Experimental Plan for Achieving Low Emittance in CesrTA

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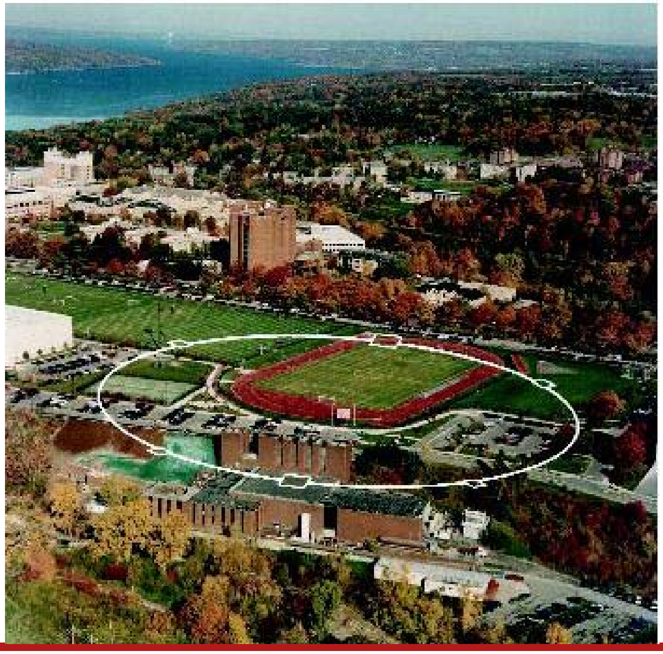
Accelerator-Based Sciences and Education



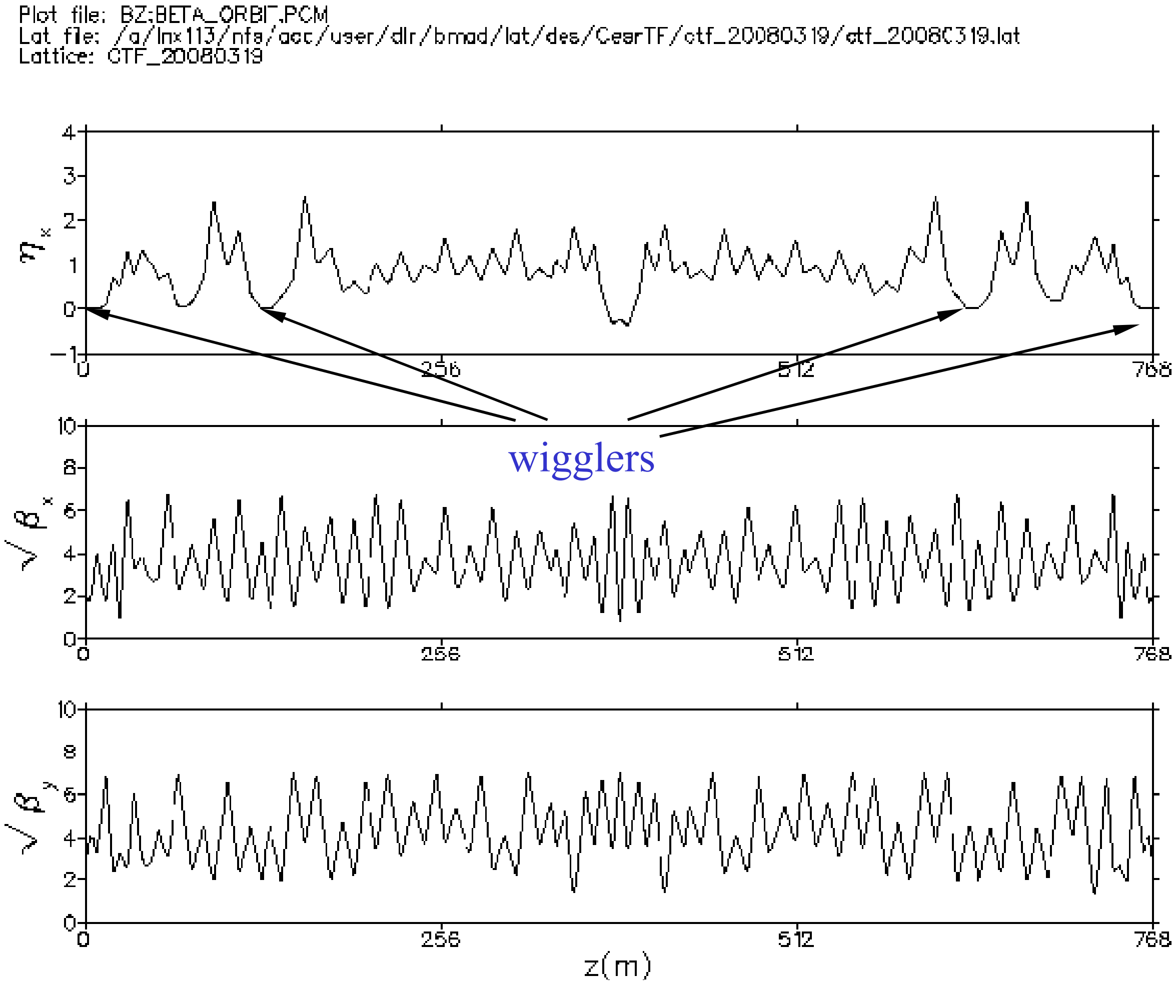
Outline

- CesrTA lattice
  - Horizontal emittance in a wiggler dominated ring
- Sensitivity of vertical emittance to optical and alignment errors
  - Contribution to vertical emittance from dispersion and coupling
  - Alignment and survey
- Beam based alignment
  - Dependence on BPM resolution
  - Beam position monitor upgrade
- Survey
  - Network of reference monuments
  - Digital level, laser tracker, quad moving hardware
  - Analysis of zero corrector orbits
- Dispersion measurement
  - AC method
  - Correction
- Coupling measurement
  - Phase/coupling measurement and ORM
- Beam size monitor
- Lifetime as a measure of beam size
- Schedule
- Status

Low Emittance Optics

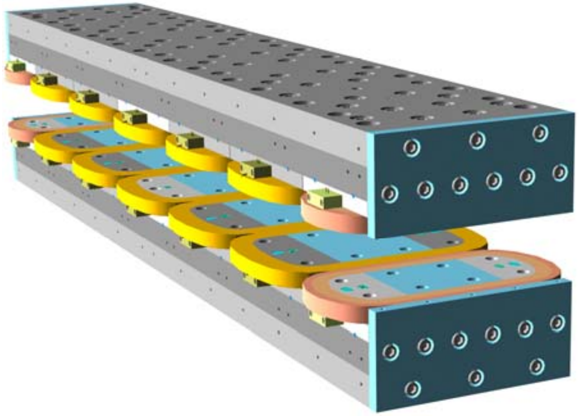
Parameter	Value
E	2.0 GeV
$N_{wiggler}$	12
B_{max} (wigglers)	1.9 T
ε_x (geometric)	2.3 nm
ε_y (geometric) Target	20 pm
$\tau_{x,y}$	56 ms
σ_E/E	8.1×10^{-4}
Q_z	0.070
Total RF Voltage	7.6 MV
σ_z	8.9 mm
α_p	6.2×10^{-3}

Wiggler dominated:
90% of synchrotron radiated
power in wigglers

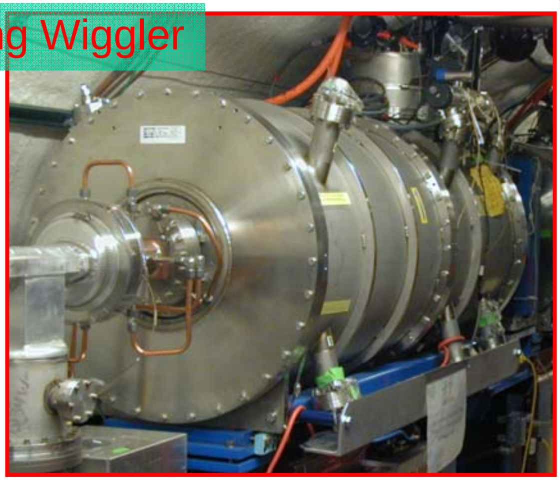


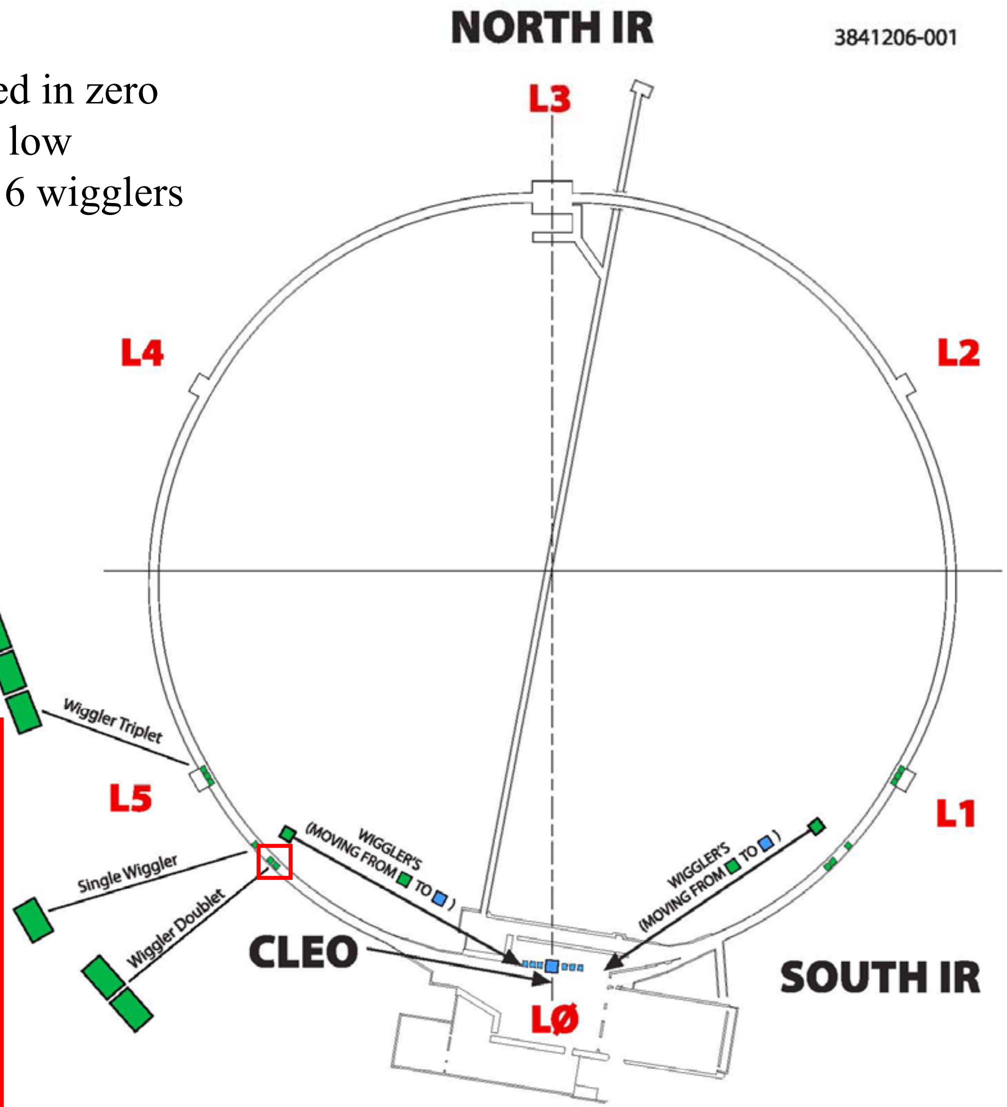
Low Emittance Optics

- CesrTA Configuration:
  - 12 damping wigglers located in zero dispersion regions for ultra low emittance operation (move 6 wigglers from machine arcs to L0)

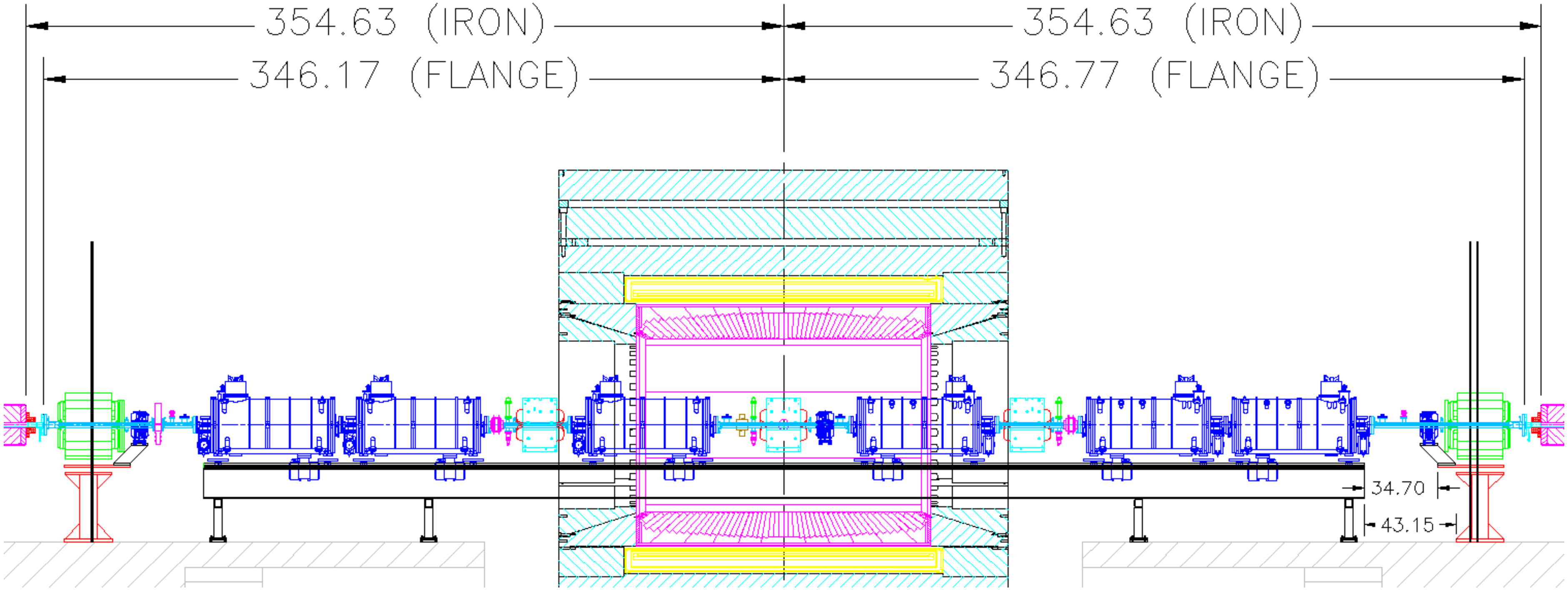


CESR-c Damping Wiggler





L0 Wiggler Region



MAIN COMPONENT POSITIONS

- L0 wiggler experimental region design work well underway
  - Installation during July down
  - Heavily instrumented throughout with vacuum diagnostics
- Note: Part of CLEO will remain in place
  - At present unable to remove full detector
  - Time savings

Minimum horizontal emittance

Can we achieve the theoretical horizontal emittance?
How does it depend on optical errors/ alignment errors?

Correct focusing errors - using well developed beam based method

1. Measure betatron phase and coupling
2. Fit to the data with each quad k a degree of freedom
    - Quad power supplies are all independent. Each one can be adjusted so that measured phase matches design
3. On iteration, residual rms phase error corresponds to 0.04% rms quad error.

→ residual dispersion in wigglers is much less than internally generated dispersion

- We find that contribution to horizontal emittance due to optical errors is neglible.
- Furthermore we determine by direct calculation that the effect of of misalignment errors on horizontal dispersion (and emittance) is negligble

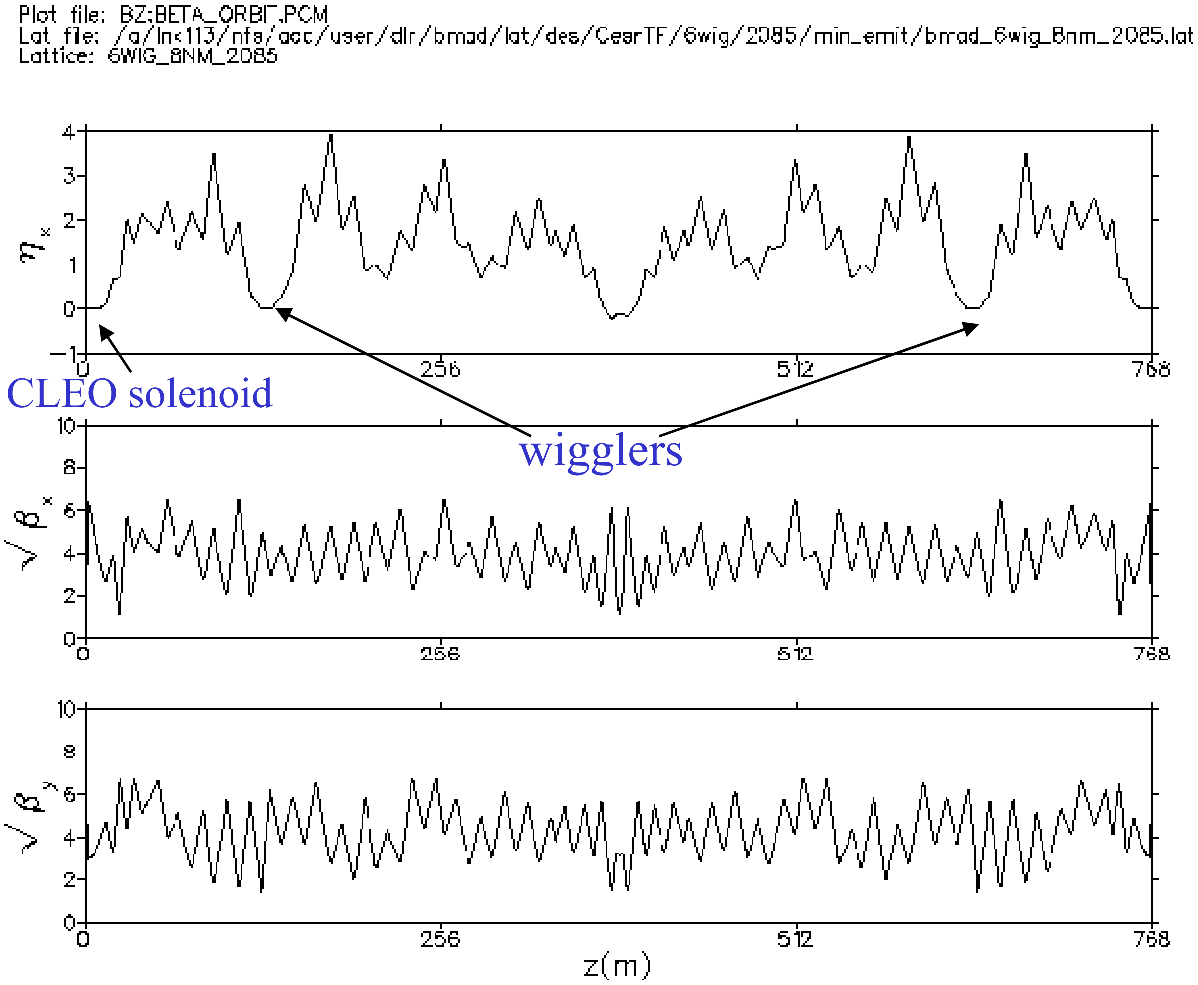
We expect to achieve the design horizontal emittance (~2.3nm)

6 wiggler optics

June 2008 machine studies

Parameter	Value
E	2.0 GeV
$N_{wiggler}$	6
B_{max} (wigglers)	1.9 T
ε_x (geometric)	7.5 nm
$\tau_{x,y}$	100 ms
σ_E/E	7.8 x 10^{-4}
Q_z	0.089
Total RF Voltage	6.8 MV
σ_z	9.0 mm
α_p	1.1 x 10^{-2}

Wiggler dominated:
80% of synchrotron radiated
power in wigglers



CLEO solenoid

wigglers

Sources of vertical emittance

- Contribution to vertical emittance from dispersion

$$\varepsilon_y = 2J_\varepsilon \frac{\langle \eta_y^2 \rangle}{\langle \beta_y \rangle} \sigma_\delta^2$$

Dispersion is generated from misaligned magnets

- Displaced quadrupoles (introduce vertical kicks)
- Vertical offsets in sextupoles (couples horizontal dispersion to vertical)
- Tilted quadrupoles (couples η_x to η_y)
- Tilted bends (generating vertical kicks)

- Contribution to vertical emittance from coupling

Horizontal emittance can be coupled directly to vertical through tilted quadrupoles

$$\varepsilon_y = \langle \overline{C}_{21}^2 + \overline{C}_{22}^2 \rangle \varepsilon_x$$

Sensitivities and beam based alignment

Simulation

1. Model ring
   - Magnet misalignments
   - Magnet field errors
   - Beam position monitor offsets and tilts
   - BPM resolution [absolute & differential]
2. "Measure"
   - Orbit
   - Dispersion
   - Betatron phase
   - Transverse coupling
3. Fit - (using dipole and skew quad correctors)
   - Fit "measured" betatron phase to ideal model using ring quadrupoles
   - Fit "measured" orbit to ideal model using dipole correctors
   - Fit "measured" dispersion to ideal model using dipole correctors
   - Fit "measured" transverse coupling to ideal model using skew correctors

(Thanks to Rich Helms)

Misalignments

For CesrTA optics:

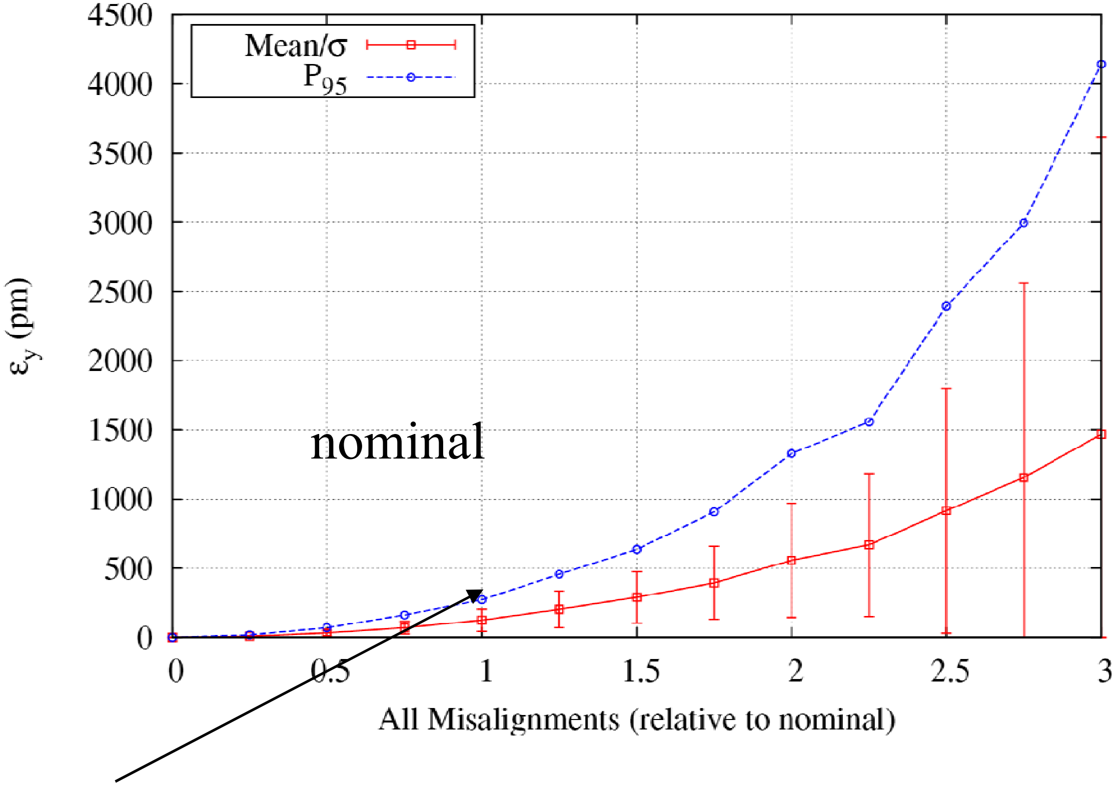
Use gaussian distribution of alignment errors to create

"N" machine models

and compute emittance of each

Element type	Alignment parameter	Nominal value
quadrupole	vert. offset	150µm
sextupole	vert. offset	300µm
bend	roll	100µrad
wiggler	vert. offset	150µm
quadrupole	roll	100µrad
wiggler	roll	100µrad
sextuple	roll	100µrad
quadrupole	horiz. offset	150µm
sextupole	horiz. offset	300µm
wiggler	horiz. offset	150µm

Dependence of vertical emittance on misalignments



Element type	Alignment parameter	Nominal value
quadrupole	vert. offset	150µm
sextupole	vert. offset	300µm
bend	roll	100µrad
wiggler	vert. offset	150µm
quadrupole	roll	100µrad
wiggler	roll	100µrad
sextuple	roll	100µrad
quadrupole	horiz. offset	150µm
sextupole	horiz. offset	300µm
wiggler	horiz. offset	150µm

For nominal misalignment of all elements, $\varepsilon_v < 270$pm for 95% of seeds

Misalignment tolerance

Contribution to vertical emittance at nominal misalignment for various elements

Element type	Alignment parameter	Nominal value	Vertical emittance
quadrupole	vert. offset	150µm	114pm
sextupole	vert. offset	300µm	8.3pm
bend	roll	100µrad	2.3pm
wiggler	vert. offset	150µm	1.4pm
quadrupole	roll	100µrad	1pm
wiggler	roll	100µrad	<< 0.01pm
sextuple	roll	100µrad	
quadrupole	horiz. offset	150µm	
sextupole	horiz. offset	300µm	
wiggler	horiz. offset	150µm	

Target emittance is < 20 pm

Estimate of quadrupole misalignment

We can estimate vertical misalignment of quads by measuring vertical orbit with no vertical correctors.

The variance of the closed orbit displacements (y_{co}) is related to the variance in quadrupole offsets ΔY_{quad} according to

$$<y^2_{co}> = <\beta_y> \sum \beta_y (K_1 l)^2 <\Delta Y^2_{quad}> /(8 \sin^2 \pi \nu_y)$$

$$\rightarrow <y^2_{co}>^{1/2} \sim 8 <\Delta Y^2_{quad}>^{1/2}$$

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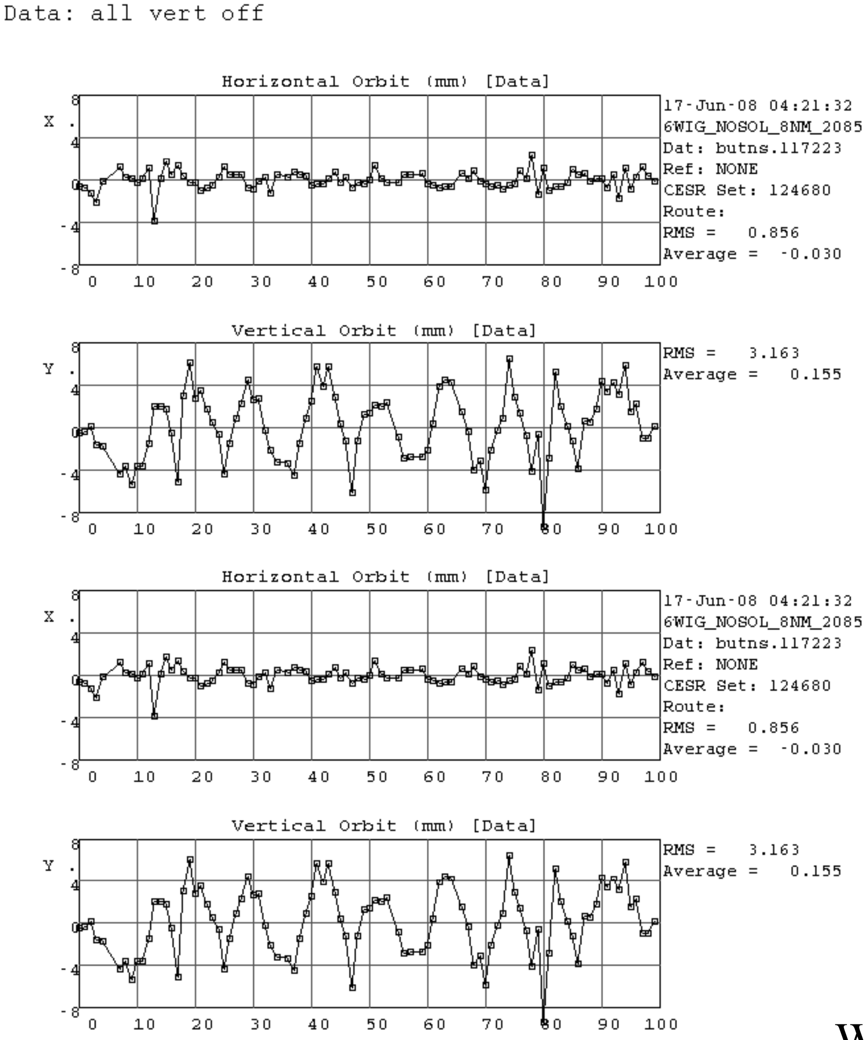
Zero corrector orbit



```
Data: all vert off
```

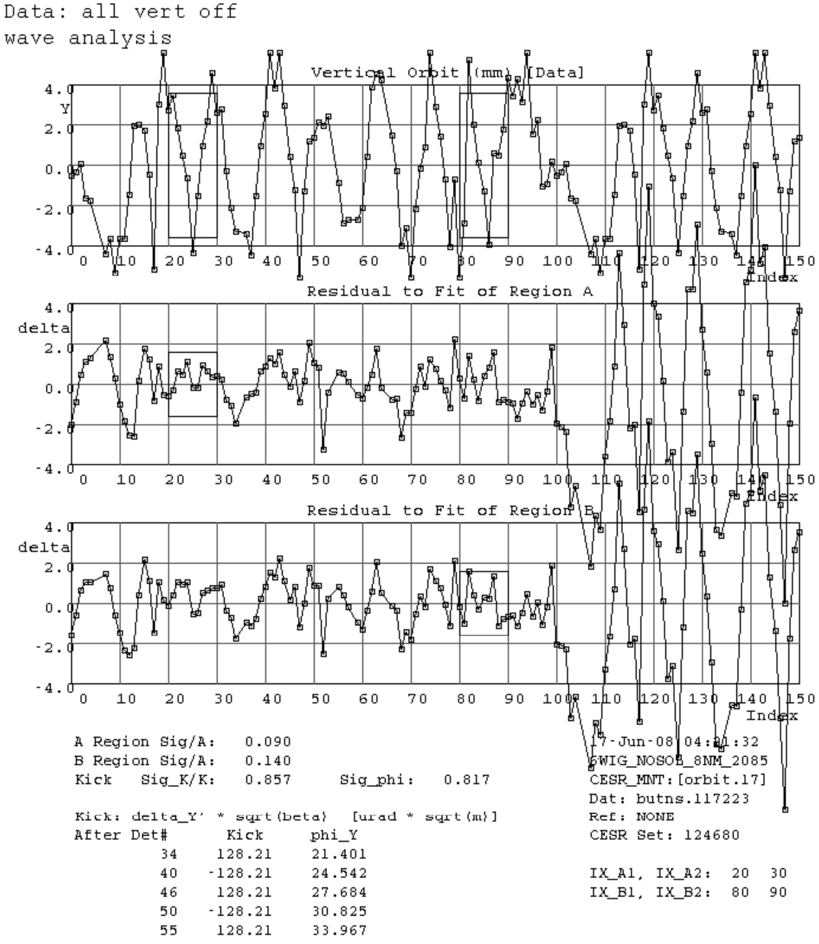
```
17-Jun-08 04:21:32
6WIG_NOSOL_8NM_2085
Dat: butns.117223
Ref: NONE
CESR Set: 124680
Route:
RMS =     0.856
Average =   -0.030
```

```
RMS =     3.163
Average =    0.155
```

```
17-Jun-08 04:21:32
6WIG_NOSOL_8NM_2085
Dat: butns.117223
Ref: NONE
CESR Set: 124680
Route:
RMS =     0.856
Average =   -0.030
```

```
RMS =     3.163
Average =    0.155
```

All vertical correctors zero



```
Data: all vert off
wave analysis
```

```
A Region Sig/A:   0.090
B Region Sig/A:   0.140
Kick   Sig_K/K:   0.857      Sig_phi:   0.817

Kick: delta_Y' * sqrt(beta)   [urad * sqrt(m)]
After Det#        Kick      phi_Y
          34    128.21     21.401
          40   -128.21     24.542
          46    128.21     27.684
          50   -128.21     30.825
          55    128.21     33.967
```

```
17-Jun-08 04:21:32
6WIG_NOSOB_8NM_2085
CESR_MNT:[orbit.17]
Dat: butns.117223
Ref: NONE
CESR Set: 124680

IX_A1, IX_A2:  20  30
IX_B1, IX_B2:  80  90
```

Wave analysis indicates misalignment in IR as source

Residual in arc ~1.2mm $\Rightarrow <\Delta y^2_{quad}>^{1/2} \sim 150\mu m$

Beam Based Alignment

- Beam base alignment algorithms and tuning strategies (simulation results)
  - Beam based alignment of BPMs (depends on independent quad power supplies)
    - $\Delta Y < 50\mu m$
  - Measure and correct
    - β-phase → design horizontal emittance
    - Orbit → reduce displacement in quadrupoles (source of vertical dispersion)
    - Vertical dispersion → minimize vertical dispersion
    - Transverse coupling → minimize coupling of horizontal to vertical emittance
  - Minimize β-phase error with quadrupoles
  - Minimize orbit error with vertical steering correctors
  - Minimize vertical dispersion with vertical steering correctors
  - Minimize coupling with skew quads

One parameter correction

- CESR correctors and beam position monitors
  - BPM adjacent to every quadrupole (100 of each)
  - Vertical steering adjacent to all of the vertically focusing quadrupoles
  - 14 skew quads - mostly near "interaction region" (L0)

- The single parameter is the ratio of the weights
- Three steps (weight ratio optimized for minimum emittance at each step)
  - Measure and correct vertical orbit with vertical steerings

    minimize $\Sigma_i (w_{c1}[\mathrm{kick}_i]^2 + w_o [\Delta y_i]^2)$
  - Measure and correct vertical dispersion with vertical steering

    minimize $\Sigma_i (w_{c2}[\mathrm{kick}_i]^2 + w_\eta[\Delta \eta_i]^2)$
  - Measure and correct coupling with skew quads

    minimize $\Sigma_i (w_{sq}[k_i]^2 + w_c[C_i]^2)$

Tuning vertical emittance

Evaluate 6 cases

2 sets of misalignments:

1. *Nominal* and *2.* Twice nominal (*Worse*)

X 3 sets of BPM resolutions:

1. No resolution error, 2. *Nominal*, and 3.*Worse* (5-10 X nominal)

	Parameter	Nominal	Worse
Element Misalignment	Quad/Bend/Wiggler Offset [µm]	150	300
	Sextupole Offset [µm]	300	600
	Rotation (all elements)[µrad]	100	200
	Quad Focusing[%]	0.04	0.04
BPM Errors	Absolute (orbit error) [µm]	10	100
	Relative (dispersion error*)[µm]	2	10
	Rotation[mrad]	1	10

$\sigma_y = 109\mu m$
May 07 survey

$\sigma(\text{one turn}) \sim 10\mu m$
$\sigma(N_{turn}\ \text{average})$
$\sim 10\mu m/\sqrt{N}$

*The actual error in the dispersion measurement is equal to the differential resolution divided by the assumed energy adjustment of 0.001

Low emittance tuning

Vertical emittance (pm) after one parameter correction:

Alignment	BPM Errors	Mean	1 σ	90%	95%
Nominal	None	1.6	1.1	3.2	4.0
“	Nominal	2.0	1.4	4.4	4.7
“	Worse	2.8	1.6	4.8	5.6
2 x Nominal	None	7.7	5.9	15	20
“	Nominal	8.0	6.7	15	21
“	Worse	11	7.4	20	26

With *nominal* magnet alignment,
we achieve emittance of 5-10pm for 95% of seeds
with *nominal* and *worse* BPM resolution

With 2 X nominal magnet alignment yields emittance near our 20pm target

Two parameter correction

Consider a two parameter algorithm

1. Measure orbit and dispersion. Minimize $\Sigma_i\, w_{c2}[\text{kick}_i]^2 + w_{o2}\,[\Delta y_i]^2 + w_{\eta 1}[\Delta\eta_i]^2$
2. Measure dispersion and coupling. Minimize $\Sigma_i\, w_{sq}[k_i]^2 + w_{\eta 2}[\Delta\eta_i]^2 + w_c[C_i]^2$

The two parameters are the ratio of the weights. The ratios are re-optimized in each step

Vertical emittance (pm) after one and two parameter correction:

Alignment	BPM Errors	Correction Type	Mean	1 σ	90%	95%
2 x Nominal	Worse	1 parameter	11	7.4	20	26
“	“	2 parameter	6.5	6.7	9.6	11.3

2 X nominal survey alignment, 10µm relative and 100µm absolute BPM resolution

- 2 parameter algorithm yields tuned emittance very < 20pm
  for 95% of seeds

Alignment and Survey

Instrumentation - new equipment

Digital level and laser tracker

Network of survey monuments

→Complete survey in a couple of weeks

Magnet mounting fixtures that permit precision adjustment

- beam based alignment

Phase/coupling correction

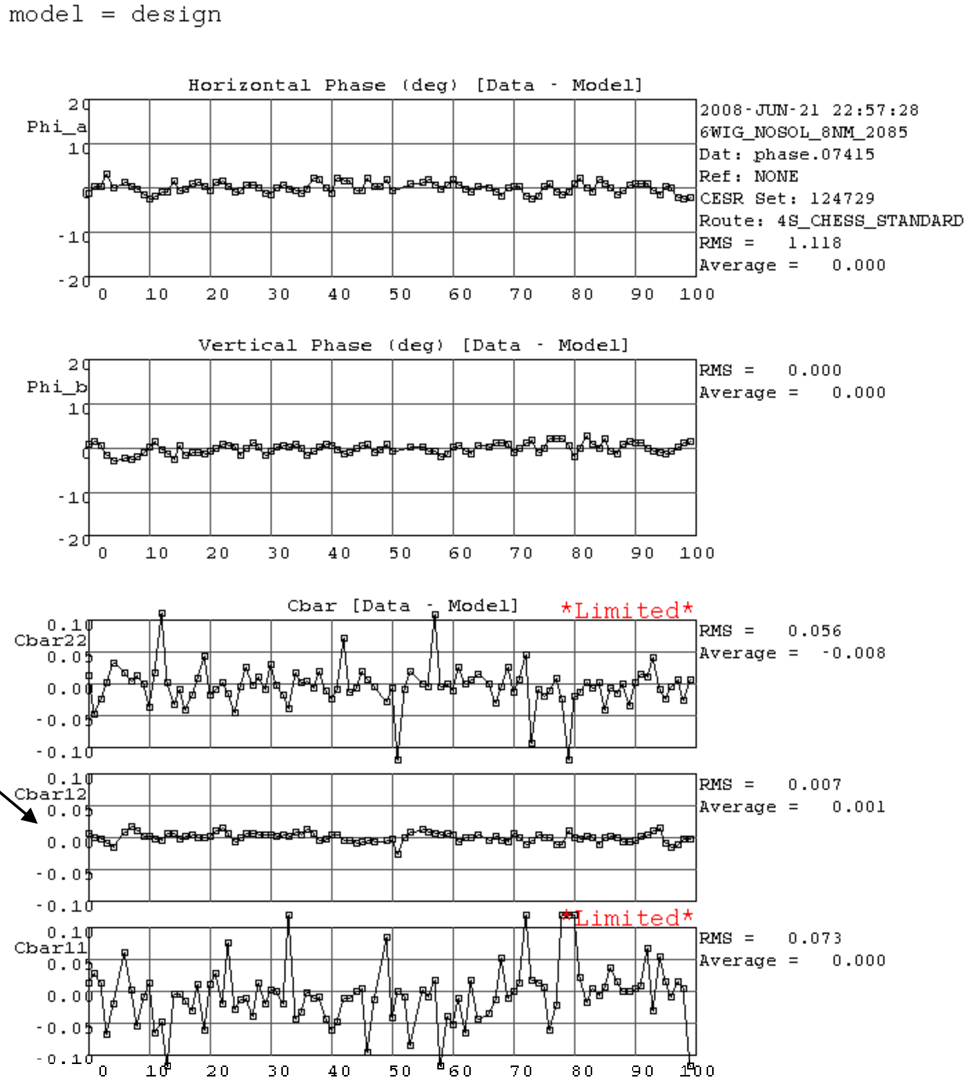
6 wiggler optics

-Measurement of betatron phase and coupling after correction using all 100 quads and 14 skew quads.

-Contribution to vertical emittance due to coupling of horizontal

$$\epsilon_v/\epsilon_h \sim (\bar{C}_{12})^2$$

$[\epsilon_h(\text{design}) = 7.5\text{nm}]$



```
model = design
```

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Dat: phase.07415
Ref: NONE
CESR Set: 124729
Route: 4S_CHESS_STANDARD
RMS =    1.118
Average =    0.000
```

```
RMS =    0.000
Average =    0.000
```

```
RMS =    0.056
Average =   -0.008
```

```
RMS =    0.007
Average =    0.001
```

```
RMS =    0.073
Average =    0.000
```

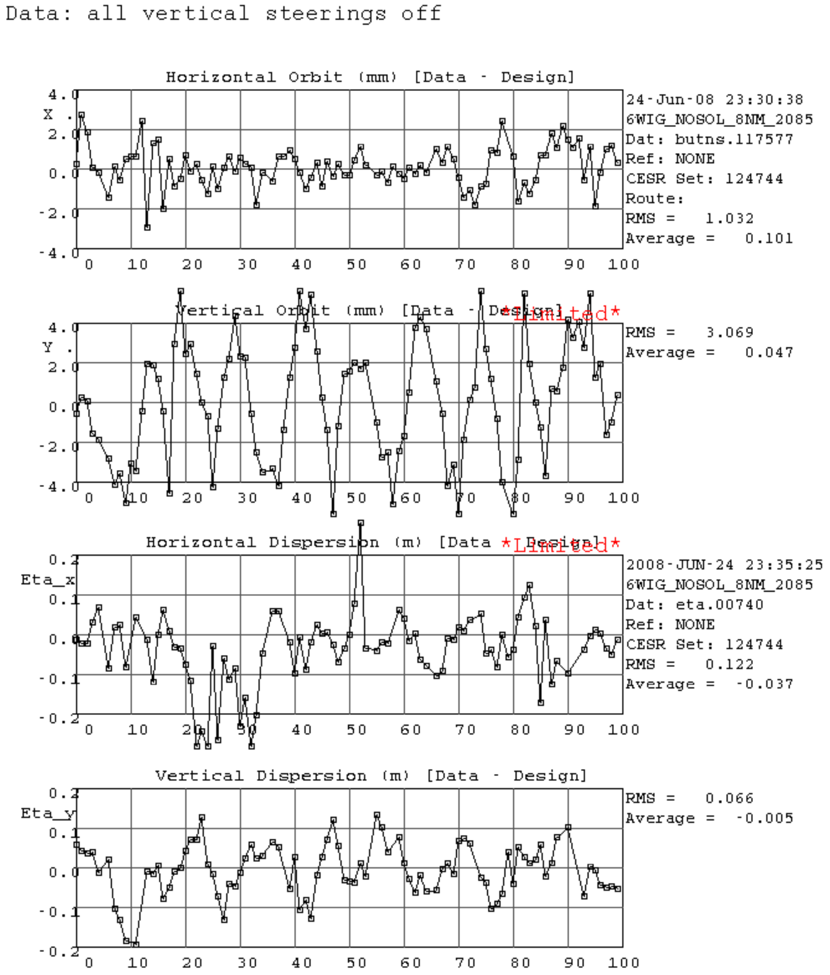
Coupling and dispersion correction

Correcting coupling to $\bar{C}_{12} < 1\%$ straightforward

Correcting dispersion is more difficult

- Dispersion measurement is sensitive to BPM tilts, nonlinearity, gain errors

Orbit and dispersion measurement and "correction"



Data: all vertical steerings off

Horizontal Orbit (mm) [Data - Design]

24-Jun-08 23:30:38
6WIG_NOSOL_8NM_2085
Dat: butns.117577
Ref: NONE
CESR Set: 124744
Route:
RMS = 1.032
Average = 0.101

Vertical Orbit (mm) [Data - Design] *Limited*

RMS = 3.069
Average = 0.047

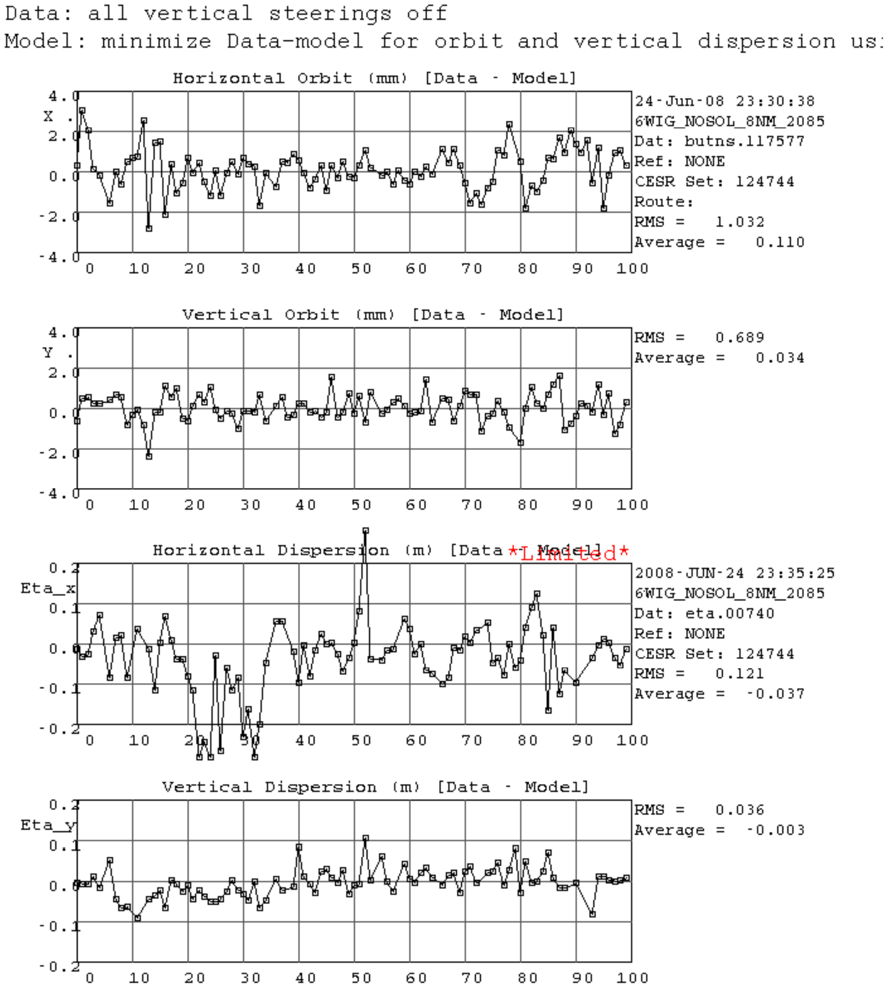
Horizontal Dispersion (m) [Data - Design] *Limited*

2008-JUN-24 23:35:25
6WIG_NOSOL_8NM_2085
Dat: eta.00740
Ref: NONE
CESR Set: 124744
RMS = 0.122
Average = -0.037

Vertical Dispersion (m) [Data - Design]

RMS = 0.066
Average = -0.005

Measured orbit and dispersion with zero vertical steering correctors.



Data: all vertical steerings off
Model: minimize Data-model for orbit and vertical dispersion us:

Horizontal Orbit (mm) [Data - Model]

24-Jun-08 23:30:38
6WIG_NOSOL_8NM_2085
Dat: butns.117577
Ref: NONE
CESR Set: 124744
Route:
RMS = 1.032
Average = 0.110

Vertical Orbit (mm) [Data - Model]

RMS = 0.689
Average = 0.034

Horizontal Dispersion (m) [Data - Model] *Limited*

2008-JUN-24 23:35:25
6WIG_NOSOL_8NM_2085
Dat: eta.00740
Ref: NONE
CESR Set: 124744
RMS = 0.121
Average = -0.037

Vertical Dispersion (m) [Data - Model]

RMS = 0.036
Average = -0.003

Measured orbit/dispersion (data) - fitted

model using all vertical steering correctors.

BPM resolution

Relative BPM resolution critical to measurement of vertical dispersion

Dispersion depends on differential orbit measurement

$\eta_v = [y(\delta/2) - y(-\delta/2)]/\,\delta \qquad \delta \sim 1/1000$

In CesrTA optics dependence of emittance on vertical dispersion is

$$\varepsilon_v \sim 1.5 \text{ X } 10^{-8} \langle \eta^2 \rangle$$

Emittance scales with square of relative BPM error

(and the energy offset δ used to measure dispersion)

σ(single pass) ~ 10µm

σ(N turn average) ~ 10µm/√N

Note:

σ(*nominal*) ~ 2µm

Achieve emittance target if $\sigma \sim 10\mu m$

Beam Position Monitor System

- Presently (and for June 08 run) have a mixed dedicated digital system with twelve stations and a coaxial relay switched analog to digital system with ninety stations.
  - Digital system stores up to 10 K turns of bunch by bunch positions with a typical single pass resolution of ~ 30 microns.
  - From the multi-turn data, individual bunch betatron tunes can be easily determined to < 10 Hz.
  - (Upgraded digital system will be fully implemented within the next year)

Meanwhile we work with digital/analog hybrid

“AC” Dispersion

(Developing “AC” dispersion measurement technique as alternative to traditional orbit difference method.)

Dispersion is coupling of longitudinal and transverse motion

Measurement

-Drive synchrotron oscillation by modulating RF at synch tune

-Measure vertical & horizontal amplitudes and phases of signal at synch tune at BPMs

Then

$\{\eta_v/\beta_v\} = (y_{amp}/z_{amp}) \sin(\varphi_y - \varphi_z)$

$\{\eta_h/\beta_h\} = (x_{amp}/z_{amp}) \sin(\varphi_h - \varphi_z)$

Advantages:

1. Faster (30k turns) (RF frequency does not change)
2. Better signal to noise -
   filter all but signal at synch tune
3. Nondestructive

Beam Size Measurements

- X-ray beam size monitor
  - 32 element linear photomultiplier array enables multi-turn bunch by bunch vertical beam size measurements using the same electronics as the digital beam position monitor system.
  - 2-3 μm resolution (ε_v=5pm →σ_v ~10 μm)
  - One each for electrons and positrons

→Allows for real time low emittance tuning using dispersion and coupling bumps

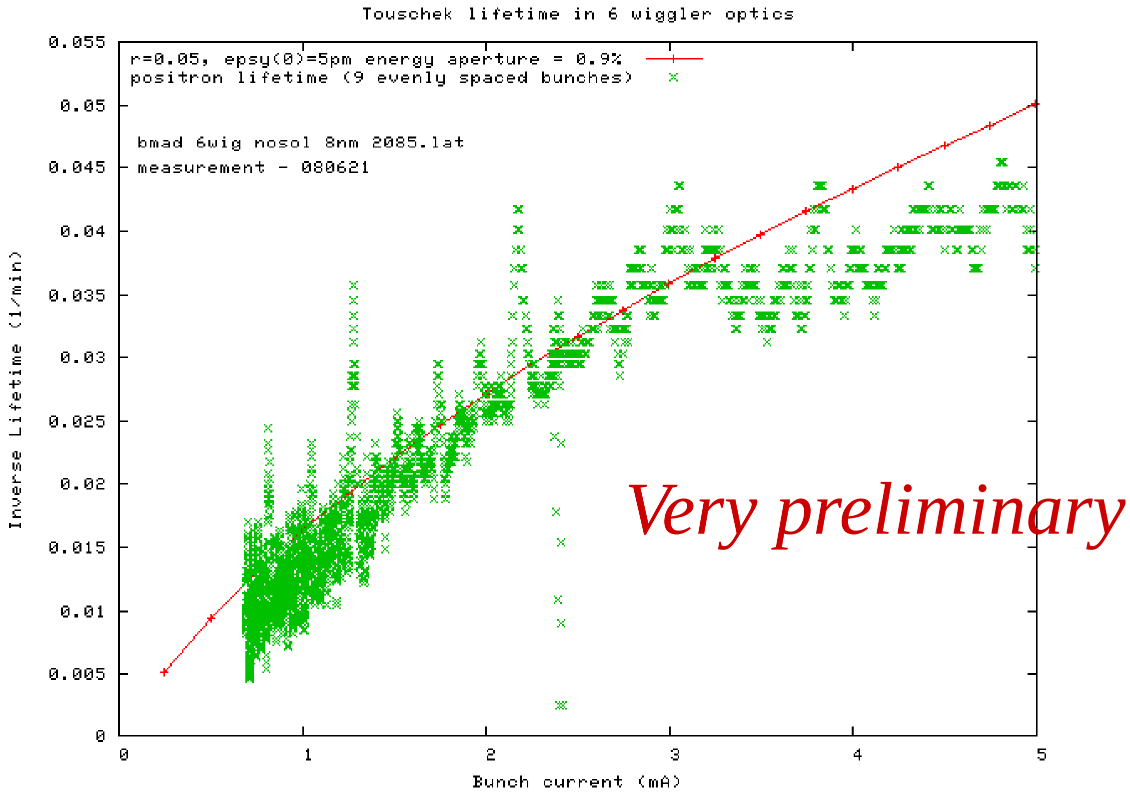
Intensity dependent effects

- Emittance and lifetime
  - Intrabeam scattering, Touschek lifetime

IBS depends on amplitude and source (dispersion or coupling) of vertical emittance and beam energy (~γ^4)

Lifetime depends beam size and energy aperture

We will measure dependency on
-beam energy (1.5-5GeV)
-RF voltage
-Transverse coupling
-Vertical dispersion
. . .



Very preliminary

Intensity dependent effects

Lifetime

Parameter	Value
E	2.0 GeV
$N_{wiggler}$	12
B_{max}	1.9 T
ε_x (geometric)	2.3 nm
ε_y (geometric) Target	5–10 pm
$\tau_{x,y}$	56 ms
σ_E/E	8.1×10^{-4}
Q_z	0.070
Total RF Voltage	7.6 MV
σ_z	8.9 mm
α_p	6.2×10^{-3}
$N_{particles}$/bunch	2×10^{10}
$\tau_{Touschek}$	>10 minutes
Bunch Spacing	4 ns

At emittance as low as 5-10pm and 2×10^{10} particles/bunch $\tau_{Touschek}$ decreases to ~10 minutes.

Experimental program

- Cesr TA electron cloud program
  - 2008
    - Install instrumented (RFA) dipole chambers (May)

    June
    - Electron cloud growth studies at 2-2.5GeV
    - Low emittance (~8nm) operation and alignment studies (Cesr-c configuration)

    July - August
    - Reconfigure CESR for low emittance (wigglers to IR)
    - Install wiggler chamber with RFA and mitigation hardware
    - Install dipole chicane
    - Optics line for xray beam size monitor
    - Extend turn by turn BPM capability to a large fraction of ring
    - Install spherical survey targets and nests and learn to use laser tracker

    Fall
    - Commission 2GeV 2.3nm optics [12 wigglers, CLEO solenoid off]
    - Survey and alignment
    - Beam based low emittance tuning
    - Characterize electron cloud growth with instrumented chambers
      Dependence on bunch spacing, bunch charge, beam size, beam energy
    - Explore e-cloud induced instabilities and emittance dilution
    - Commission positron x-ray beam size monitor (~2µm resolution)

Experimental program

- Cesr TA electron cloud program
  - 2009

    Winter
    - Install instrumented quadrupole chambers, and dipole chambers with e-cloud mitigation
    - Complete upgrade of BPMs
    - Complete survey and alignment upgrade
    - Commission electron x-ray beam size monitor
    - Install solenoid windings in drift regions

    Spring
    - Single pass measurement of orbit and dispersion
    - Electron cloud growth, instability and emittance dilution
    - Low emittance tuning

    Summer
    - Install optics line for electron xray beam size monitor
    - Complete longitudinal feedback upgrade
    - Install chambers with alternative mitigation techniques*
    - Install photon stop for 5GeV wiggler operation

    Fall
    - Complete evaluation of electron cloud growth in wiggler, dipole, quadrupole
      - Compare with simulation
    - Continue program to achieve ultra-low vertical emittance
    - Characterize electron cloud instability and emittance dilution effects at lowest achievable emittance
    - Measure electron cloud growth and mitigation in wigglers at 5GeV

System status

- Status of beam based measurement/analysis
  - Instrumentation - existing BPM system is 90% analog with relays and 10% bunch by bunch, turn by turn digital
    - Turn by turn BPM -
      - A subset of digital system has been incorporated into standard orbit measuring machinery for several years
      - Remainder of the digital system will be installed during the next year
  - Software (CESRV, Tao Cesr) / control system interface has been a standard control room tool for beam based correction for over a decade
    - For measuring orbit, dispersion, betatron phase, coupling
    - With the flexibility to implement one or two corrector algorithm
    - To translate fitted corrector values to magnet currents
    - And to load changes into magnet power supplies
    - ~ 15 minutes/iteration
    - Orbit response matrix measurements and analysis (characterize BPMs)