Low Emittance Program

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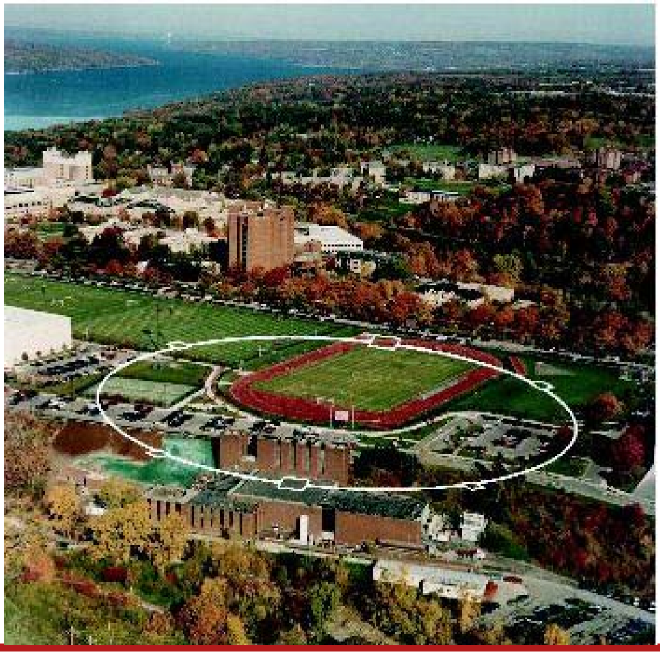


Low Emittance Tuning

Objectives

- Develop strategies for systematically tuning vertical emittance
  - Rapid survey
  - Efficient beam based alignment algorithm
- Demonstrate ability to reproducibly achieve our target of 5-10pm (geometric)
  - In CesrTA this corresponds to a vertical beam size of about ~10-14 microns
- Enable measurement of instabilities and other current dependent effects in the ultra low emittance regime for both electrons and positrons

  For example - dependencies of
  - Vertical emittance and instability threshold on density of electron cloud
  - Cloud build up on bunch size
  - Emittance dilution on bunch charge (intrabeam scattering)

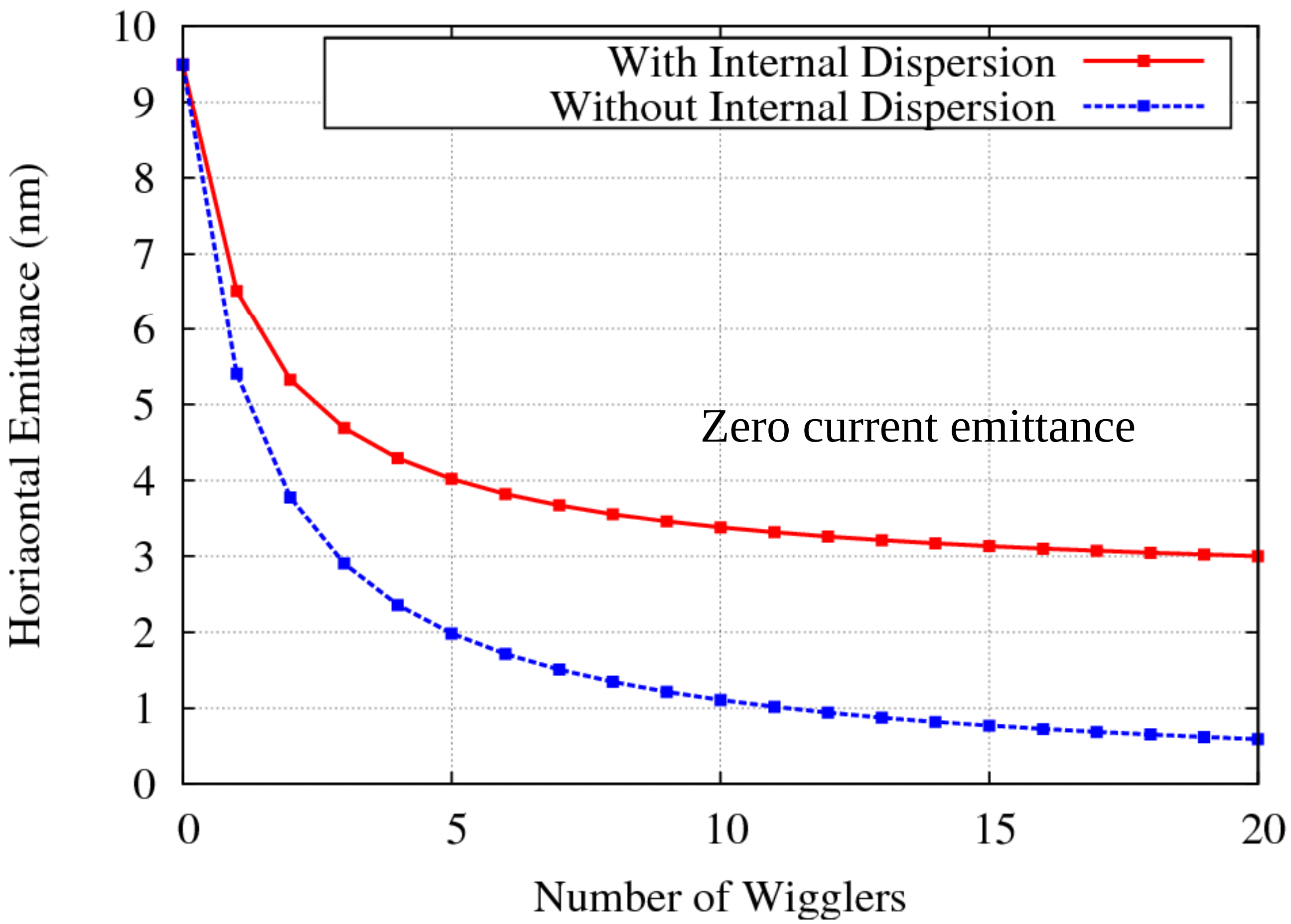
Low Emittance Tuning

Outline

- Horizontal emittance in a wiggler dominated ring
- Sensitivity of horizontal emittance to optical and alignment errors
- Contribution to vertical emittance from dispersion and coupling
- Dependence of vertical emittance on misalignments of guide field elements
- Beam based alignment
- Alignment and survey
- Dependence on BPM resolution
- Beam position monitor upgrade
- Beam size monitors
- Intensity dependent effects
- First experiments with low emittance optics
- Experimental plan

Wiggler Emittance

Dependence of emittance on number of wigglers



In CesrTA - 90% of the synchrotron radiation generated by wigglers

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)

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

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

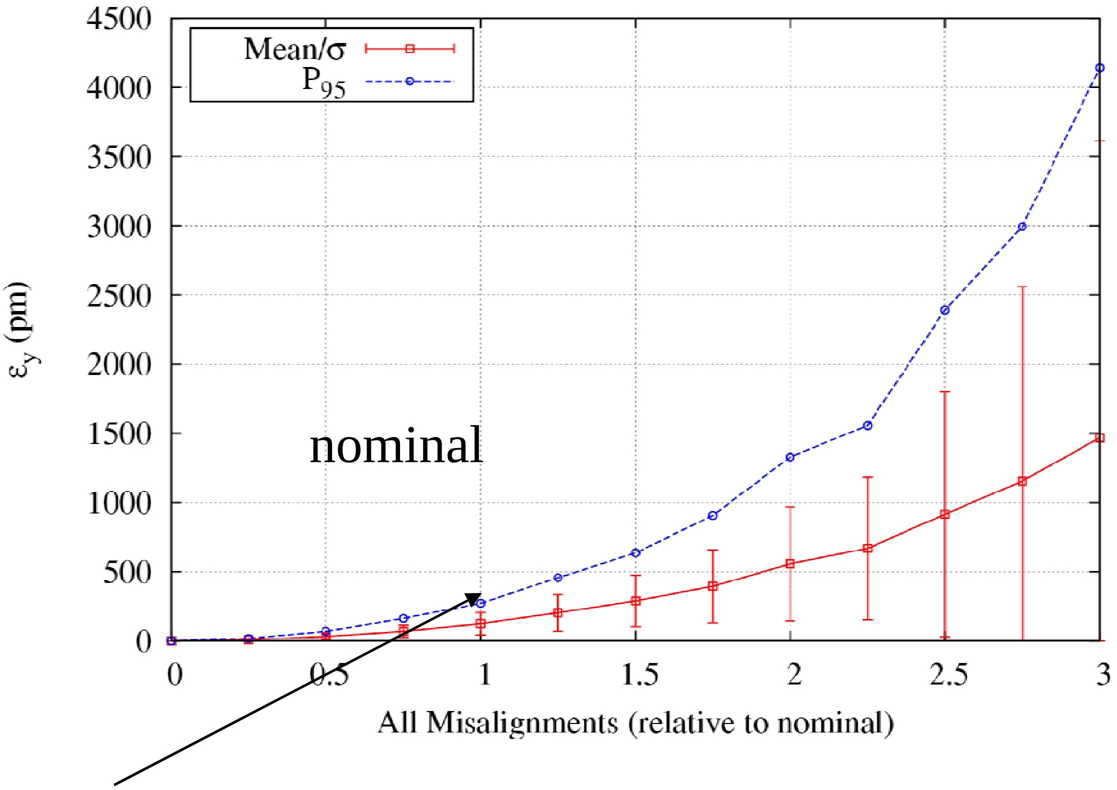
Effect of misalignments

For CesrTA optics:

- Introduce gaussian distribution of alignment errors into our machine model and compute emittance

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 5-10pm

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 quadrupole
  - 14 skew quads - mostly near interaction region

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

    minimize $\Sigma_i (w_{c2}[kick_i]^2 + w_\eta[\Delta\eta_i]^2)$
  - 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	2

σ_y=109μm
May 07 survey

σ(one turn) ~ 27μm
$\sigma(N_{turn}$ average)
~ 27μm/√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 our target emittance of 5-10pm for 95% of seeds
with *nominal* and *worse* BPM resolution

With 2 X nominal magnet alignment, one parameter correction is not adequate

Two parameter correction

Consider a two parameter algorithm

1. Measure orbit and dispersion. Minimize $\Sigma_i\, w_{c2}[kick_i]^2 + w_{o2}\,[\Delta y_i]^2 + w_{\eta 1}[\Delta\eta_i]^2$
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 close to target (5-10 pm) 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

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) ~ 27μm

σ(N turn average) ~ 27μm/√N

Note:

σ(*nominal*) ~ 2μm

Achieve emittance target if

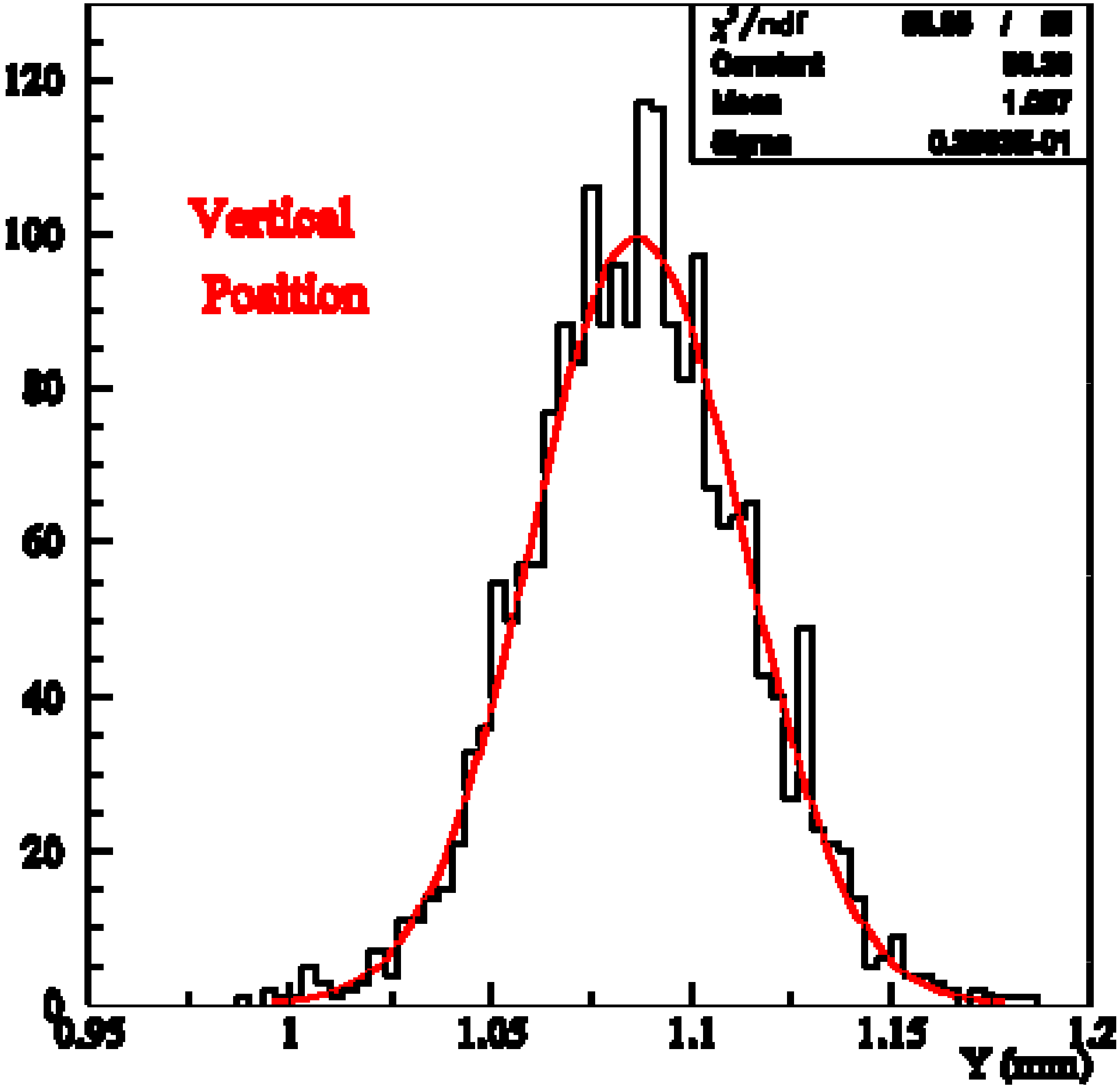
$\sigma < 10\mu m$

Beam Position Monitor System

- Presently 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.
- Digital system will be fully implemented within the next year

Beam Position Monitor System

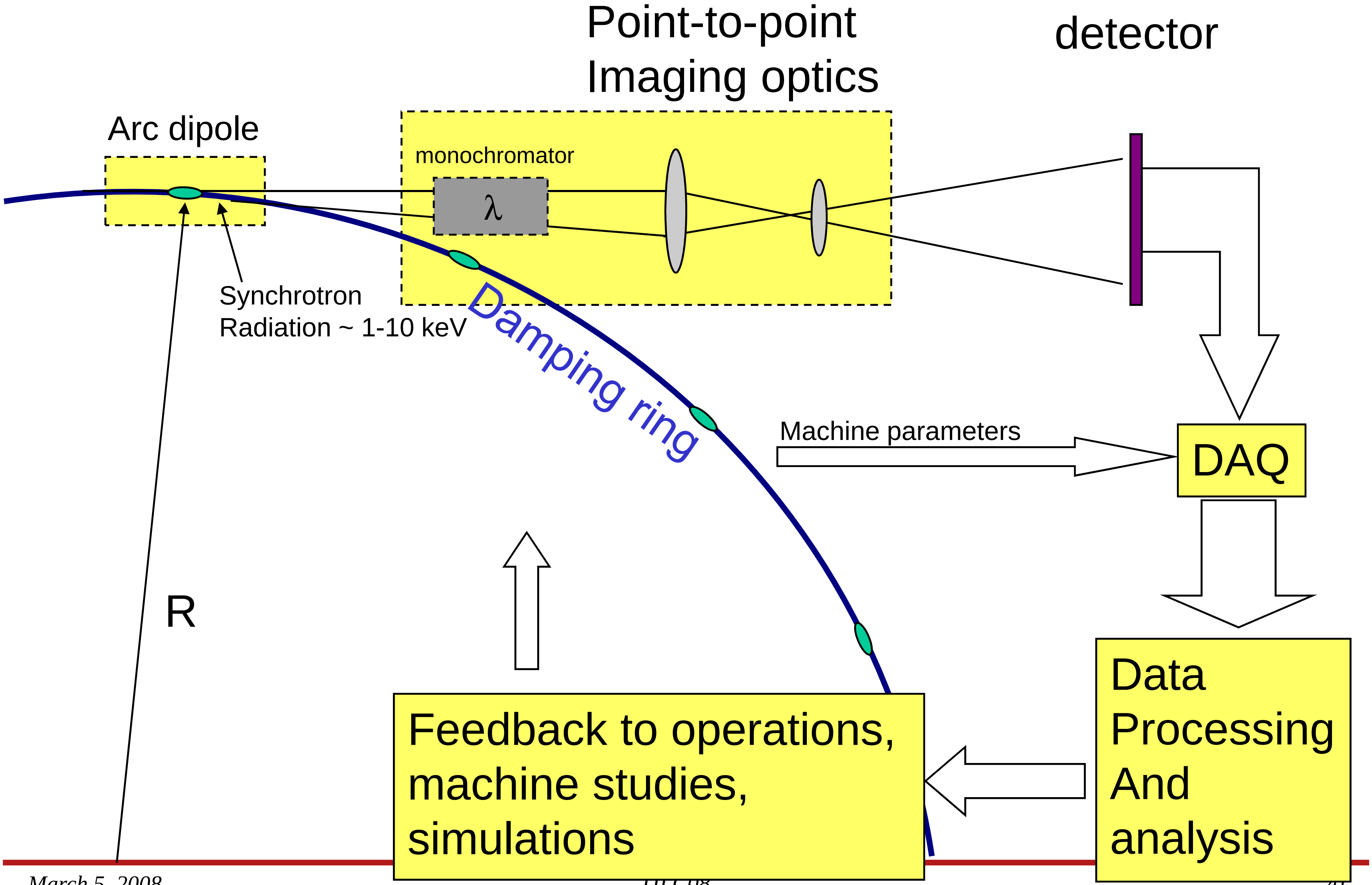
- BPM resolution



Beam Size Measurements

- Conventional visible synchrotron light imaging system for light from arc dipoles for both electrons and positrons with a vertical beam size resolution of ~ 140 microns.
- 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.
- A double slit interferometer system using the same 32 element linear photomultiplier array. Anticipated resolution
  - ~ 100 micron single pass bunch by bunch vertical beam size resolution
  - 50 micron multi-pass bunch by bunch vertical beam size resolution
- X-ray beam size monitor
  - Bunch by bunch 2-3 μm resolution
  - One each for electrons and positrons

X ray beam size monitor Concept



Point-to-point Imaging optics

detector

Arc dipole

monochromator

λ

Synchrotron Radiation ~ 1-10 keV

Damping ring

Machine parameters

DAQ

R

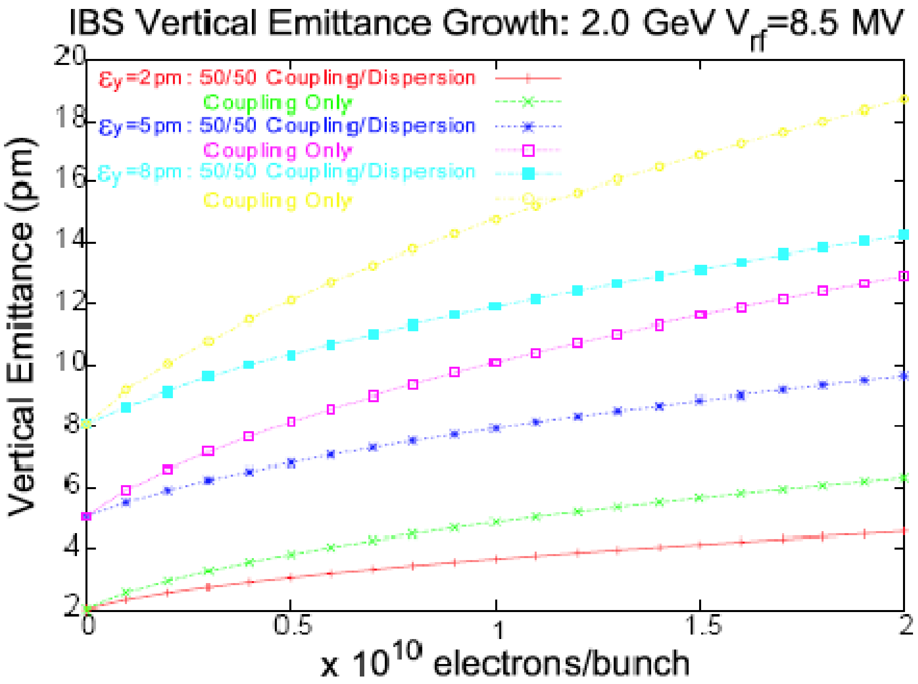
Feedback to operations, machine studies, simulations

Data Processing And analysis

Intensity dependent effects

- Emittance
  - Intrabeam scattering

Depends on amplitude and source (dispersion or coupling) of vertical emittance



IBS has strong energy dependence (~γ^4)
Flexibility of CESR optics to operate from1.5-5GeV will allow us to distinguish IBS from other emittance diluting effects.

Intensity dependent effects

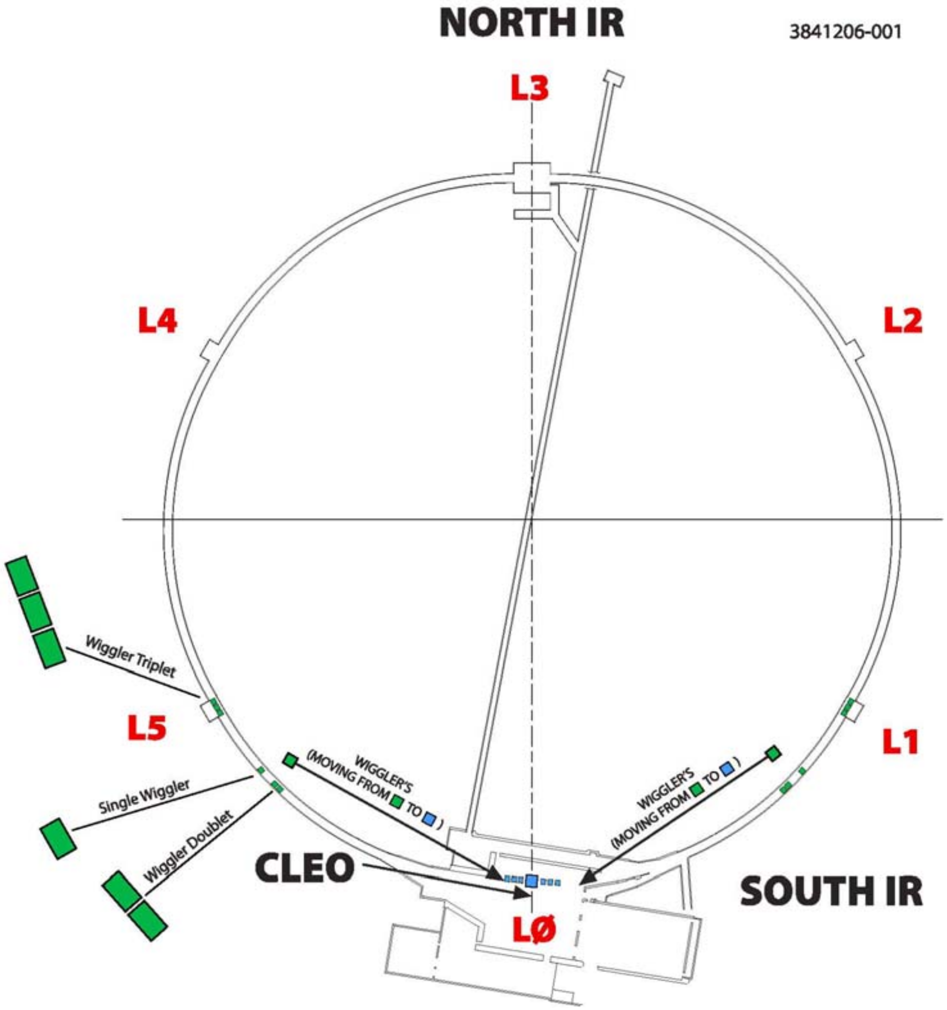
Lifetime

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

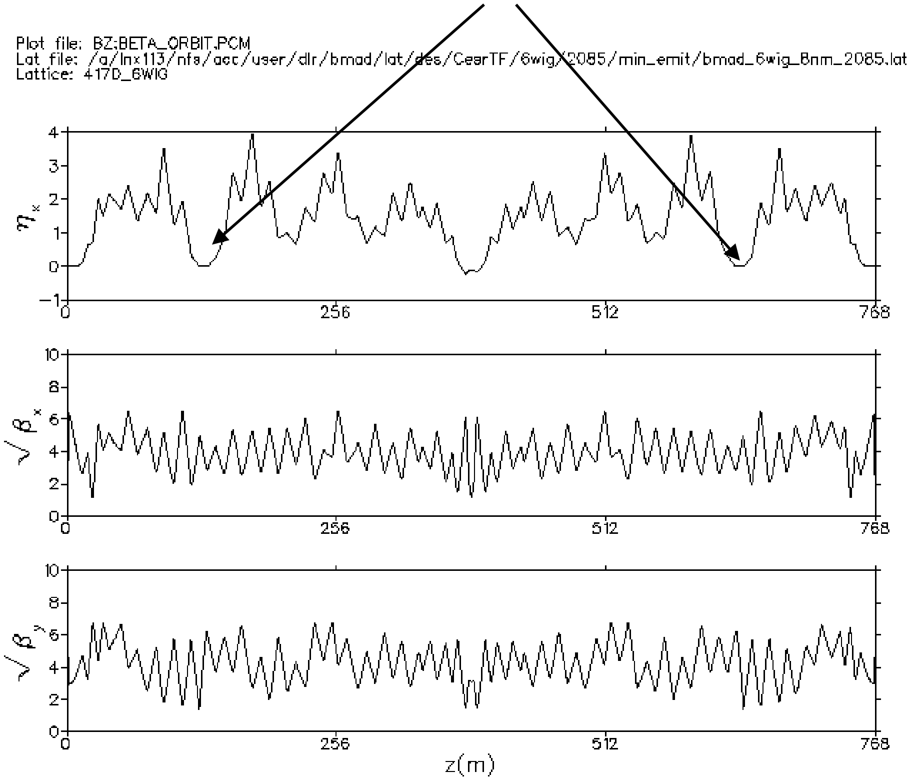
As we approach our target emittance of 5-10pm and 2×10^{10} particles/bunch $\tau_{Touschek}$ decreases to ~10 minutes.

Initial experiments with low emittance optics

- 6 Wiggler low emittance optics - $\sigma_h \sim 7.5$nm - 2.085GeV



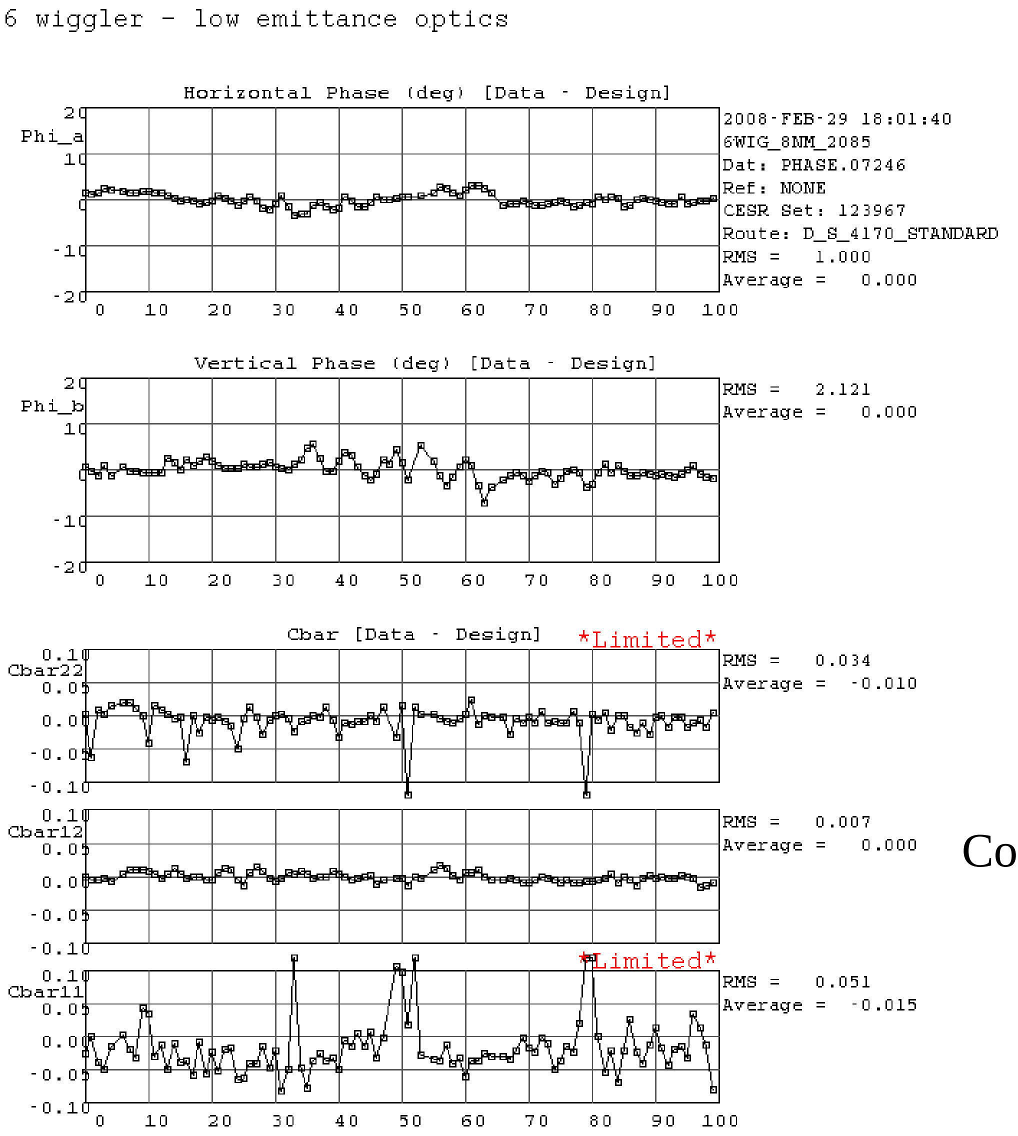
Wiggler triplet



```
Plot file: BZ:BETA_ORBIT.PCM
Lat file: /a/lnx113/nfs/acc/user/dlr/bmad/lat/des/CesrTF/6wig/2085/min_emit/bmad_6wig_8nm_2085.lat
Lattice: 417D_6WIG
```

Emittance tuning

- 6 wiggler optics
- ε_x~7.5nm

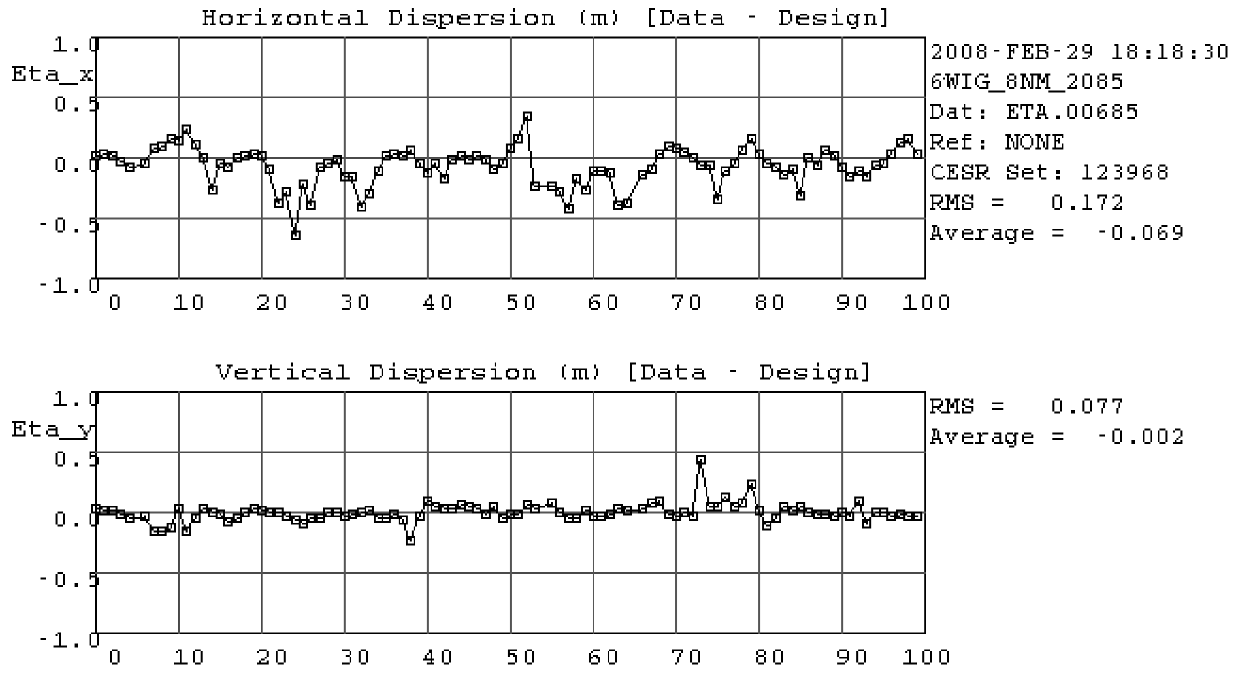

6 wiggler - low emittance optics

```
2008-FEB-29 18:01:40
6WIG_8NM_2085
Dat: PHASE.07246
Ref: NONE
CESR Set: 123967
Route: D_S_4170_STANDARD
RMS =    1.000
Average =    0.000
```

Coupling < 1%

Dispersion

6 wiggler, low emittance optics



```
2008-FEB-29 18:18:30
6WIG_8NM_2085
Dat: ETA.00685
Ref: NONE
CESR Set: 123968
RMS =    0.172
Average =  -0.069
```

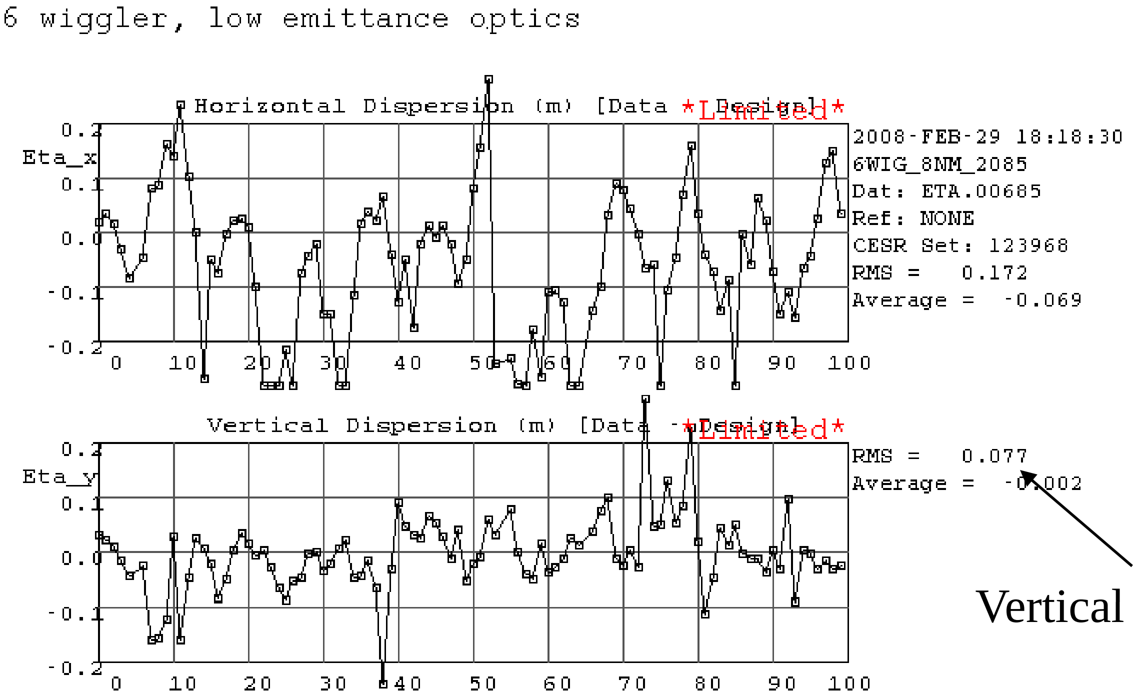
```
RMS =    0.077
Average =  -0.002
```

Wigglers are located between 18-19 and 80-81

Correction of horizontal dispersion is required

6 wiggler optics

- Dispersion



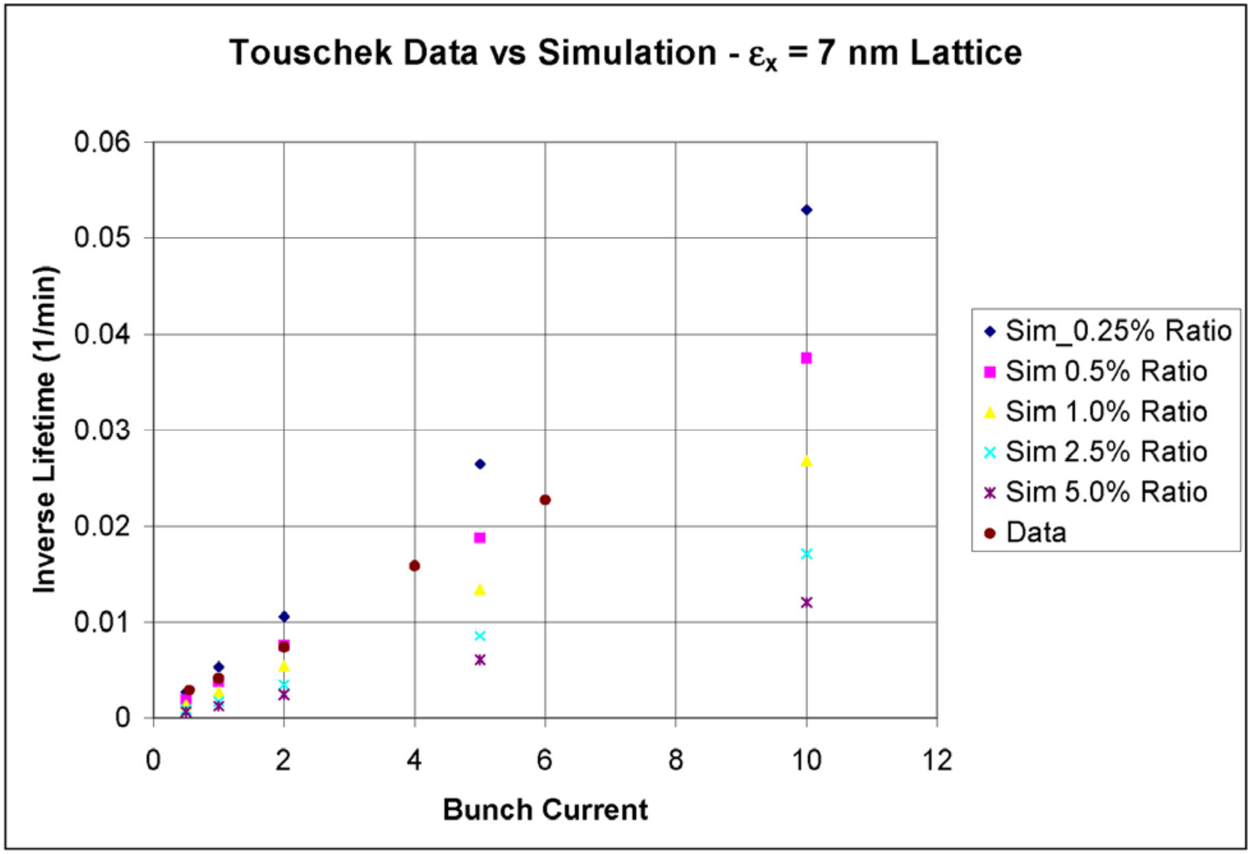
IR is primary source of vertical dispersion

Vertical dispersion

In order to achieve $\varepsilon_v < 5$pm, we require $\langle\sqrt{\eta^2}\rangle < 9$mm

Touschek Lifetime

6 wiggler, 1.89GeV optics

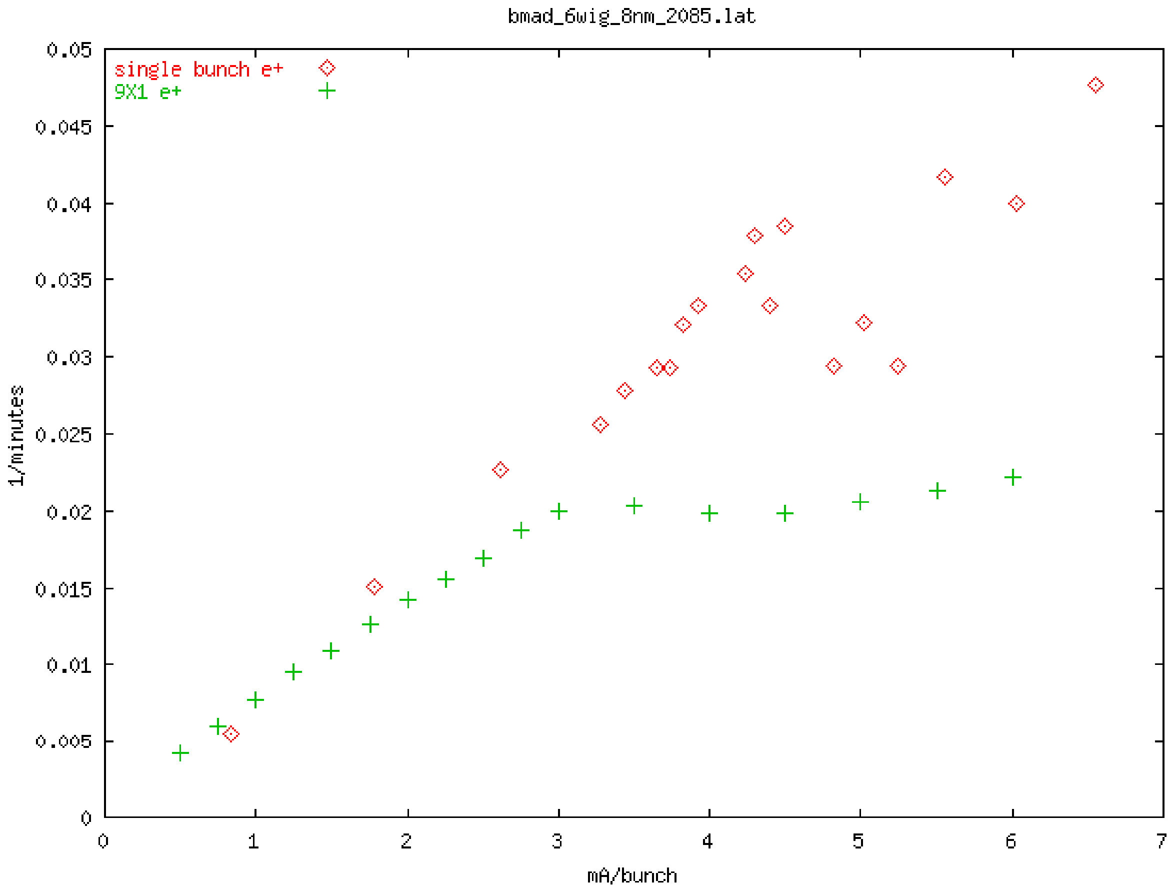


preliminary

11-September 2007

Lifetime

- Lifetime vs current - 6 wiggler low emit optics
- - ε_x~7.5nm
- 2.085GeV

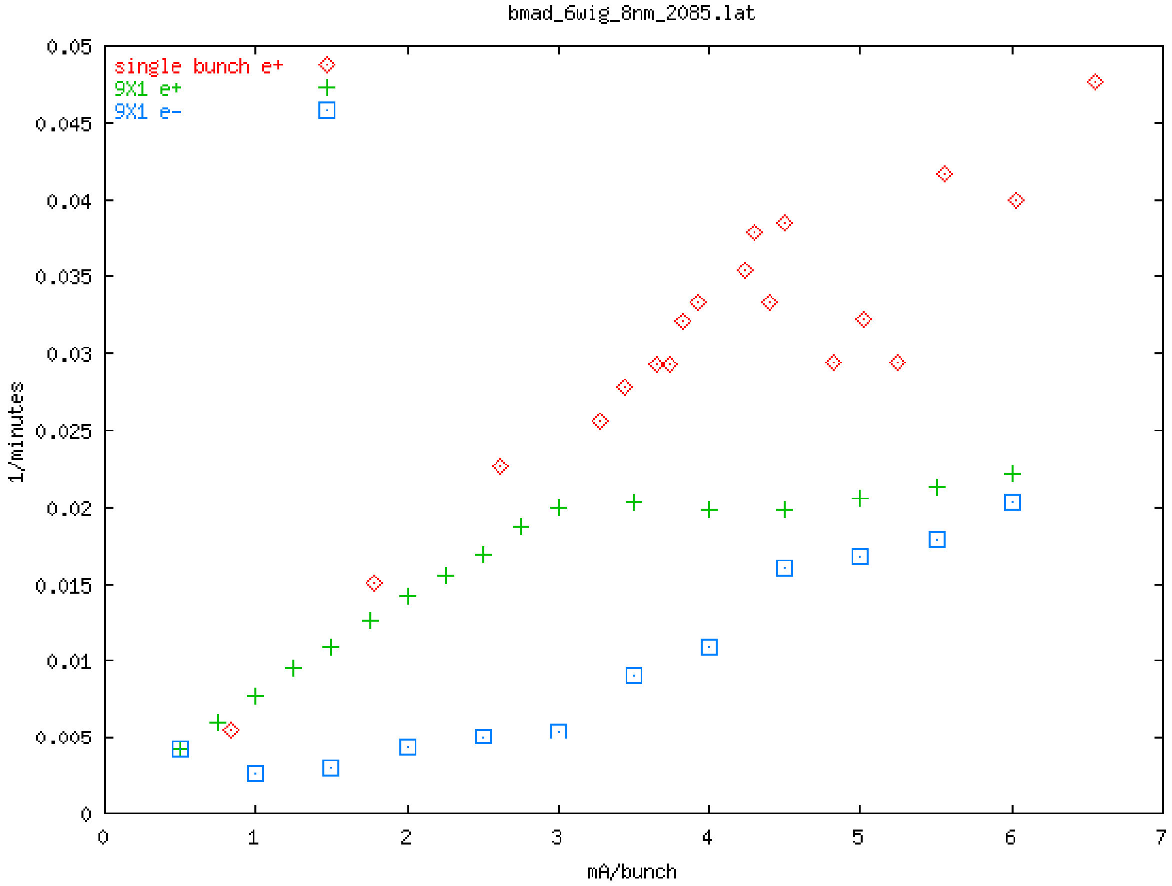


positrons

preliminary

29-february-2008

- Lifetime vs current - 6 wiggler low emit optics - ε_x~7.5nm



positrons
and
electrons

29-february-2008

Dispersion

- AC dispersion measurement

Dispersion is coupling of longitudinal and transverse motior

-Drive synchrotron oscillation by modulating RF at synch tune

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

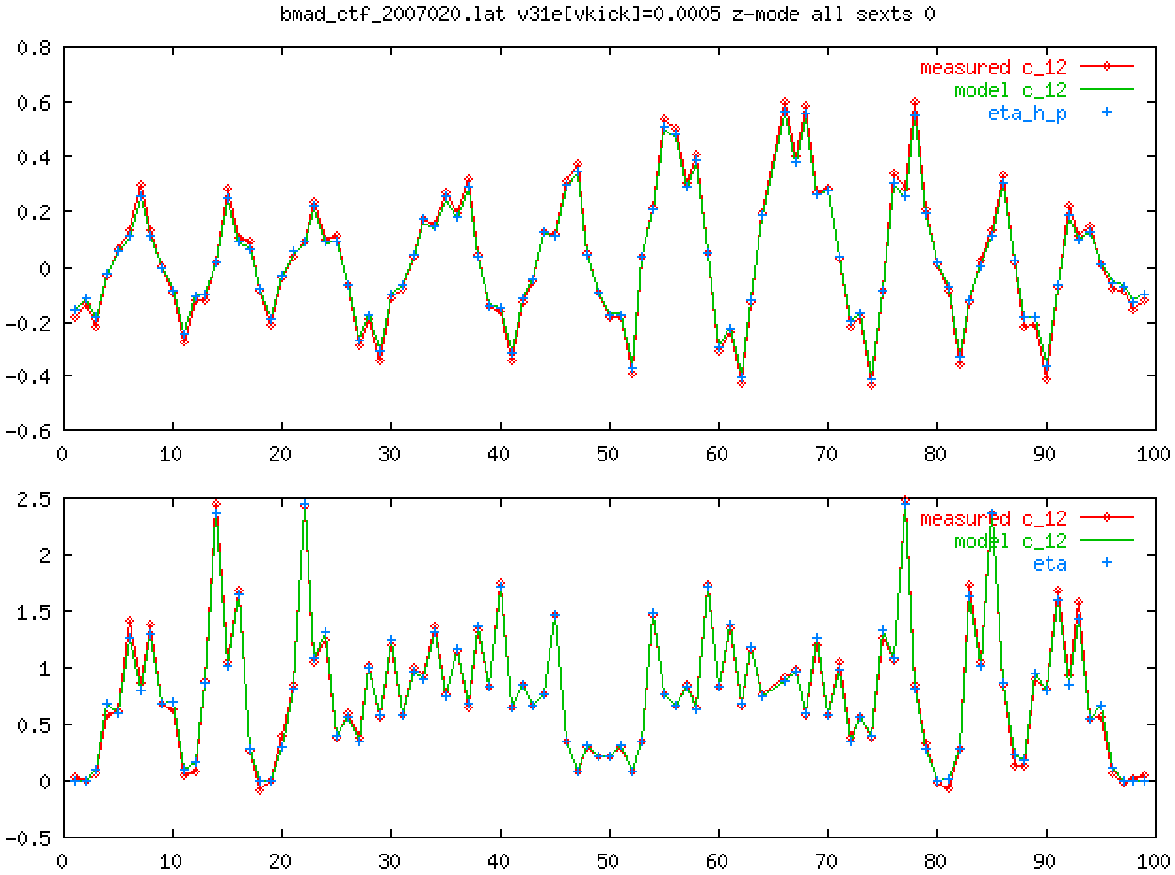
Then

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

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

Advantages:

1. Faster (30k turns)
2. Better signal to noise - filter all but signal at synch tune



"measured c_12" - 30k turn simulation
"model c_12" - Model y-z and x-z coupling
"model eta" - Model dispersion

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) / 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

Experimental program

- Cesr TA low emittance program
  - 2008
    - Install quad leveling and adjustment hardware

      new hardware simplifies alignment of quadrupoles
    - Extend turn by turn BPM capability to at large fraction of ring
    - Commission 2GeV 2.3nm optics [12 wigglers, CLEO solenoid off]

      Survey and alignment

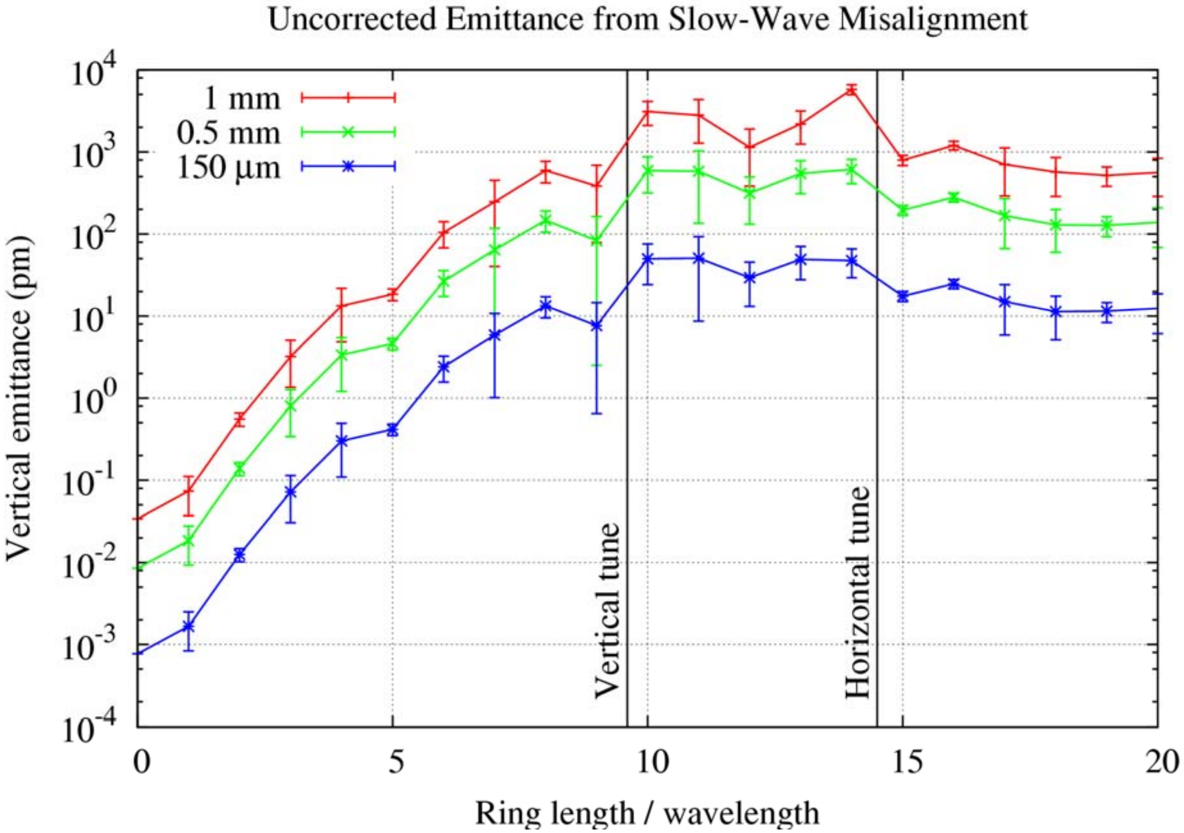
      Beam based low emittance tuning
    - Commission positron x-ray beam size monitor (~2μm resolution)
    - Install spherical survey targets and nests and learn to use laser tracker

      More efficient survey and alignment
  - 2009
    - Complete upgrade of BPMs

      Single pass measurement of orbit and dispersion
    - Commission electron x-ray beam size monitor
  - 2010
    - Complete program to achieve ultr-low emittance

Correlated misalignment

- Correlated misalignment - temperature dependence
  - Magnets move as tunnel warms with operation
  - Temperature change is not uniform - slowly varies along circumference
  - $(dy/dT)\Delta T < 30\mu m$



Slow wave

$\Delta y = A\sin(k_n s+\phi)$

$k_n=2\pi n/\text{circumference}$

A< 30µm, → ε< 1pm

Time dependence of survey

Is the survey stable?

Short time scale

- Measured quadrupole vibration amplitude at frequency > 2Hz is less than 1μm

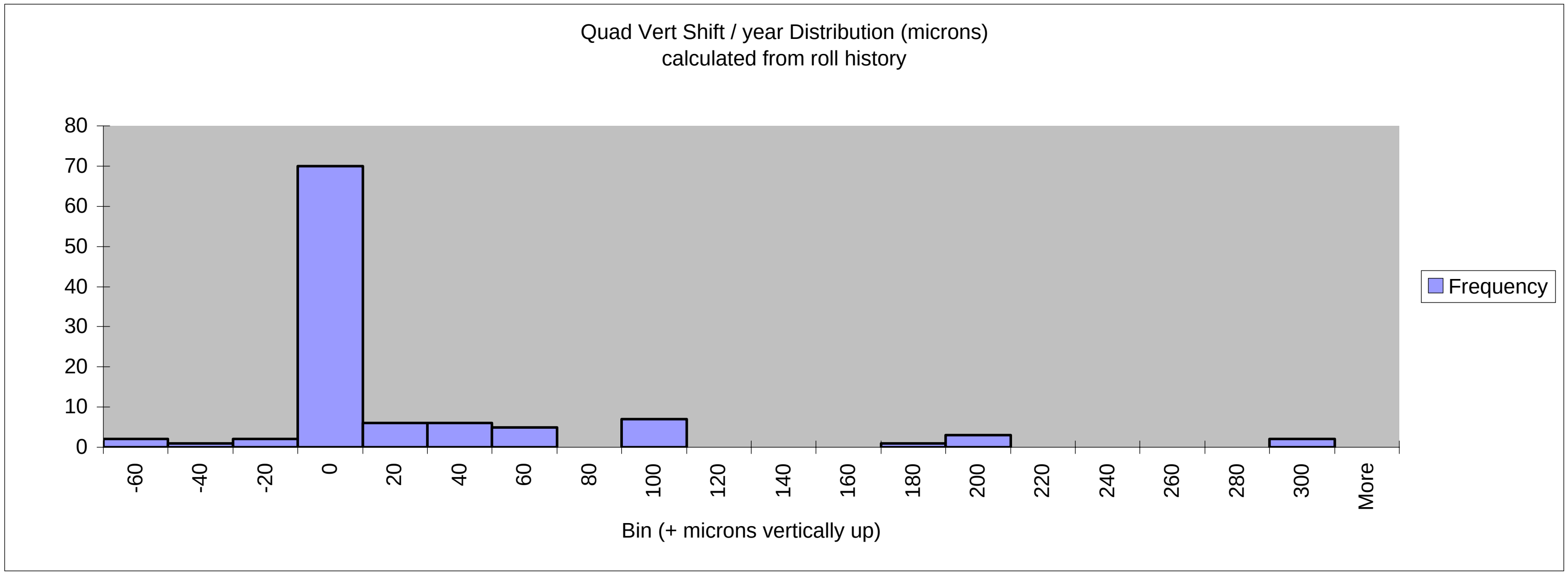
→ Corresponding to $\Delta\varepsilon_y \ll 2\text{pm}$

Element	Misalignment	$\langle\varepsilon_y\rangle = 2\text{pm}$	95% $\varepsilon_y < 2\text{pm}$
Quad	Vertical offset [μm]	19	13
Quad	tilt [μrad]	141	95
Sextupole	Vertical offset [μm]	147	101
Bend	tilt [μrad]	51	34
Wiggler	Vertical offset [μm]	183	111

Time dependence of survey

Is the survey stable?

Long time scale



For most quads *nominal* alignment (~150µm) is preserved for at least a year
A few magnet stands will have to be secured