STATUS OF LOW EMITTANCE TUNING AT CesrTA[*]

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Abstract

We report on the status of emittance tuning techniques at the CESR Test Accelerator (CesrTA). The CesrTA experimental program requires that we operate in a variety of machine lattices, each with the smallest possible emittance. We utilize high-bandwidth BPM electronics for fast, precision measurements of orbit, betatron phase, transverse coupling, and dispersion. Analysis of the data and implementation of corrections are completed in a few minutes. An x-ray beam size monitor (xBSM) capable of bunch-by-bunch, turn-by-turn measurements provides a real time check on the effectiveness of the procedure. The procedure typically yields an emittance less than 20pm at 2.1GeV in 1-2 iterations. We have achieved 6pm vertical emittance with adjustment of closed coupling/vertical dispersion bumps, betatron tunes, and modification of beta functions at the xBSM source point.

INTRODUCTION

Damping rings for linear colliders are required to deliver beams of electrons and positrons with ultra-low vertical emittance. Vertical emittance is generated when photons are radiated in regions of vertical dispersion. Damping rings by design have no bending in the vertical plane and therefore the sources of vertical dispersion are restricted to magnet misalignments and field errors. Clearly, precision survey and alignment of the magnetic guide field components is essential to minimize vertical emittance. Further refinement depends on beam-based measurements to identify remaining sources of vertical dispersion, and deployment of correctors to eliminate them. Ongoing survey and alignment has been performed on the 768m Cornell Electron Storage Ring (CESR) storage ring magnets. CESR has been equipped with precision high-bandwidth Beam Position Monitor (BPM) electronics with bunch-by-bunch, turn-by-turn capability for efficient beam-based measurement of orbit, betatron phase and coupling, and dispersion. Dipole and skew quadrupole corrector magnets are distributed throughout the machine and powered based on the analysis of measured lattice functions to minimize vertical dispersion, coupling, and vertical emittance. We have reproduced our emittance correction procedure in a computer model based on the BMAD accelerator simulation library [1] in order to further characterize and understand the corrections. We report on the status of our effort to minimize vertical emittance in CESR and the degree to which the measurements are in agreement with the model results.

MACHINE MODEL

Our simulation [2] is based on a machine model that includes all magnets, quadrupoles, dipoles, damping wigglers, sextupoles, correctors (skew quadrupoles, vertical and horizontal steerings), RF cavities and BPMs. All guide field magnetic elements can be arbitrarily misaligned. BPM absolute and differential measurement resolution and tilts can be specified.

The surveyed distributions of alignment errors are shown in Table 1. Misalignments in the simulation are based on those same distributions.

Table 1: Surveyed Magnet Alignment

Parameter	RMS
Quad tilt	120μm
Quad vertical offset	50μm
Dipole roll	100μrad
Sextupole vertical offset	250μm
Wiggler roll	200μm

BPM Resolution and Coupling

There are 100 BPMs in CESR available for optics measurement, distributed more or less uniformly around the circumference. The reproducibility of the measurement of the beam position is established by comparing multiple consecutive measurements to be within 10μm. We conclude that differential position resolution is 10μm. The absolute position resolution is based on the reproducibility of the quad centering method [3], and is taken to be 100μm.

Dispersion measurements are performed by resonantly exciting the beam longitudinally at the synchrotron tune. Typically this results in an energy oscillation with amplitude $\pm0.1\%$. The 10μm differential resolution then corresponds to an uncertainty of about 5mm in dispersion.
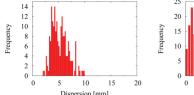
Low-Emittance Tuning Procedure

The Low-Emittance Tuning (LET) procedure is based on an iterative series of beam-based measurements and corrections. The procedure is as follows:

1. Measure orbit and correct using all 55 horizontal and 58 vertical steering correctors.

2. Measure betatron phase and transverse coupling by resonant excitation of normal mode tunes [6]. Correct betatron phase to the design using all 100 independently-powered quadrupoles, and minimize transverse coupling using 15 dedicated skew
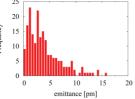
Figure 1: Vertical dispersion and emittance after low emittance tuning procedure for 200 machine configurations with alignment errors and measurement resolution described in the text.

quadrupoles and 12 skew-quad-like trim windings on sextupole magnets.

3. Remeasure orbit and transverse coupling, and measure dispersion by resonant excitation of the synchrotron tune. We extract the dispersion function from the measured amplitude and phase of the transverse motions at the synchrotron tune at each BPM. Simultaneously optimize to minimize orbit errors, transverse coupling and vertical dispersion using skew quadrupoles and vertical correctors and load the corrections.

4. Measure the beam size with X-Ray Beam Size Monitor (xBSM) [5] and convert to emittance by use of the fitted beta and dispersion functions at the source point.

Effectiveness of LET Procedure - Simulation

We simulate the low emittance tuning procedure by generating guide field configurations with a distribution of misalignments and measurement resolution as tabulated above. The distributions of vertical dispersion and emittance for 200 configurations after correction are shown in Figure 1. Typical correction levels in simulation are an RMS of 5mm vertical dispersion and emittance < 5pm.

EFFECTIVENESS OF LET PROCEDURE – MEASUREMENT

All emittance measurements reported here were made in the December 2010 CesrTA run, using the xBSM with a pinhole optic. Although more sophisticated optics (Fresnel Zone Plate and Coded Aperture) were available for use with the xBSM, robustness of fitting routines had not yet been established at the time of these measurements.

The measured image on the xBSM is a convolution of the finite source size σ_y with an effective finite pinhole height σ_p. Therefore, the vertical beam size in terms of the observed image height σ_{im} is $\sigma_y = \sqrt{(\sigma_{im}/M)^2 - \sigma_p^2}$, with $M = 2.39$ being the magnification of the pinhole, defined as the ratio of distances image-to-optic over optic-to-source.

This is used to calculate the emittance in the usual way:

Beam Dynamics and EM Fields

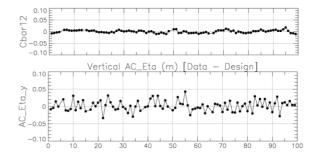**Dynamics 01: Beam Optics (lattices, correction, transport)**

Figure 2: Measured coupling and vertical dispersion after low-emittance tuning. Horizontal axis is BPM index. RMS Cbar12 = 0.006, RMS vertical dispersion = 15mm.

$$\epsilon_y = \frac{\sigma_y{}^2 - \left(\eta_y \frac{\delta_E}{E}\right)^2}{\beta_y} \quad (1)$$

where η_y is the vertical dispersion at the source point, and $\delta_E/E = 8.125 \times 10^{-3}$ is the energy spread.

Emittance was minimized using the procedure previously described. A tune scan was performed by varying the horizontal and vertical tunes over a grid and sampling the turn-by-turn vertical beam size at each point. From the tune scan we found the working point $Q_x = 14.584$, $Q_y = 9.636$ produced consistently small beam size. Additionally, to remain above the resolution of the pinhole optic of $19\mu m$, the vertical beta at the xBSM source was increased from 16.8m to 40m. Although this also increases the vertical dispersion at the source, we find that we are able to correct the local dispersion to the same levels independent of β. Therefore, increasing β_y at the source has the added benefit of decreasing the fractional contribution of the local dispersion at the xBSM source point to the beam size.

After the lattice optics are corrected, the low-emittance tuning procedure was repeated. Then closed coupling and dispersion bumps that include the xBSM source point were varied to minimize the measured beam size. Residuals of the measured betatron phase, coupling, dispersion and vertical emittance at the conclusion of the emittance minimization procedure are summarized in table (2).

Table 2: Correction Levels after Iterating LET Correction Procedure

Parameter	RMS
RMS Betatron Phase Error	1.2 deg
RMS Beta Beat	0.22%
RMS Betatron Coupling ($\bar{C}_{12}$)	0.006
RMS Vertical Dispersion	14mm
Vertical Emittance ϵ_y	6.0pm

The measured transverse coupling and vertical dispersion after correction are shown in Figure 2.

SOURCES OF UNCERTAINTY

Fully stating our expression for the emittance:

$$\epsilon_y = \frac{\left(\frac{\sigma_{im}^2}{M^2} - \sigma_p^2\right) - \left(\eta_y \frac{\delta_E}{E}\right)^2}{\beta_y} \quad (2)$$

The uncertainties in η_y and β_y are defined as the RMS residual between measurement and fitted model. M, η_y, and β_y depend on the longitudinal position s, which is taken to be a systematic uncertainty. The longitudinal dependence of the Twiss parameters is estimated as linear, and the magnification $M(s) = \frac{9.6}{4-s}$. We assume that the magnification, pinhole gap σ_p, and energy spread δ_E/E have no random uncertainties.

Consider the statistical and systematic contributions to $\delta\epsilon_y$ separately:

$$\delta\epsilon_y^{stat} = \sqrt{\left|\frac{\partial\epsilon_y}{\partial\beta_y}\right|^2 \delta\beta_y^2 + \left|\frac{\partial\epsilon_y}{\partial\eta_y}\right|^2 \delta\eta_y^2 + \left|\frac{\partial\epsilon_y}{\partial\sigma_{im}}\right|^2 \delta\sigma_{im}^2}$$

$$\delta\epsilon_y^{sys} = \left|\frac{d\epsilon_y}{d\sigma_p}\right|\delta\sigma_p + \left|\frac{d\epsilon_y}{ds}\right|\delta s \quad (3)$$

where

$$\left|\frac{d\epsilon_y}{ds}\right| = \left|\frac{\partial\epsilon_y}{\partial\beta_y}\frac{\partial\beta_y}{\partial s} + \frac{\partial\epsilon_y}{\partial\eta_y}\frac{\partial\eta_y}{\partial s} + \frac{\partial\epsilon_y}{\partial M}\frac{\partial M}{\partial s}\right| \quad (4)$$

The uncertainties in equation (4) are all linearly dependent on s, therefore we use their linear sum. Systematic errors add linearly (rather than in quadrature). $\partial\beta_y/\partial s$ and $\partial\eta_y/\partial s$ are estimated from phase and dispersion measurements taken in the same machine conditions as the recorded beam size measurement.

A model of the ring optics is fitted to the measured betatron phase. We use the model to compute local values of β and η and their derivatives.

Table (3) summarizes parameters associated with the reported emittance measurement, and their uncertainties.

Table 3: Parameter Values and Uncertainties used for Calculating Uncertainty in Beamsize Measurement

Parameter	Value
σ_{im}	$59.4 \pm 4.5\ \mu m$
σ_p	$19 \pm 2.0\ \mu m$
M	2.39
β_y	41.3 ± 2.0 m
η_y	3.7 ± 14 mm
$\partial\beta_y/\partial s$	-6.4 m/m
$\partial\eta_y/\partial s$	-2.58×10^{-4} m/m
$\partial M/\partial s$	0.6/m
δs	± 0.15m
σ_E/E	8.125×10^{-4}

Using the fitted values in table (3) for the parameters in equation (2) and computing uncertainties using equations (3), we have:

$$\epsilon_y = 6.0\ \text{pm}$$
$$\delta\epsilon_y^{stat} = \begin{cases} +2.3\ \text{pm} \\ -5.3\ \text{pm} \end{cases}$$
$$\delta\epsilon_y^{sys} = \pm 2.8\ \text{pm}$$

The upper and lower statistical uncertainties differ because $\delta\eta_y > \eta_y$, and ϵ_y is maximal when $\eta_y - \delta\eta_y = 0$.

CONCLUSION AND FUTURE PLANS

Comparing the transverse coupling, vertical dispersion and emittance that we achieve with the low emittance tuning procedure in measurement and simulation, we find the measurements are somewhat larger than predicted by the simulation. We suspect the discrepancy is due in part to systematic uncertainty in BPM electrode gains and BPM tilts. We have developed techniques for measuring the relative BPM electrode gains [4] and physical BPM tilts but have yet to incorporate those corrections as part of standard emittance minimization. We have demonstrated measurement of BPM button electrode gains to within one percent and BPM tilts to 6mrad. This will allow for measurement of vertical dispersion with resolution of better than 10mm. These BPM calibrations will be incorporated as part of the tuning procedure in the next CesrTA run.

Additionally, fitting routines for analyzing Coded Aperture and Fresnel Zone Plate images with the xBSM will be tested during the next CesrTA run. These alternative x-ray optics will permit measurement of sub $19\mu m$ beam size and provide redundant cross-checks of the beam size measurements.

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