Cornell University
Laboratory for Elementary-Particle Physics

Optics Correction at CesrTA

David Sagan
Cornell University

Outline

- Coupling Nomenclature
- Betatron Phase & Coupling Measurement
- Phase / Coupling Correction
  - Example
- Locating Phase & Coupling Errors
- AC Dispersion Measurement
- ORM Measurements
- Conclusion

Characterizing the Coupling

Similarity Transformation of 1-Turn 4x4 matrix transforming (x, p_x, y, p_y):

$$\mathbf{T}_1(s) = \mathbf{VUV}^{-1} = \begin{pmatrix} \gamma\mathbf{I} & \mathbf{C} \\ -\mathbf{C}^+ & \gamma\mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix} \begin{pmatrix} \gamma\mathbf{I} & -\mathbf{C} \\ \mathbf{C}^+ & \gamma\mathbf{I} \end{pmatrix}$$

"a"-mode ($\gamma \approx 1$)

"b"-mode

C(s) = 0 <==> No coupling

Normalize **C** to take out beta dependence:

$$\overline{\mathbf{C}}(s) = \mathbf{G}_a \mathbf{C} \mathbf{G}_b^{-1} \qquad \mathbf{G} = \begin{pmatrix} 1/\sqrt{\beta} & 0 \\ \alpha/\sqrt{\beta} & \sqrt{\beta} \end{pmatrix}$$

Relationship between **C** and emittance:

$$\varepsilon_b = \varepsilon_b(\text{coupling}) + \varepsilon_b(\text{dispersion})$$

$$\frac{\varepsilon_b(\text{coupling})}{\varepsilon_a} \cong \left\langle \overline{C}_{21}^2 + \overline{C}_{22}^2 \right\rangle_s \cong 2\left\langle \overline{C}_{ij}^2 \right\rangle_s$$

$\overline{C}_{ij}(s) \sim 1/\sqrt{2}$ <==> Full coupling (round beam with $\varepsilon_b \sim \varepsilon_a$)

Betatron Phase & Coupling Measurement

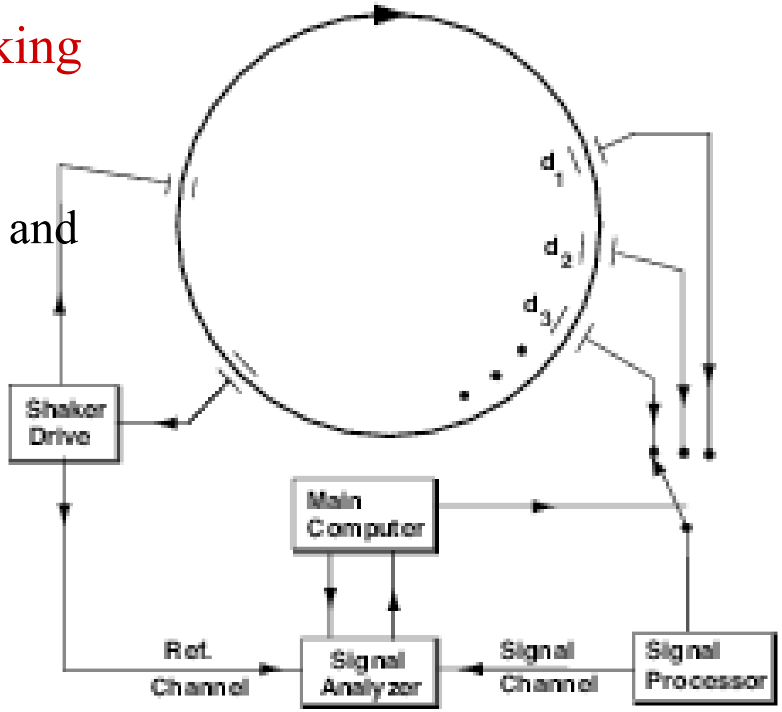
Coupling and betatron phase and are measured by shaking the beam at a betatron resonance and looking at the response at the BPMs.

- Shake the beam simultaneously at both "a"-mode and "b"-mode resonance frequencies.
- Sample the position at a BPM 32k times.
- To filter signal look at average of:

$(x_n, y_n) * e^{i\omega_a n}$ $n = 1, \ldots, 32k$

$(x_n, y_n) * e^{i\omega_b n}$

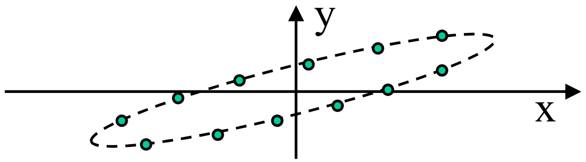
- Measurement time: 40 sec. for 100 BPMs.
- Resolution ~ 0.1^o



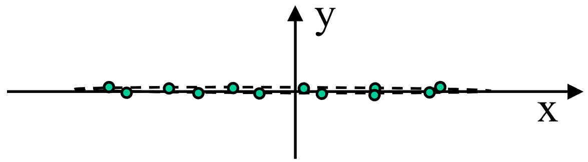
•Shaking gives much better signal to noise than pinging the beam and watching it decay.

Beam Motion at a BPM

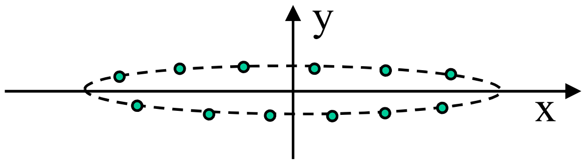
a-mode excitation:



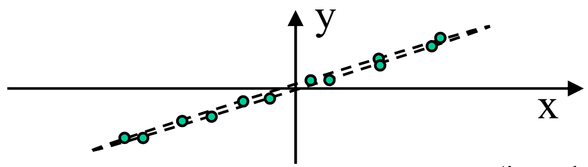
General case: beam motion is elliptical



No coupling case



$\overline{C}_{12} \neq 0,\ \overline{C}_{22} = 0$ $\quad \overline{C}_{12} \sim \dfrac{y_{amp}\text{(out-of-phase)}}{x_{amp}}$



$\overline{C}_{12} = 0,\ \overline{C}_{22} \neq 0$ $\quad \overline{C}_{22} \sim \dfrac{y_{amp}\text{(in-phase)}}{x_{amp}}$

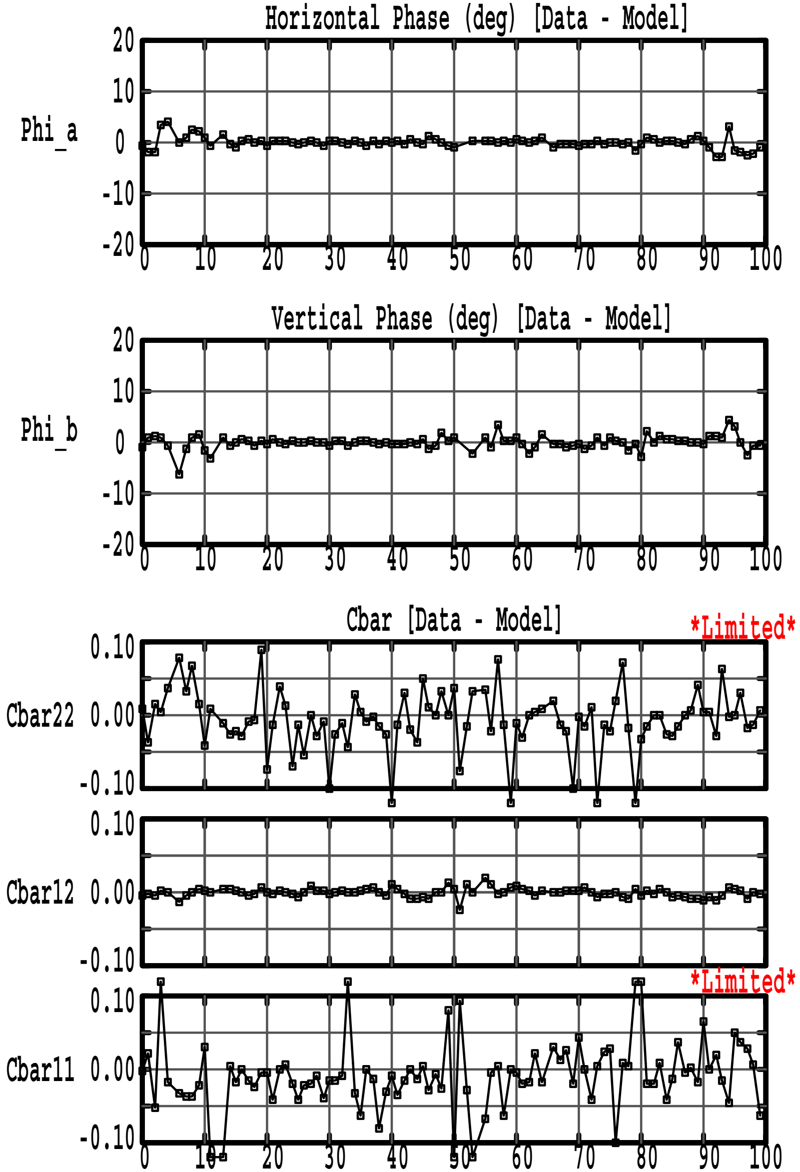
- Betatron phase: ϕ_a = phase of oscillation of the x-component.
- $\overline{C}_{12}$ & ϕ_a are ***insensitive*** to BPM tilts and individual BPM button gain errors. ⇒ Can cleanly measure.
- $\overline{C}_{22}$ is ***sensitive*** to BPM tilts and individual BPM button gain errors. ⇒ Data generally not as clean.
- $x_{amp} \propto \sqrt{\beta_a}$ is ***sensitive*** to BPM button gain errors. ⇒ Data generally not as clean.

b-mode excitation:

$\overline{C}_{12} \sim \dfrac{x_{amp}\text{(out-of-phase)}}{y_{amp}} \qquad \overline{C}_{11} \sim \dfrac{x_{amp}\text{(in-phase)}}{y_{amp}}$

- Betatron phase: ϕ_b = phase of oscillation of the x-component
- $\overline{C}_{12}$ & ϕ_b are ***insensitive*** to BPM tilts and individual BPM button gain errors. ⇒ Can cleanly measure.
- $\overline{C}_{11}$ is ***sensitive*** to BPM tilts and individual BPM button gain errors. ⇒ Data generally not as clean.
- $y_{amp} \propto \sqrt{\beta_b}$ is ***sensitive*** to BPM button gain errors. ⇒ Data generally not as clean.

Example Measurement



- Since the $\overline{C}11$ and $\overline{C}22$ data generally is noisy, it is generally not used in correcting the phase or coupling.
- Also the amplitude data is not used.

Phase / Coupling Correction

Phase / coupling correction procedure:

1. Start with:
   a) Measured phase and/or coupling data
   b) A model lattice that describes the machine.
2. Vary the quadrupole and/or skew quadrupole strengths in the model until the phase and/or coupling values as calculated from the model matches the measured data. This is done by minimizing a Merit function:

   $M = \Sigma_i W_i\,(Data_{i,meas} - Data_{i,model})^2 + \Sigma_j W_j\,(k_{j,meas} - k_{j,model})^2$
3. The change in quadrupole strength for the correction is:

   $dk_j = k_{j,design} - k_{j,model}$

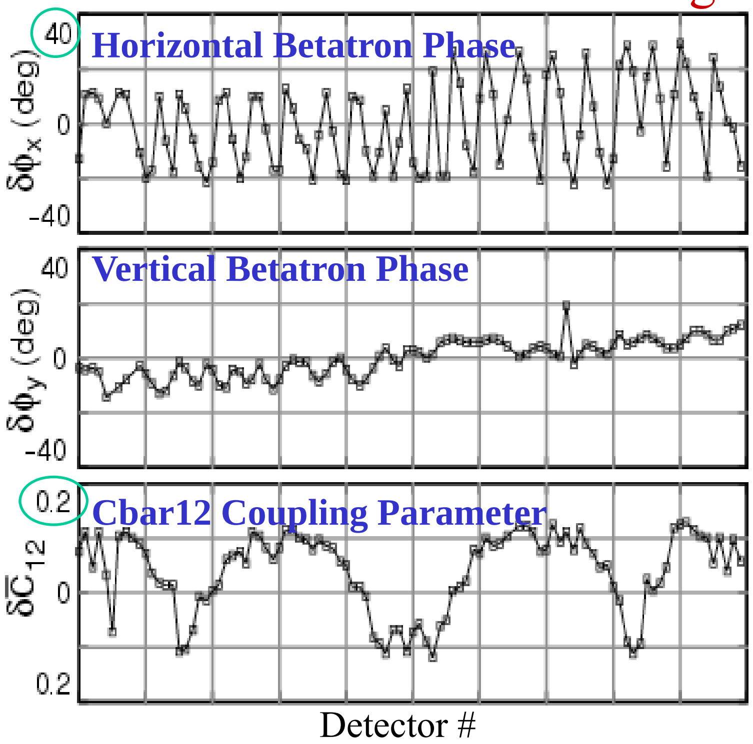
Note: This procedure allows for normal and skew quadruple calibrations:

1. Data is taken before and after a given quadrupole is varied.
2. The corresponding quadrupole in the model is fit to the phase or coupling difference.

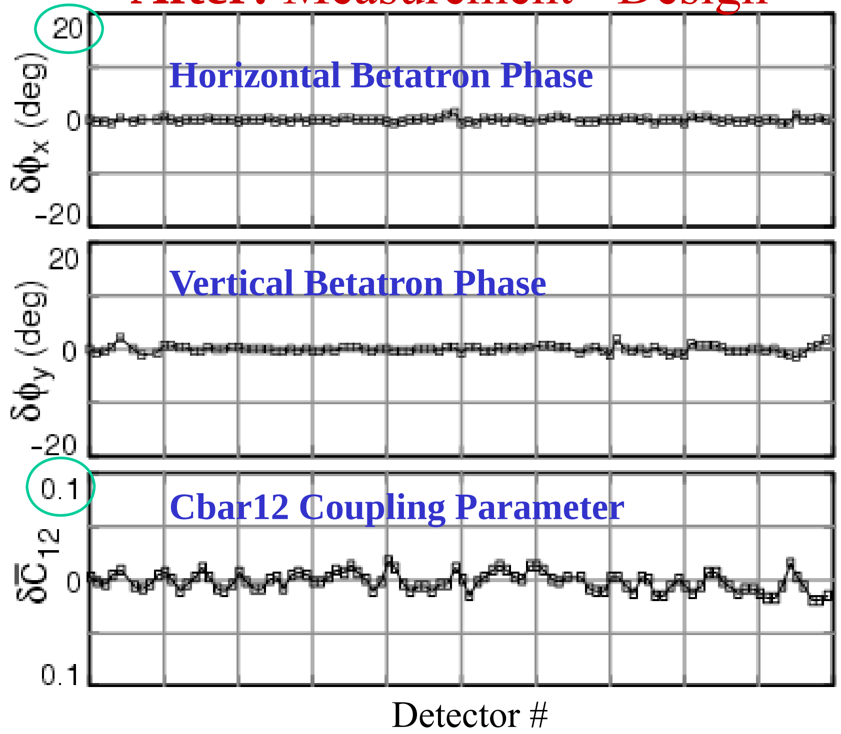
Example Correction

- Time to measure data, calculate and load a correction: few minutes.
- Typically it will take 2 to 3 corrections for the measurement to converge.

Before: Measurement - Design



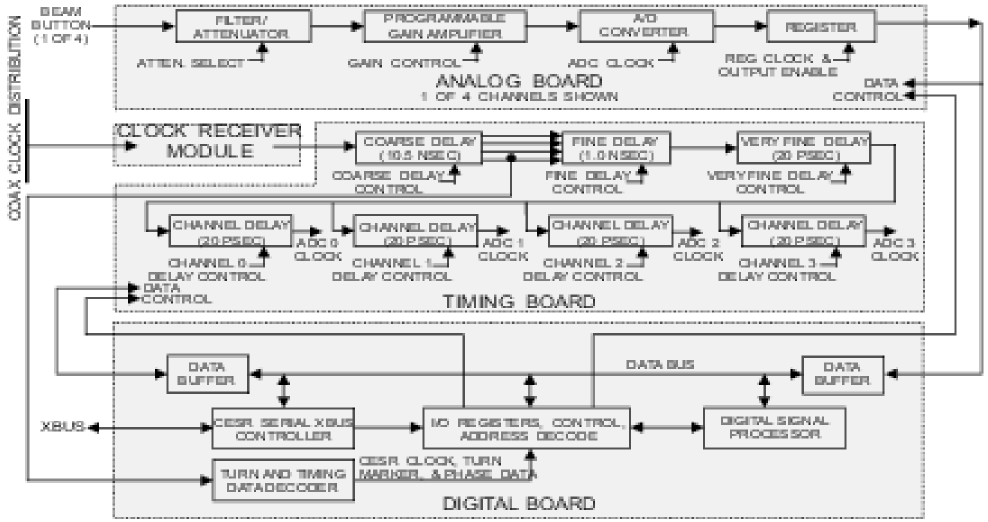
After: Measurement - Design



- $\sigma_{\delta\beta/\beta} \sim \sigma_{\delta\phi} \quad \Rightarrow \quad \sigma_{\delta\phi} \sim 1^{o} \Leftrightarrow \sigma_{\delta\beta/\beta} \sim 1.5\%$
- $\bar{C}_{12} \sim 0.01$ => ε_b(coupling)/$\varepsilon_a \sim 10^{-4}$ => ε_b(dispersion) will dominate in CesrTA

New BPM Electronics

- With all BPMs instrumented with individual readout modules, coupling, betatron phase, and position measurements could be made in real time (~1 second).
- Complete installation scheduled for Early 2009.



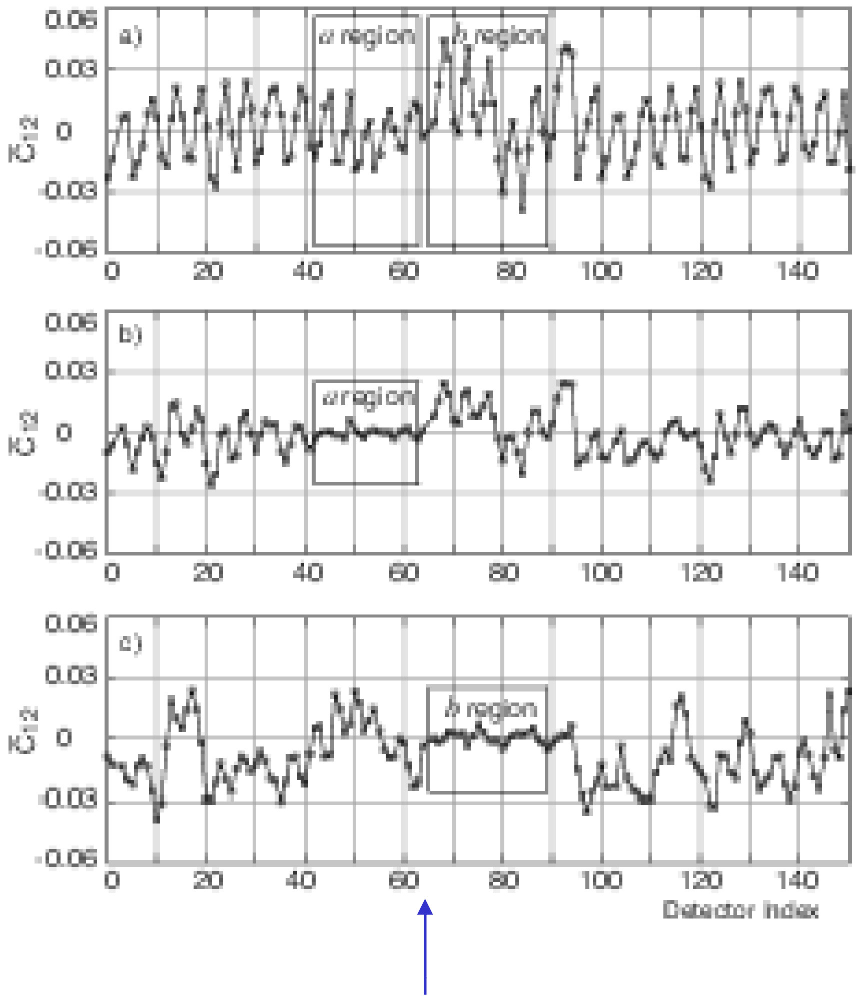
BPM Readout Module Block Diagram

Locating Phase and Coupling Errors

The phase and coupling data can be used to locate and calculate the strength of quadrupole and skew quadrupole errors.

Example: A backleg winding for a steering coil accidentally located near the beam pipe caused a skew quadrupole field in the vicinity of the beam.

Using the coupling data, the location of the winding was pinpointed to within ~1meter.



"AC" Dispersion Measurement

- Minimizing the vertical dispersion is critical to achieving low vertical emittance.
- Dispersion is coupling of longitudinal and transverse motion.

Therefore: Analogous to the transverse coupling measurement, we can measure the dispersion by

1. Driving synchrotron oscillations via modulation of the RF amplitude at synchrotron tune.
2. Measure the resulting vertical & horizontal oscillations at the BPMs.

Advantages over DC dispersion measurement:

1. Faster (changing the RF frequency is a relatively slow process).
2. 1/f noise is greatest at DC.
3. AC measurement requires less of a perturbation of the beam.

[See David Rubin's Wednesday talk for more details.]

ORM Measurements

- Taking data for an orbit response matrix analysis involves taking difference orbits while varying the steerings.
- Taking ORM data at CesrTA involves varying ~120 steerings and takes about 2 hours.
- ORM is typically used to correct quadrupole strength errors but at CesrTA it does not make sense to use ORM for this purpose at CesrTA given our ability to make fast phase/coupling measurements.
- Currently it is being explored whether ORM can be used to measure BPM tilts and/or gains which is important for accurate measurement of the vertical dispersion.

[See Jim Shank's talk next.]

Conclusion

- Software and hardware has been developed at CesrTA which permits the rapid measurement and correction of orbits, dispersion, betatron phase, and coupling. Combining measurement, analysis and correction loading capabilities in a single program greatly streamlines the process.
- The ability to **rapidly** make corrections is essential for reaching the required low vertical emittance in CesrTA and almost certainly will be essential for the ILC dampling ring as well.
- Software has been developed which can locate isolated steering, qudrupole, and skew quadrupole errors.
- Software has been developed to calibrate steerings, quadrupoles, and skew quadrupoles.
- Individually powered magnets provides great flexibility in designing optics and correcting phase/coupling errors.
- Until now, data such as $\overline{C}_{11}$ and $\overline{C}_{22}$ has been ignored since acceptable corrections could be made without this data. With the current demand for lower vertical emittance, a reexamination is in process.