CesrTA Low-Emittance Tuning - First Results*

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Abstract

The Cornell Electron Storage Ring has been reconfigured as a test accelerator (CesrTA) for damping ring R&D for the International Linear Collider (ILC). As part of the research effort, low emittance tuning techniques are being developed with a goal of achieving a vertical emittance approaching that of the ILC damping rings. These techniques include gain mapping to characterize beam position monitor (BPM) electrode gains, orbit response analysis to determine BPM button misalignments, betatron phase and coupling measurements to characterize optical errors, and orbit and dispersion measurements to locate sources of vertical dispersion. We are also investigating a fast, minimally-invasive dispersion measurement technique. Additionally, an x-ray beam size monitor is being deployed that will allow us to monitor vertical emittance in real time.

INTRODUCTION

One of the primary goals of the CesrTA project is to reduce the vertical emittance to less than 20pm. This requires that field and alignment errors be minimized, and that vertical dispersion and transverse coupling be measured with sufficient accuracy to identify and eliminate local sources. To this end, new beam position monitor (BPM) system is being installed which will allow us to make differential position measurements with a resolution of 10 microns [1].

Several correction techniques are being explored to help achieve this goal: 1) Beam based calibration of BPM electrode gains; 2) Correct the orbit using steering magnets; 3) Measure by resonant excitation the betatron phase and transverse coupling, and correct using quadrupoles and skew quadrupoles; 4) Measure BPM misalignments including tilts, using Orbit Response Matrix (ORM) analysis; and 5) Measure and correct vertical dispersion using vertical steerings and skew quadrupoles. We intend to use an iterative process, where upon completion of 5 we return to 2.

BPM BUTTON GAIN MAPPING

We are developing a new method of determining BPM electrode gains. This method, called gain mapping, has been successfully implemented at the Accelerator Test Facility (ATF) [2].

By varying steering strengths, we measure the response of each of the four buttons on each BPM for a set of trajectories that spans an approximately 20mm X 10mm grid. The button measurements are converted to (x, y) positions based on solving the 2D Poisson equation [3]. Using this method, a 10-micron uncertainty in position corresponds to a button gain uncertainty of 0.06%.

For every measurement at a four-button BPM, there are five known values (the button response and the beam current), and two unknown values ({x,y} position). In addition, the gains of the four buttons are considered unknown. Therefore, for N measurements there are $4N$ equations and $4 + 2N$ unknowns.

The analysis consists of minimizing χ^2 between model and data button values b:

$$\chi^2 = \sum_{i,j} (b_{ij}^{(meas)} - b_{ij}^{(model)})^2, \quad (1)$$

$$b_{ij}^{(model)} = g_i \cdot I_j \cdot F_i(x_j, y_j) \quad (2)$$

where the sum is over $i = 1, \ldots, 4$ buttons for $j = 1, \ldots, N$ measurements at a given BPM; g_i is the gain of the i^{th} button; I_j is the current of the j^{th} measurement; and $F_i(x_j, y_j)$ is the response function of each button.

To demonstrate the efficacy of this method, the analysis was performed on a data set of 30 orbits using the present BPM electronics. The quality of the fit was determined by considering a "goodness of fit" parameter defined by

$$\sigma_i^2 = \frac{1}{N} \sum_j ((b_{ij}^{(meas)} - b_{ij}^{(model)})/b_{ij}^{(meas)})^2$$

For this paper, we present the results for a sample of BPMs that fit well. These results are summarized in Table 1. The fitted gains of these BPMs are all within 10% of unity.

The best σ_i values in this test are on order of $\sim 0.7\%$. From other analysis techniques we believe the resolution of the current BPM system is about 35 microns, corresponding to a 0.2% gain uncertainty. We are investigating several possible sources for the large residuals, including: inaccuracies in the Poisson calculation; orbit data spanning an insufficient cross-section at all BPMs; and poor reproducibility with current BPM electronics.

BPM	σ_i for each button
14	{0.69%, 0.78%, 0.73%, 0.79%}
15	{0.70%, 0.64%, 1.01%, 0.92%}
43	{0.76%, 0.69%, 1.19%, 1.15%}
93	{0.87%, 0.86%, 0.82%, 0.89%}

Table 1: Residuals in fitted button gains.

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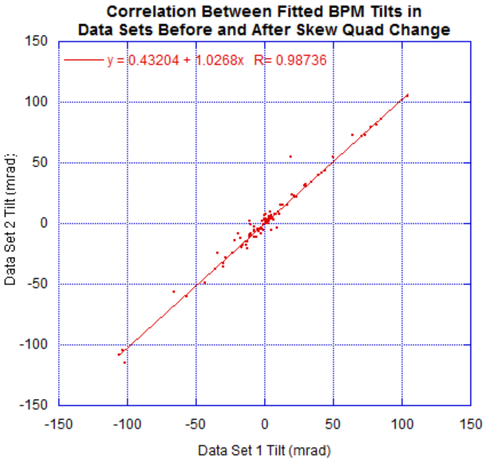

Figure 1: Correlation between BPM tilt fits in both ORM data sets. The two sets of tilt values agree with an RMS difference of 5.7 mrad.

BETATRON PHASE AND COUPLING

By measuring the phase and amplitude response at each BPM of a resonantly excited beam at the horizontal and vertical tunes, the betatron phase advance and horizontal/vertical coupling are determined [4]. A machine model is to the measured data by varying the model quadrupole and skew quadrupole strengths. All 100 quadrupoles in CESR are independently powered, as are the 14 skew quad correctors. The betatron phase can typically be corrected to an RMS of $1\ \mathrm{deg}$ (equivalent to correcting β functions to within 2% RMS), and horizontal/vertical coupling $\langle \bar{C}_{12}^2 \rangle^{1/2} < 1\%$. Since $\epsilon_y/\epsilon_x \sim \langle \bar{C}_{12}^2 \rangle$, in the CesrTA lattice an RMS of 1.5% coupling corresponds to a vertical emittance of roughly 1pm.

ORBIT RESPONSE ANALYSIS

Orbit Response Matrix (ORM) analysis is used to measure beam position monitor misalignment. In order to achieve our vertical emittance target, residual vertical dispersion must be less than $\sim 1\ \mathrm{cm}$. Typical horizontal dispersion in the CesrTA optics is 1m. Therefore, BPM tilts must be measured to an accuracy better than $10\ \mathrm{mrad}$. The CESR beam position monitor consists of a top block and a bottom block, each with a pair of button electrodes. When mounted on a vacuum chamber, there is the possibility that the top block is horizontally displaced with respect to the bottom block, a condition that we refer to as shear. In order to account for this possibility, BPM misalignments are modeled by a combination of a rotation (tilt) and a shear, or as a tilt and a crunch, with the crunch defined by:

$$\begin{pmatrix} x_m \\ y_m \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \qquad (3)$$

where θ_c is the crunch angle.

In order to investigate the effectiveness of the ORM technique, two consecutive ORM data sets were acquired. Each data set consisted of 115 difference orbits generated by varying steering corrector magnets. Before the second set, eight skew quadrupoles were changed to produce a known difference in the lattice.

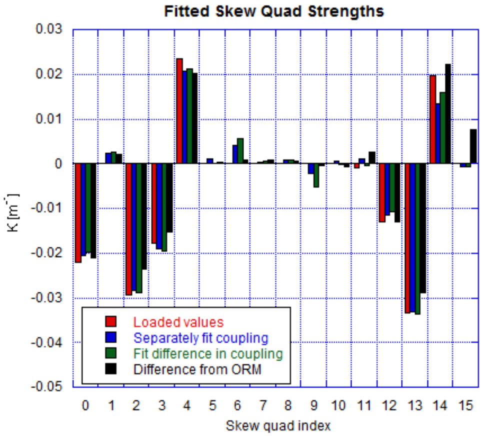

Figure 2: Comparing skew quad strengths from saved values in the machine, fitting coupling data, and from fitting ORM orbit data.

The ORM analysis uses the Bmad library for modeling [5]. In addition to ORM orbit data, the analysis program allows for inclusion of other data types such as dispersion, coupling, and phase, as well as providing a wide range of fitting parameters (such as magnet strengths, BPM misalignments, etc.). In this analysis, we first fit against the source kick for the orbit difference, then skew quadrupole strengths, and finally BPM tilts.

The correlation of fitted BPM tilts for the two data sets is shown Figure 1. This corresponds to an RMS difference of 5.7 mrad between the two fits. When BPM crunch is fitted simultaneously with BPM tilt, the fits agree within 8.3 mrad. Both are consistent with a 35-micron resolution, and below our 10 mrad target.

A coupling measurement, using resonant excitation, was taken with each ORM data set. We fit the difference between the two coupling measurements using all 14 skew quads as variables and compared this to the fitted skew quad strengths from the ORM analysis, as shown in Figure 2. The results of the fits to the coupling and ORM data are in good agreement.

AC DISPERSION

An RMS vertical dispersion η_y of 1cm corresponds roughly to a vertical emittance of 15pm. Sources of vertical dispersion include vertical offsets in quadrupoles, coupling due to offsets in sextupoles and quadrupole tilts, and vertical kicks from dipole rolls.

At present, our most precise dispersion measurement is based on the traditional technique of measuring the displacement due to a change in energy. The energy change is achieved by varying the RF cavity frequency. Drawbacks to this technique are that it is time consuming to vary the

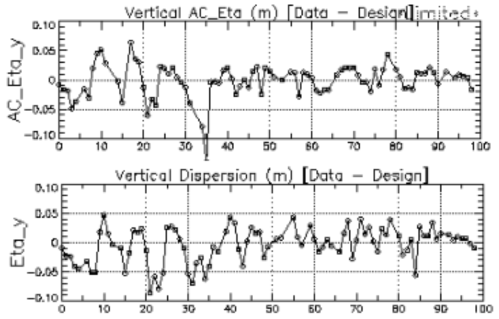

Figure 3: Top: New AC dispersion measurement. Bottom: Standard dispersion measurement.

RF frequency, there is significant risk of beam loss, and lattice nonlinearities can compromise the measurement.

We are exploring an alternative technique for measuring dispersion based on resonant excitation of the synchrotron tune. Measurement of the phase and amplitude at each BPM yields the horizontal and vertical dispersion. Dispersion measurements made by the traditional orbit difference method and by the resonant excitation (AC) method are shown in Figure 3. The AC method is advantageous since it is fast, there is minimal risk of beam loss, and the measurement is linear. Our existing BPM electronics do not provide precise normalization of the measured amplitude, thus limiting the quality of the AC method. We anticipate a significant improvement in the accuracy of the AC method with the implementation of the new BPM system.

LOW EMITTANCE TUNING

We corrected orbit, coupling, betatron phase and dispersion using the following method. We measured and corrected the orbit, then betatron phase and coupling. We then measured vertical dispersion and remeasured orbit and coupling, and fit simultaneously using vertical correctors and skew quadrupoles.

A coupling of less than 1% was achieved, as shown in Figure 5. Similarly, Figure 4 shows an RMS η_y of 2.4cm. Further analysis showed that the residual η_y cannot be fit with a localized source, indicating that the dispersion was corrected to our present measurement resolution.

Using the x-ray beam size monitor (xBSM) [6], we measured the vertical emittance to be 35pm. This is consistent with an RMS η_y of 1.7cm, which is comparable to our measurement.

CONCLUSIONS

To date, our low emittance tuning techniques have yielded a vertical emittance of 35pm. Our ability to correct vertical dispersion and measure BPM tilts is limited by the precision of the existing BPM system, which is in the process of being upgraded. We believe the principle source of our vertical emittance is residual vertical dispersion. Our measured coupling indicates that its contribution to vertical emittance is negligible.

We have developed the machinery for gain mapping as a technique to characterize BPM button gains. We are continuing to investigate sources of the large residuals between our data and model.

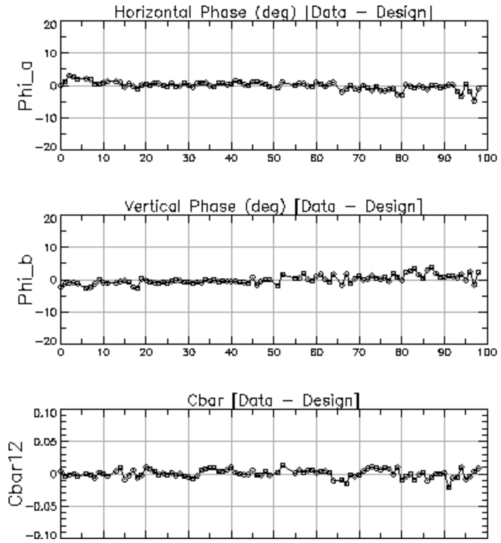

Figure 4: Residual betatron phase and coupling after loading corrections. RMS residual phase is $< 1.5\,\mathrm{deg}$ in both horizontal and vertical. Residual coupling is $< 1\%$.

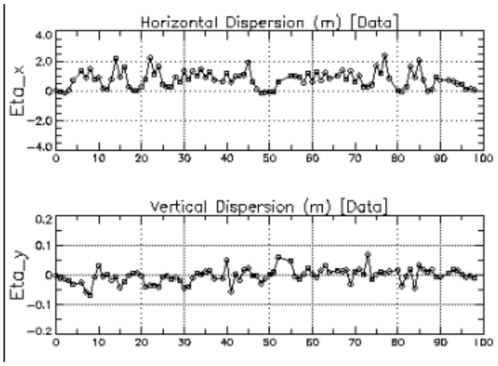

Figure 5: Residual vertical dispersion after correction.

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