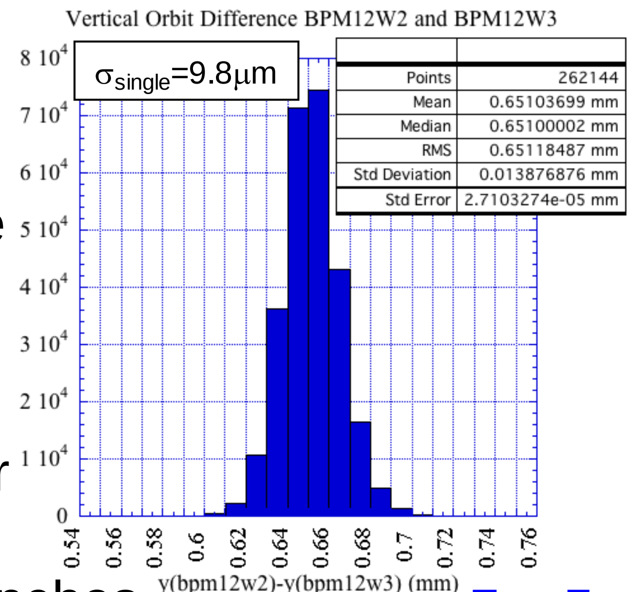
CBPM Module

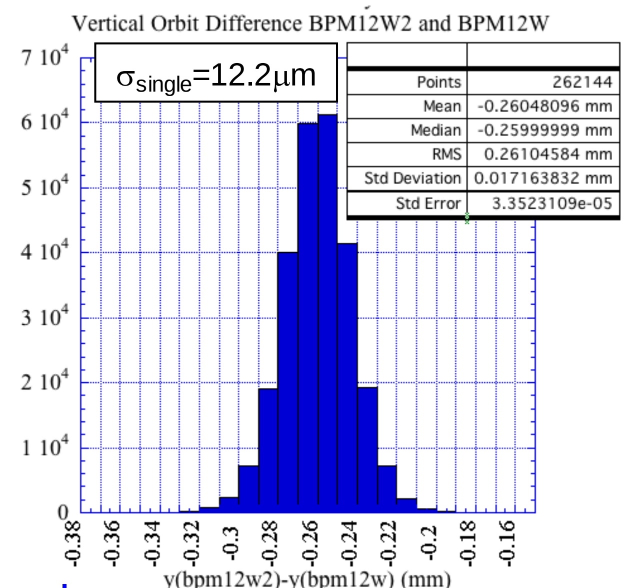
- Module Layout (BPM system uses ~110 modules)
  - 4 Analog boards, each containing
    - 2 16b-digitizers at 125 MHz
    - ≥ 40 dB variable gain + precision fixed gain amp’s
    - Independently timed for peak detection
  - Timing board
    - Clocking, delay & triggering
  - Digital board
    - FPGA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



CPBM Module Characterization

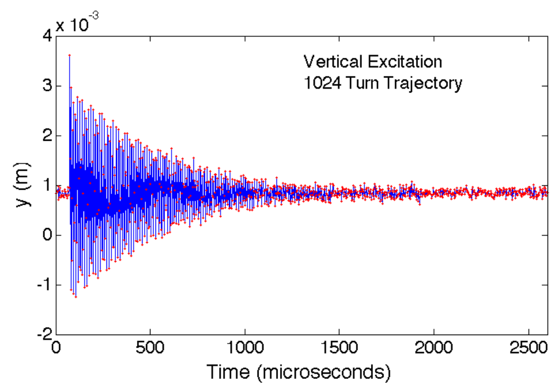
- Triplet BPM Position Measurement
  - Resolution: ~10 μm
    - dominated by timing drift
    - auto-timing feature being completed



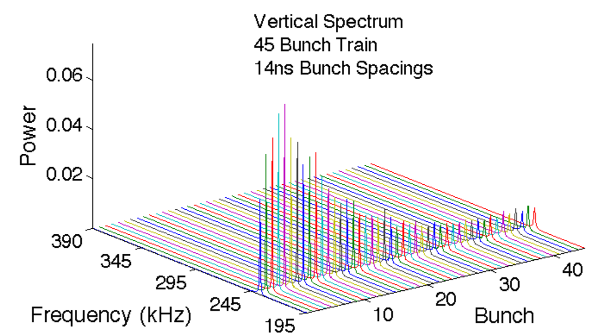


Two Examples

- Multi-bunch TBT
  - Synchronous trigger for all modules for any sequence of bunches
  - ADC memory depth
    - 250k bunch-turns
- Timing Diagnostics
  - Displacing sampling trigger to zero-crossing of signal -> timing variation check



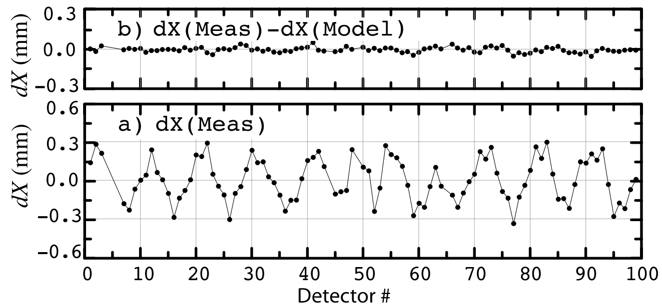
Single bunch TBT trajectory



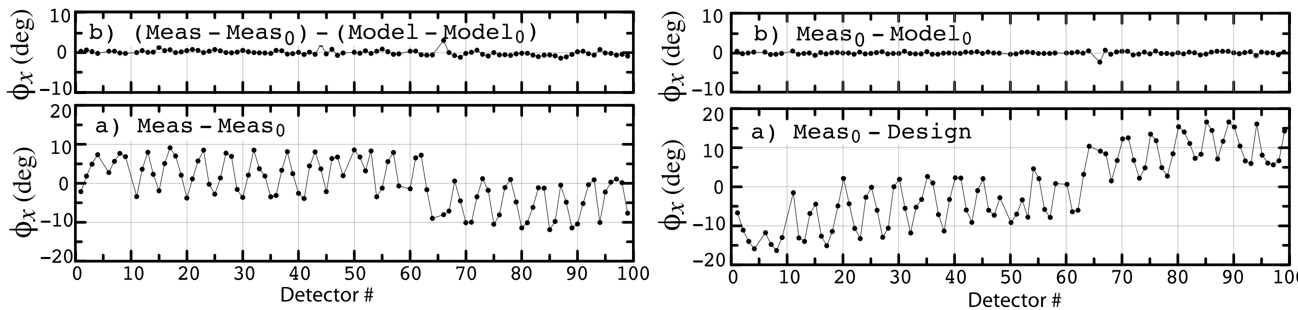
FFT of 45-bunch train trajectories

CBPM Measurements

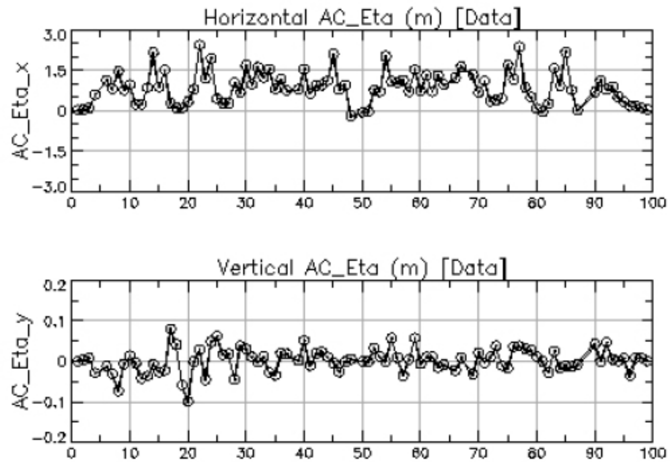
- Orbit
- Betatron ϕ & Coupling
  – See explanation below
- Dispersion
  – Conventional & AC



Fitted orbit error for single corrector change



Fitted phase error for single quad changes



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

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**:

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(in-phase)

(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:

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= x/y components, via standard BPM "Δ/Σ"

= 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 coupled motion
  - Able to “diagonalize” motion
  - 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 = C matrix in 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:

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(phase advance)

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from **horiz.** mode

from **vert.** mode

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from **horiz.** mode

from **vert.** mode

Cbar12 is "**out-of-phase**" component of coupling matrix

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

Cbar 22 and **Cbar11** are "**in-phase**" components

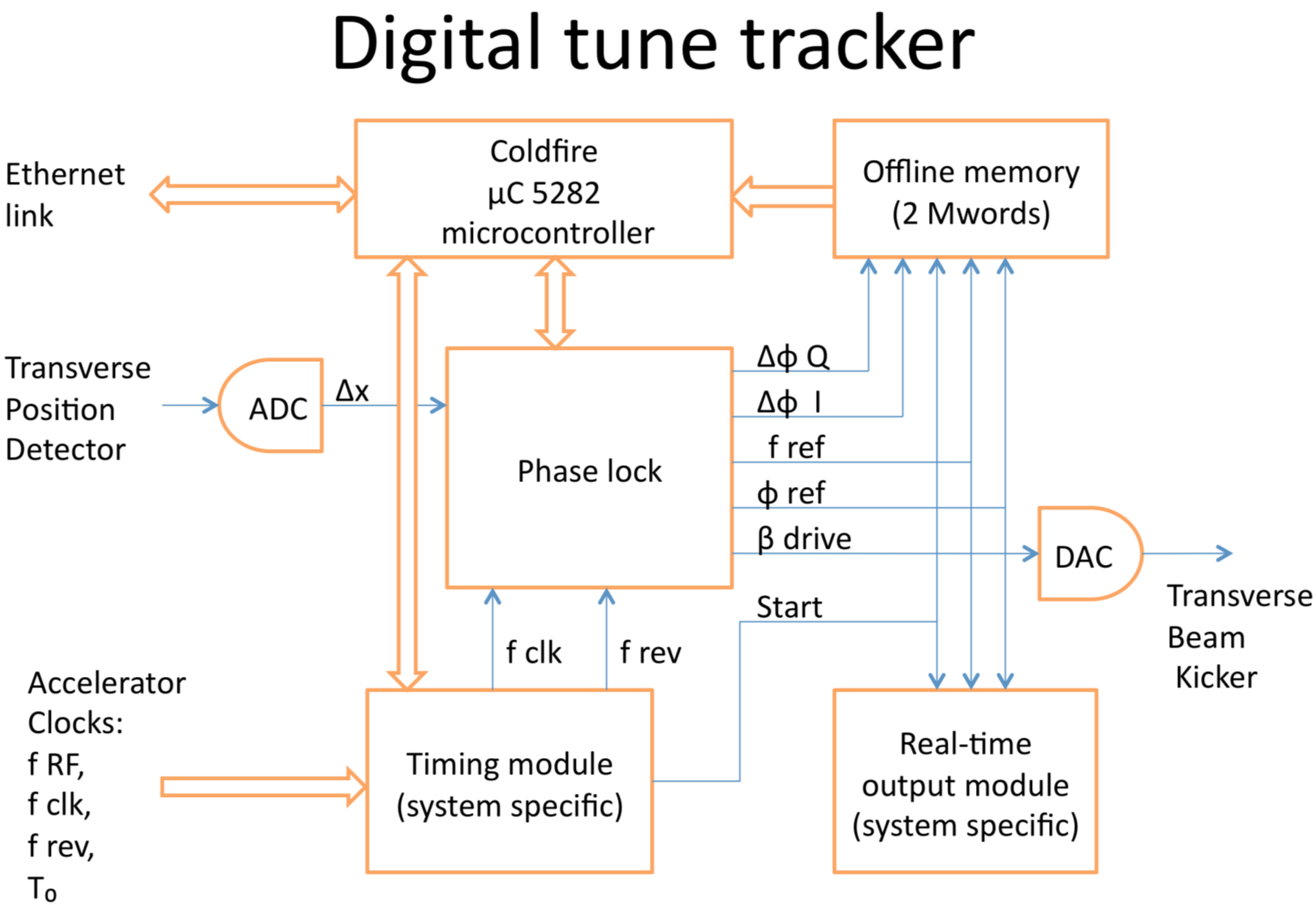
- Sensitive to rotation of x-y coordinates - Dependent on BPM tilts

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

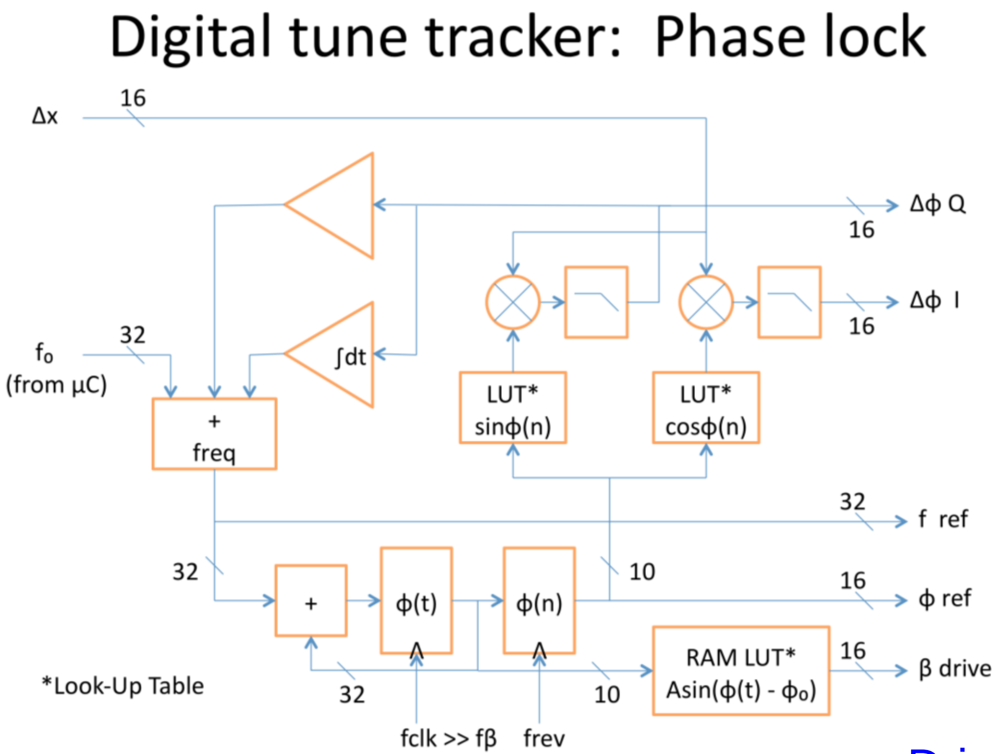
Purpose – Phase stable reference

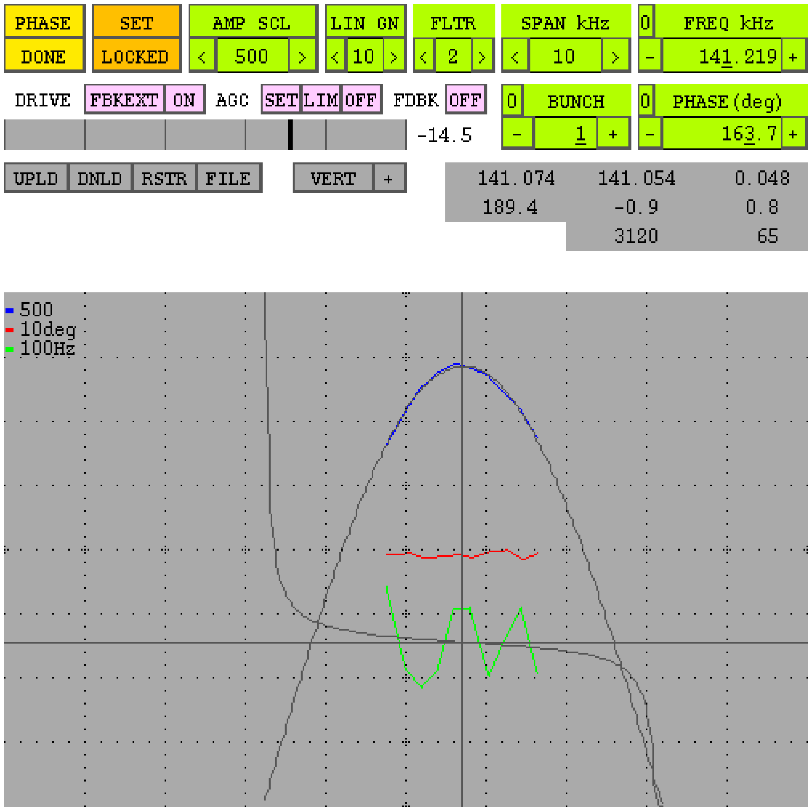
- Locks to betatron and synchrotron tunes by resonantly exciting beam via either
  - Narrowband shaker magnet
  - Stripline kicker
- Provides phase information to BPM modules, which in turn yield
  - Phase advance information around ring → beta functions
  - Betatron coupling information
  - Dispersion information
- Can lock on any one bunch in the ring
- Critical element for betatron phase accuracy if any betatron tune drift during measurement

• Functional block diagram



- # Phase locking section





Drive phase sweep showing fit to Lorentzian resonance model.

Blue: Betatron amplitude
Red: Betatron phase error
Green: Direct Digital Synthesizer freq. offset
Black: Fit functions and new operating point

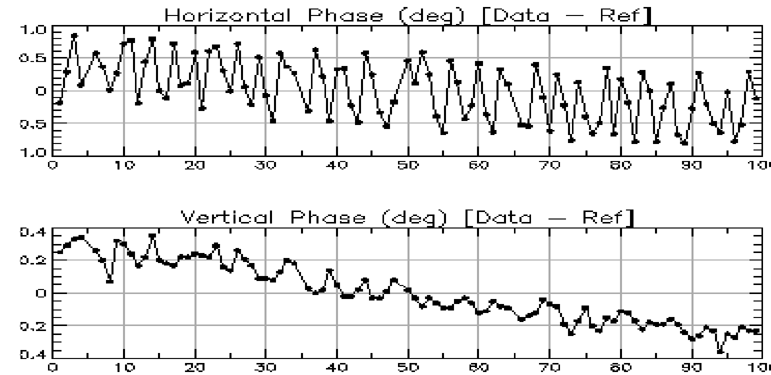
CBPM & Digital Tune Tracker

- 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

ϕ_H

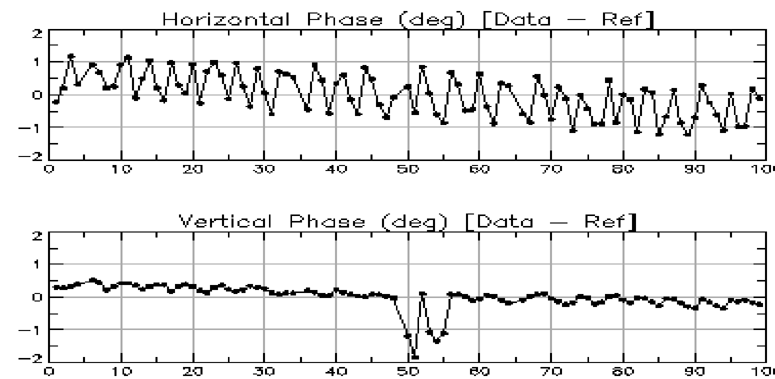
ϕ_V



Bunch 15 phase, showing a spurious electron cloud signal

ϕ_H

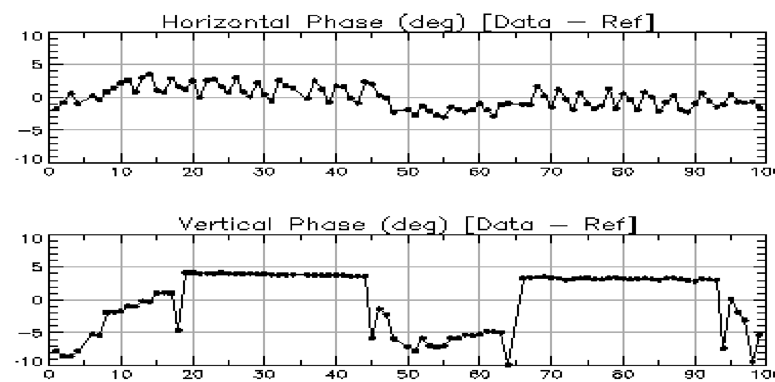
ϕ_V



Bunch 25 phase, showing expanding electron cloud.

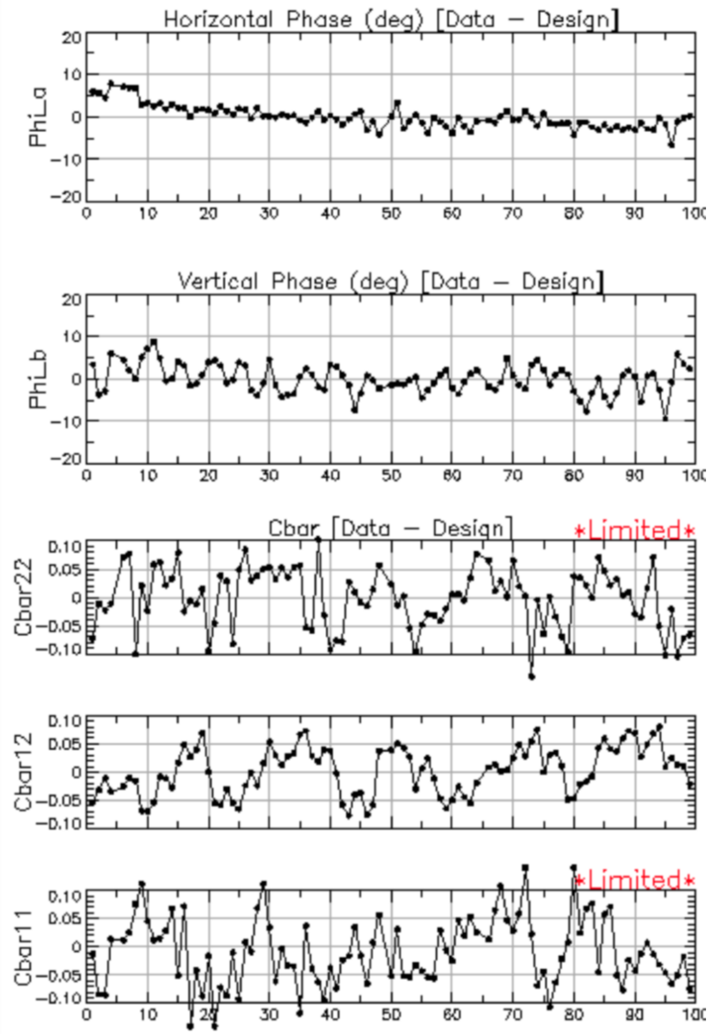
ϕ_H

ϕ_V



Using CBPM & Digital Tune Tracker Results

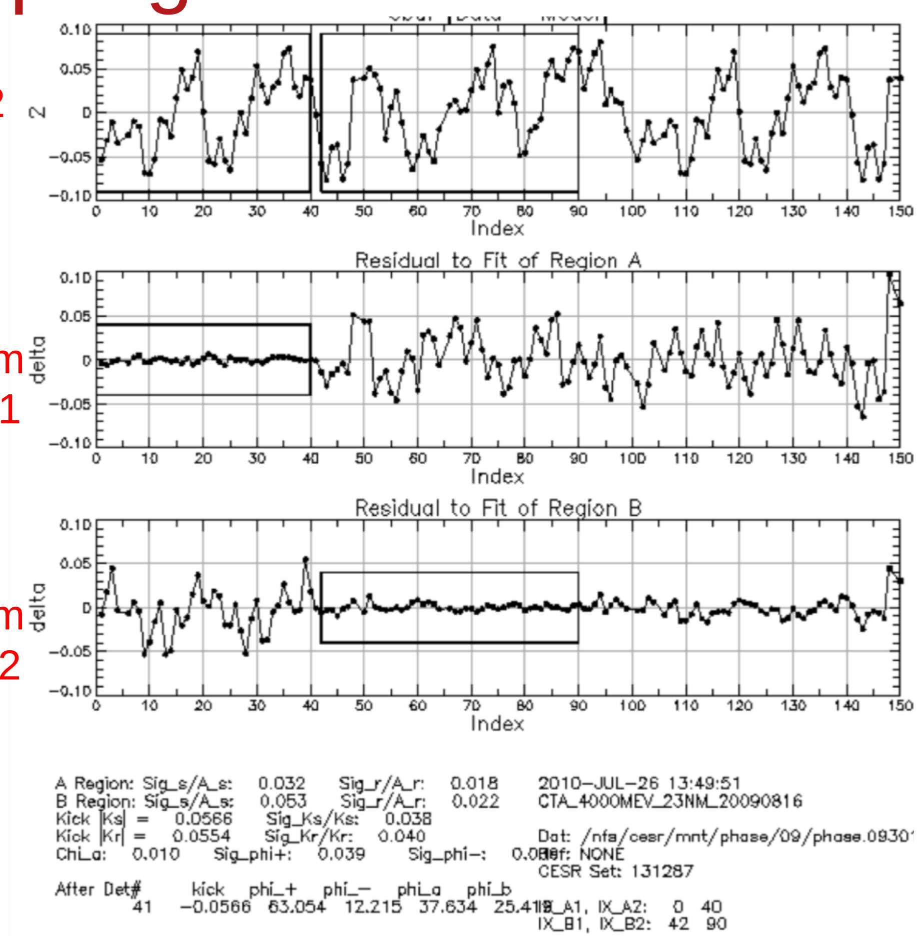
- Example: Finding a coupling error



Cbar 12

Cbar 12
- Fit from Region1

Cbar 12
- Fit from Region2



Select 2 regions: Fit freely propagating

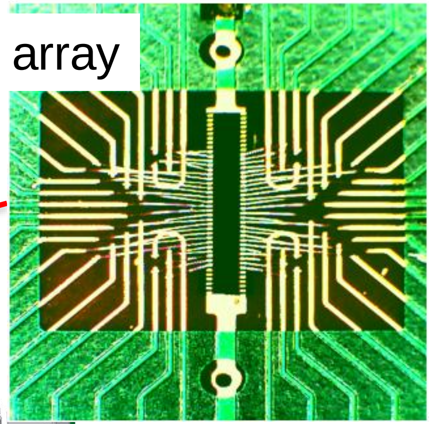
Gives phase location of single error.

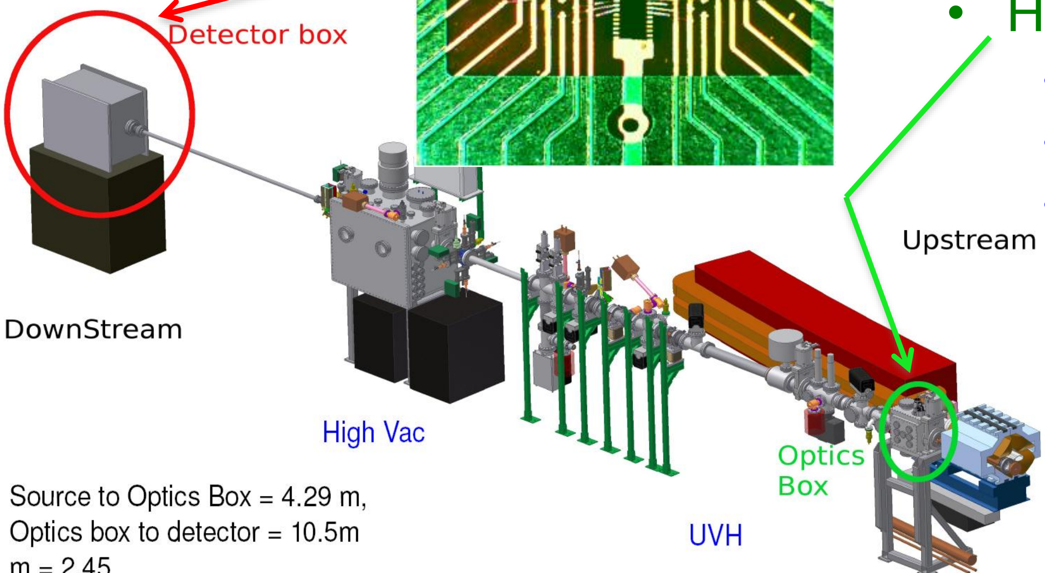
Phase & Coupling Measurements (Bottom 2 plots show measurement-fits)

X-ray Beam Size Monitor

xBSM diode array

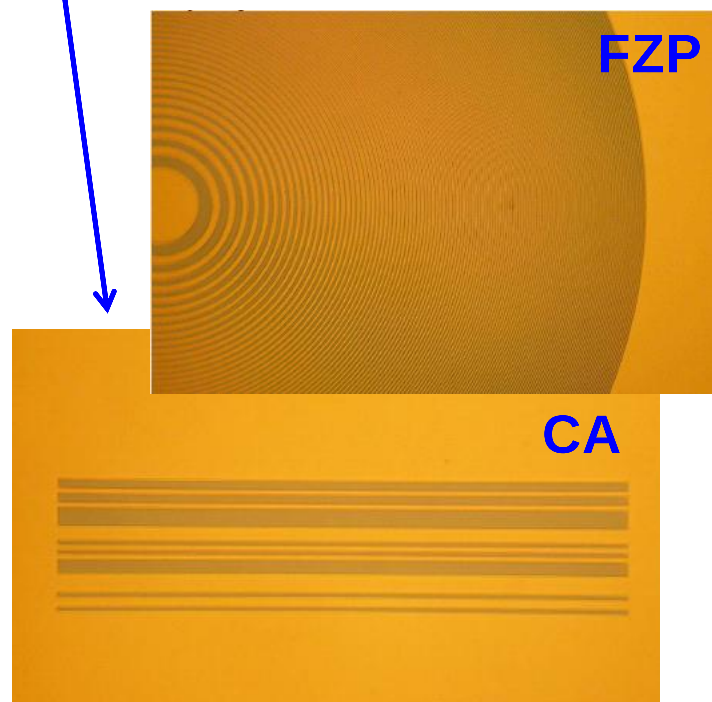
50 μm pitch





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

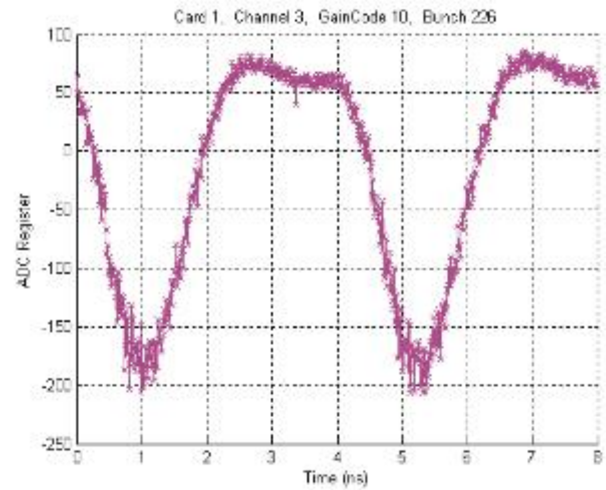
- X-ray Beam Size Monitor (xBSM)
  - Images X-rays from bending magnet
  - Uses 1D 32-chan vertical diode array
  - Has 3 choices for Optics Element
    - Adjustable Slit ("Pinhole" optics)
    - Fresnel Zone Plate (FZP)
    - Coded Aperture (CA)



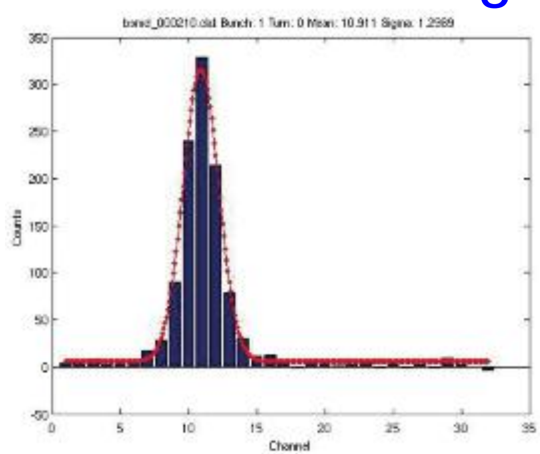
- Functions
  - Capable of measuring TBT bunch size for ≥ 4ns-spaced bunches
  - 40 dB gain adjustment
  - Primary tool for checking vertical emittance corrections

xBSM Measurements

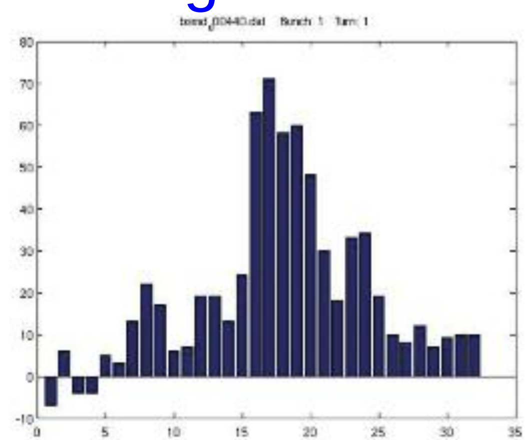
- Observe signal with single bunches with different x-ray optics
  – Slit (Gap)
  – Coded Aperture
  – Fresnel ZP



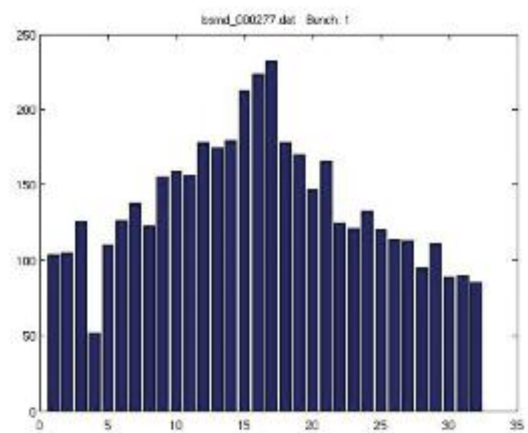
Single Pass-Single Bunch Distributions



Vertically Limiting Slit (Pinhole)



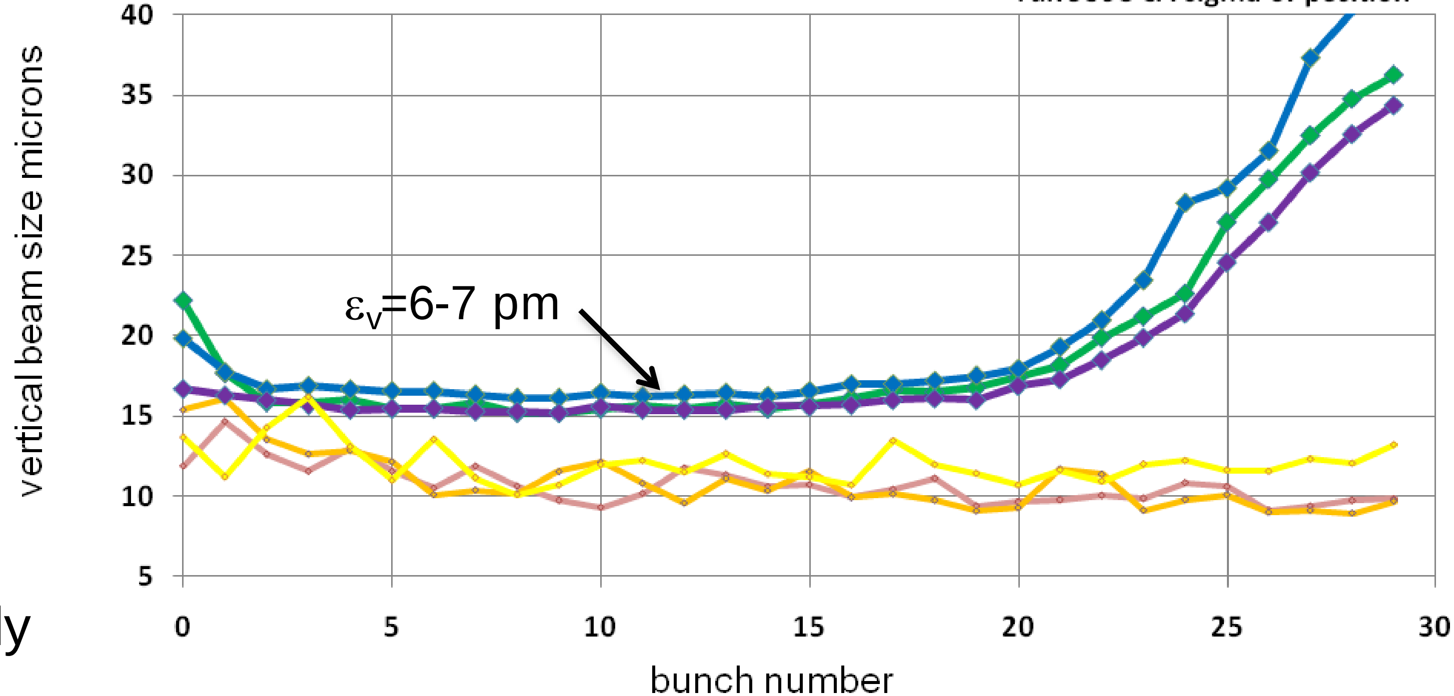
Coded Aperture



Fresnel Zone Plate

xBSM Measurements

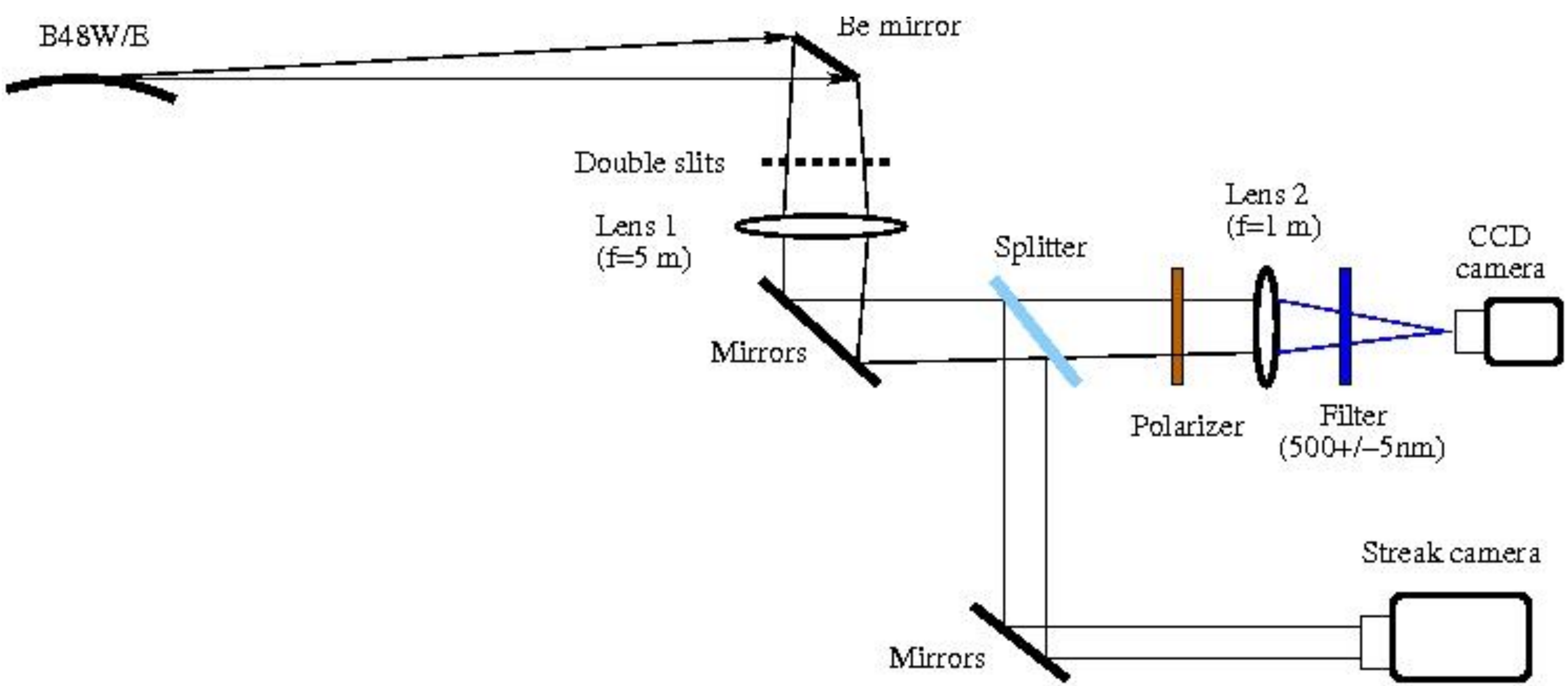
- Systematic studies of multi-bunch performance with different x-ray optics (30 bunch train)
  - Slit (Gap) size & position
  - Fresnel ZP size & position
  - Coded Aperture size & position



Data for each optic taken simultaneously

Horizontal Visible Beam Size Monitor

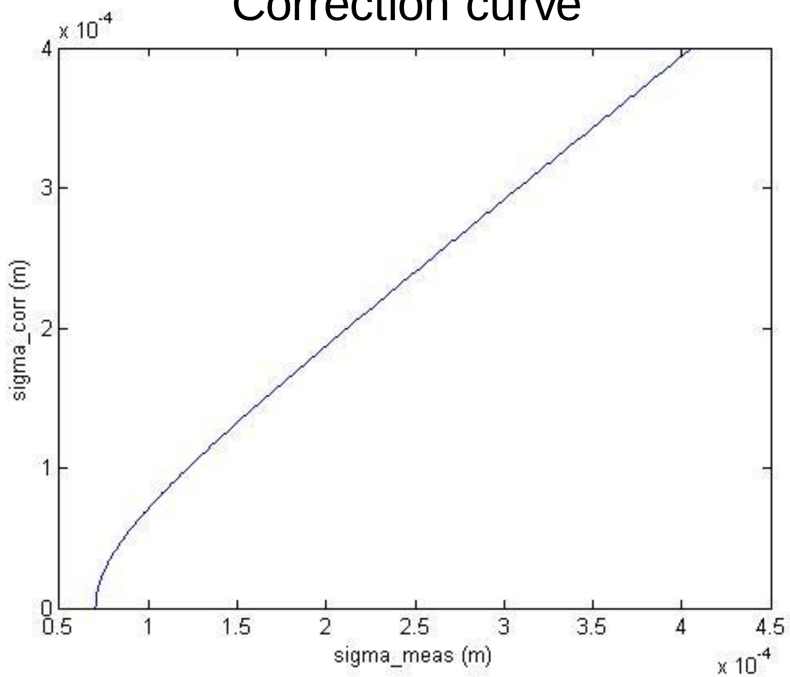
- Interferometer
  - Being tested
  - Uses light from final soft bends on either side of L3 straight section for both positron and electron bunches



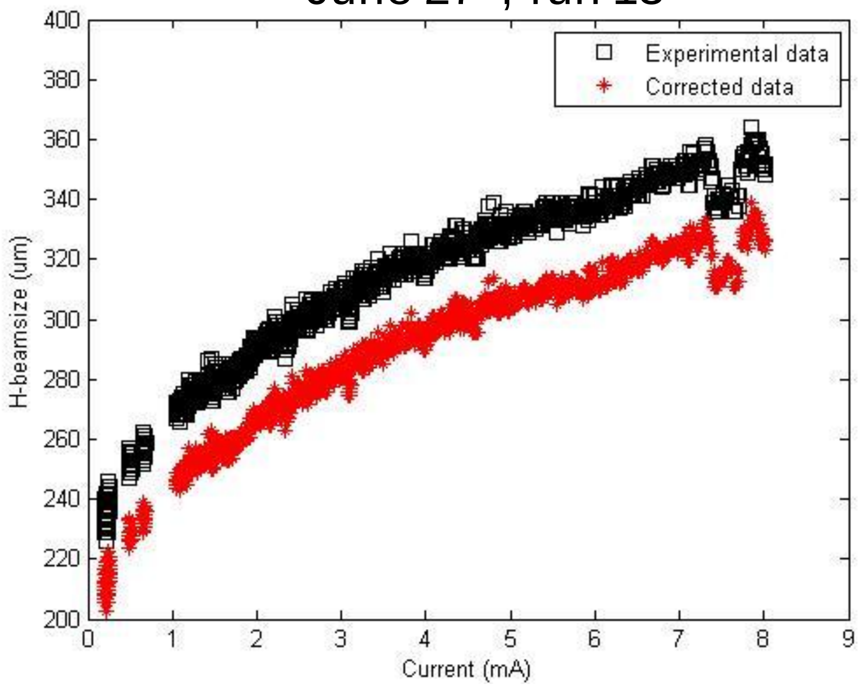
Horizontal Visible Beam Size Monitor

- Studying effect of errors
  1. Effect of curvature of the trajectory in the bending magnet
  2. Imbalance between the intensities of the two modes of light
  3. Beam size difference along the longitudinal position
  4. Depth of the field
- Yields correction curve

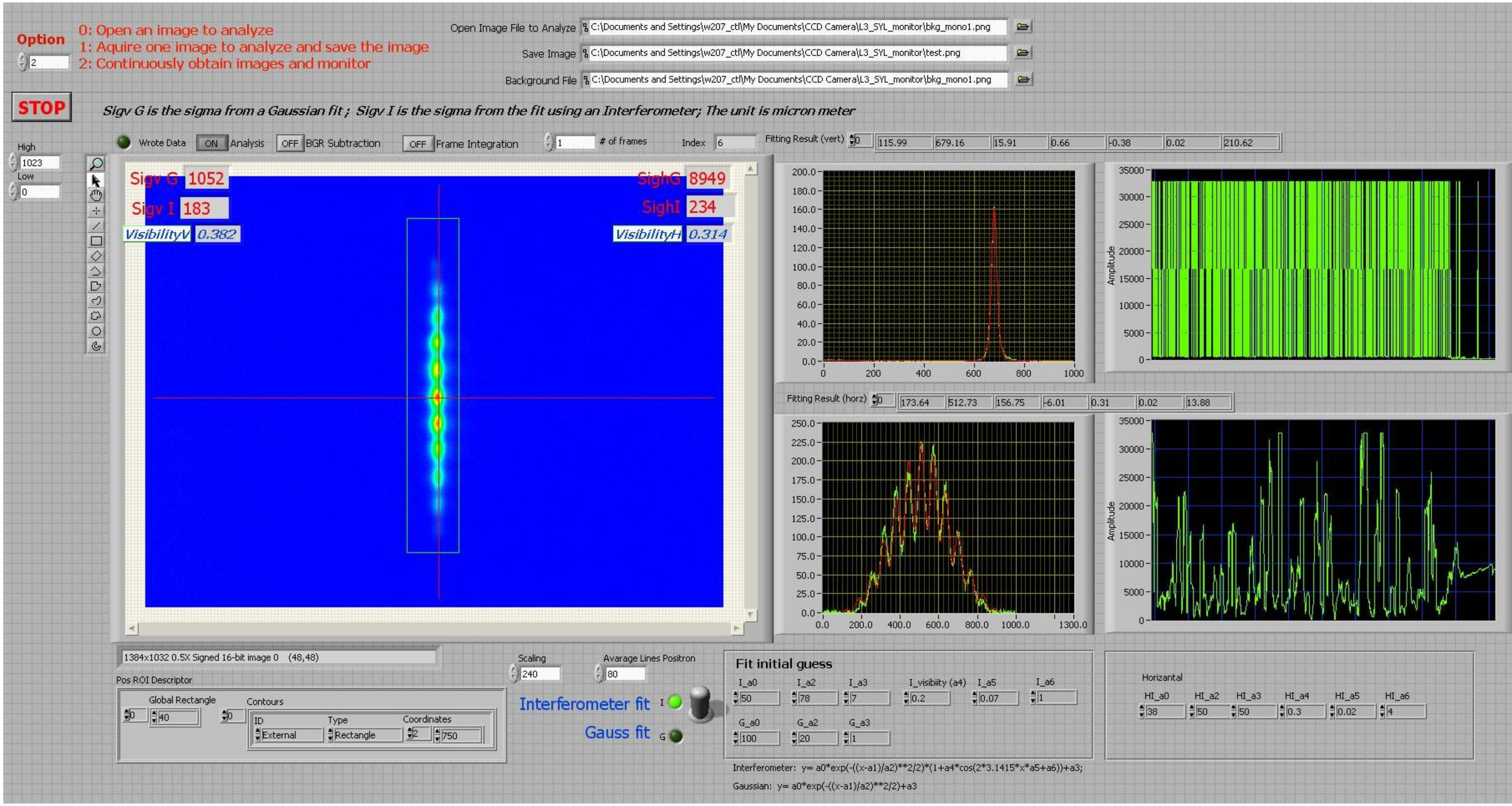
Correction curve



June 27th, run 13



Horizontal Visible Beam Size Monitor



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

ODR: Under Development

- Joint Planning: CESRTA & CLIC
  - Movable ODR radiator (variable gaps) for injection
  - Using η_v controls in CESR, σ_v can be varied x4-5
  - Phase 1: Install detector (Summer of 2012)
    - Initial studies at optical wavelengths
    - To be located in L3 straight section
      - 2.1 GeV: $\beta_H = 38$ m → $\sigma_h = 320\ \mu m$; $\beta_V = 8.7$ m → $\sigma_v \sim 9.2\ \mu m$
      - 5.3 GeV: $\beta_H = 23$ m → $\sigma_h = 2500\ \mu m$; $\beta_V = 2.5$ m → $\sigma_v \sim 65\ \mu m$
  - Phase 2: Reinstall at former IP for CESR (2013)
    - Will consider X-Ray monitor
    - To reconfigure CESRTA with original L3 Mini-beta Insert
      - 2.1 GeV: $\beta_H \sim 1$ m → $\sigma_h \sim 51\ \mu m$; $\beta_V \sim 10$ cm → $\sigma_v \sim 2\ \mu m$
      - 5.3 GeV: $\beta_H \sim 1$ m → $\sigma_h \sim 380\ \mu m$; $\beta_V \sim 10$ cm → $\sigma_v \sim 7\ \mu m$

Final Slide

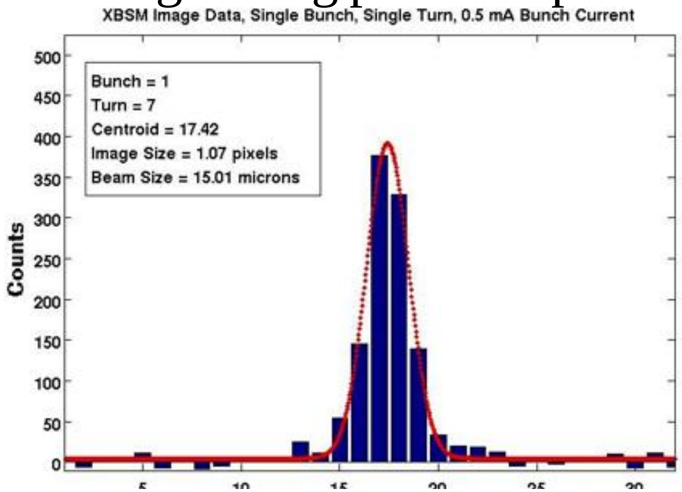
- Additional slides to follow

CBPM: Resonant Measurements

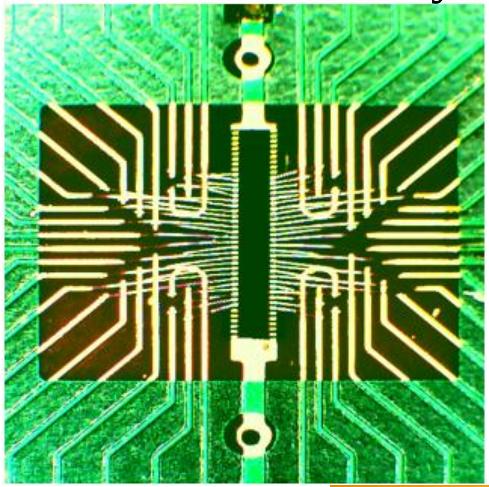
- CBPM system:
  - Capable of multibunch, turn-by-turn readout
    - Measure positions by peak detection for an arbitrary bunch pattern (down to 4ns bunch spacing) on every turn
    - Collect up to ~250k turns of beam position data
      - Turns depth is buffer-limited; dependent on number of bunches 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 (see below): ~1 minute
  2. Record TBT data: ~30s
     - 40k turns used for most common measurements
  3. Onboard FPGA analyzes data to extract betatron phase + coupling, or dispersion: ~10s to collect data on disk

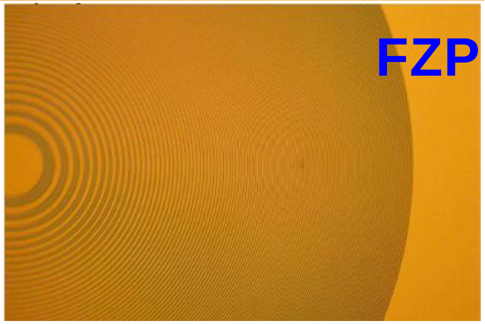
X-ray Beam Size Monitor

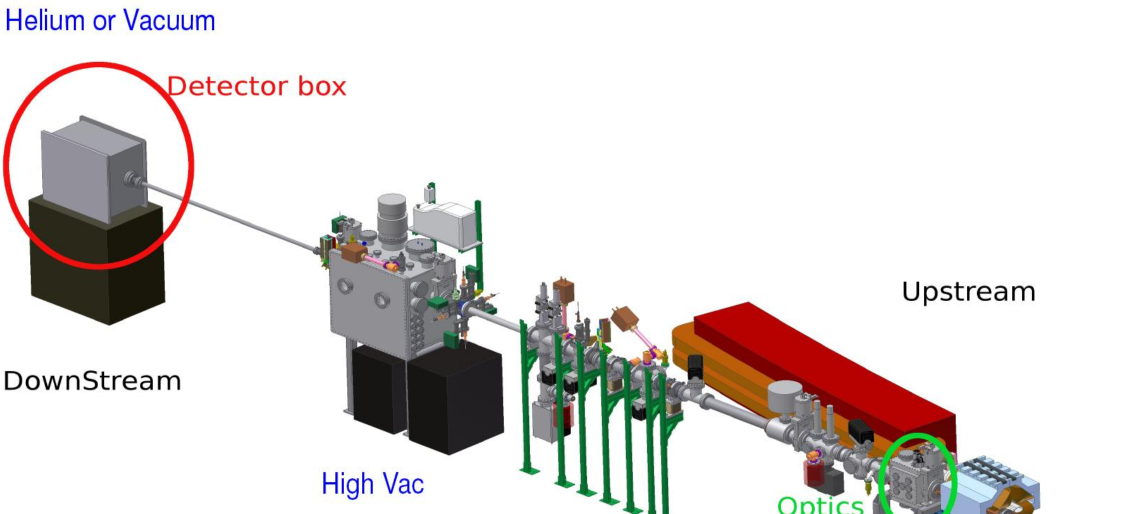
Image using pinhole optic



xBSM diode array







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