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OPTICS CHARACTERIZATION AND CORRECTION AT PEP-II*

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Abstract

The linear optics of both the high energy ring (HER) and low energy ring (LER) for SLAC's PEP-II B-Factory were characterized with two algorithms: analysis of the measured closed orbit response matrix and analysis of betatron phase advance measurements. The results of the two analyses were in good agreement. When the HER was first run in a low β optics in autumn 1997, the measured β functions showed more than a factor of two discrepancy from the design. The source of the optics distortion was diagnosed and corrected using these methods.

1 INTRODUCTION

The PEP-II collider consists of two storage rings - a high energy ring (HER) for 9 GeV electrons and a low energy ring (LER) for 3 GeV positrons. The storage rings are each 2.2 km long, and they intersect at a single interaction point (IP) to produce collisions for high energy physics experiments.

In order to maximize luminosity, the LER and HER optics were designed with small β functions at the IP. When the HER was first commissioned in this low β optics during the autumn of 1997, the measured β_y showed a large discrepancy from the design model. Fig. 1 compares the measured and design model β_y in the region of the ring ± 60 meters from the IP. The beam size is large in the final focus doublet (QD4 and QF5), and the beam is focused tightly at the IP. The measured β_y data points were generated by measuring the tune shifts, $\Delta\nu_y$, from small changes in integrated quadrupole gradients, ΔKL.

$$\beta_y = 4\pi \frac{\Delta\nu_y}{\Delta KL} \quad (1)$$

The measured β_y differed by as much as a factor of 2.5 from the design model. The error in β_y was seen throughout the ring. The measured β_x agreed much better with the design.

Two methods were applied to investigate the source of this optics distortion - analysis of the measured closed orbit response matrix, and analysis of betatron phases determined using turn-by-turn measurements of betatron oscillations.

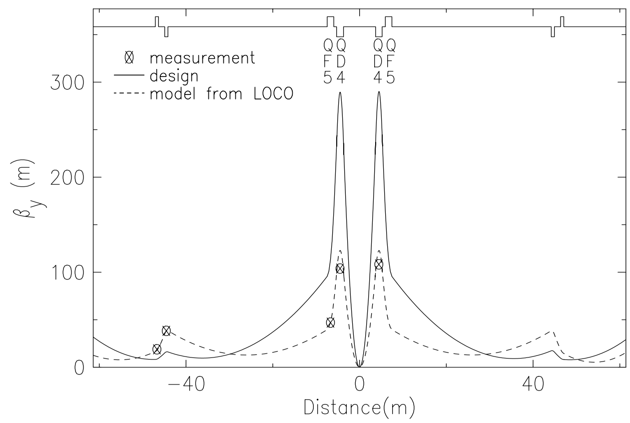

Figure 1: The β_y measured at quadrupoles compared to the design and to the model fit by LOCO. The IP is at the center of the graph.

2 LOCO FOR HER

2.1 Method

The closed orbit response matrix is the shift in orbit at each BPM for a change in strength of each steering magnet. The HER has 144 horizontal and 143 vertical steering magnets with about 150 horizontal and 150 vertical BPMs, so the HER orbit response matrix has more than 40,000 data points. Differences between the model and measured response matrix can arise from quadrupole gradient errors, BPM gain errors, and steering magnet calibrations errors.

The computer code LOCO[1] (Linear Optics from Closed Orbits) was used to vary the quadrupole gradients, BPM gains, and steering magnet calibrations in a computer model of the HER to minimize the χ^2 difference between the model and measured response matrices. In total about 770 parameters were varied to fit the model to the 40,000 measured data.

The HER has about 300 quadrupoles. The number of BPMs in the ring and the accuracy of the BPM measurements are not sufficient to accurately calibrate the gradient in each of these quadrupoles independently. For this reason it was assumed that all quadrupoles driven by the same power supply had the same gradient. Also the gradients of the two QD4's as well as the two QF5's were assumed to be the same, even though each of these quadrupoles are powered with its own supply. In total this gave 68 families of

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quadrupoles varied.

The β_y for the model fit to the response matrix is included in Fig. 1. The prediction of the measured β_y is greatly improved. The fit model also accurately reproduced the measured β_x. The difference between the fit and design model gradients, ΔK, is plotted as a function of position around the ring in Fig. 2 for all 300 HER quadrupoles. Rather than simply plotting ΔK, the plot shows $\beta_y \Delta KL$, the integrated quadrupole gradient error multiplied by β_y at each quadrupole. $\beta_y \Delta KL$ is the contribution to β_y distortion from each quadrupole gradient error. (The β_y distortion from a single quadrupole gradient error, ΔKL, is[2]

$$\frac{\Delta\beta_y(s)}{\beta_y(s)} = \beta_y(s_0)\Delta KL \frac{\cos 2[|\phi(\mathrm{s}) - \phi(\mathrm{s_0})| - \pi\nu]}{2\sin 2\pi\nu}, \quad (2)$$

where the quadrupole is at position s_0.) The LOCO fit indicated that errors in the IP doublet quadrupoles, QD4 and QF5, drove nearly all of the β_y distortion.

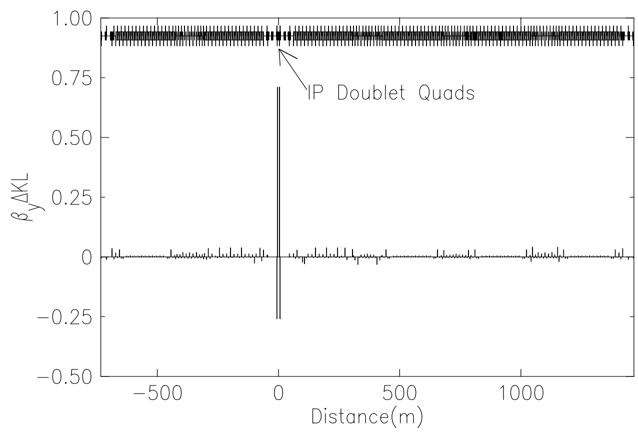

Figure 2: The magnitude of the driving term for β_y distortion as a function of position around the ring according to the LOCO fit.

2.2 Error Analysis

Once LOCO had converged to find the model with the best statistical fit to the data, the rms difference between the measured and model response matrices was 88 μm horizontal and 32 μm vertical. The accuracy of the fit was considerably worse than the noise level of the closed orbit measurements (4 μm), presumably due to systematic errors associated with gradients from horizontal orbit offsets in sextupoles as well as variation in gradients of quadrupoles powered by the same power supply. The steering magnet kicks used to measure the response matrix gave rms orbit shifts of 1.7 mm, so the model orbit shifts fit the measured shifts to 5% and 2% horizontally and vertically.

Figure 3 shows the error bars for Fig. 2 from the 4 μm random BPM measurement error. The error bars were calculated analytically assuming a normal measurement error distribution. The error bars are quite small, indicating the quadrupoles on individual supplies around the IP can be calibrated to about 1 part in 10,000., and the QD and QF quadrupoles in the arcs with many magnets on one supply can be calibrated to 5 parts in a million. Of course, with systematic errors included, the error bars are much larger. (Not to mention that the QD and QF power supplies are not even stable to this level.)

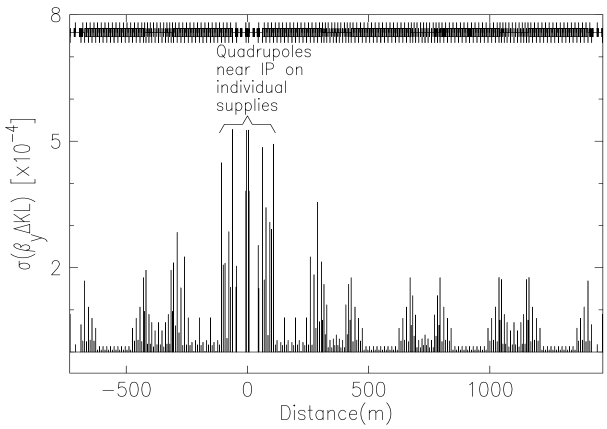

Figure 3: The error bars for Fig. 2 due to the random 4 μm BPM measurement error.

Nonetheless, Fig. 3 is useful in demonstrating that the expected error bars on $\beta_y \Delta KL$ for quadrupoles on individual supplies tend to be the same order of magnitude from quadrupole to quadrupole. In other words, QD4 and QF5 sticking out like sore thumbs in Fig. 2 indicates a real problem with these quadrupoles, not just uncertainty in the fit parameters.

2.3 Optics Correction

Starting from the fit optics model and reducing QD4 and QF4 by .60% and .49% restored the optics to the design. QD4 and QF5 were reduced in the ring, and measurements confirmed that the design optics were restored. No good explanation of the gradient errors was found. It was noted that longitudinal displacement of the IP doublets 3 cm closer to the IP would give nearly the same optics distortion as the strength errors. Measurements of the quadrupole positions indicated no such large position errors.

When the IP was rebuilt during the installation of the LER, the effective error in the IP doublet strengths was greatly diminished, to about 0.13%.

3 PHASE FITTING

Using buffered data acquisition of Beam Position Monitor (BPM) data, which records beam position for 1024 consecutive turns, the relative phase of the betatron motion between the BPMs may be found. The phase fitting is now available on-line [4]. Because of beta function mismatch, this phase will be different from the ideal (model) phase between the BPMs. It is possible to fit this phase error using errors in the strength of quadrupole families as the fitting variable. We used the program LEGO [5] as the fitting code.

The results obtained by such fitting were consistent with the LOCO results. The whole table of quadrupole gradient errors showed some correlation between the two methods but was conclusive only when the beta functions were taken into account. The comparison between the errors found by the two methods is given in Table 1.

Table 1: Comparison of results obtained by LOCO and phase fitting method

	phase fit results	LOCO results
QD	0.20	0.18
QF	-0.04	-0.04
QD4	0.55	0.60
QF5	0.69	0.49

Figures 4 and 5, and show the measured phase differences before the fitting.

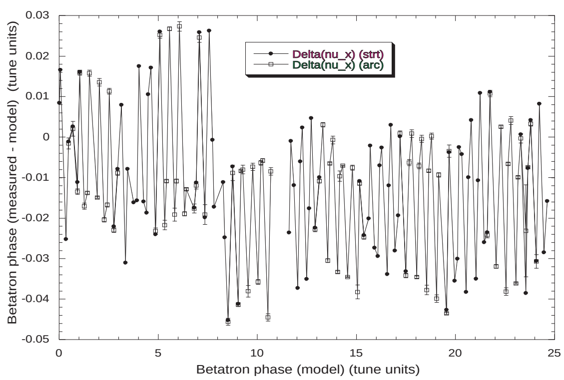

Figure 4: Error in the horizontal betatron phase. The phase error (measured - model) is plotted as a function of horizontal phase advance. The phase is in tune units i.e. $\mu/2\pi$.

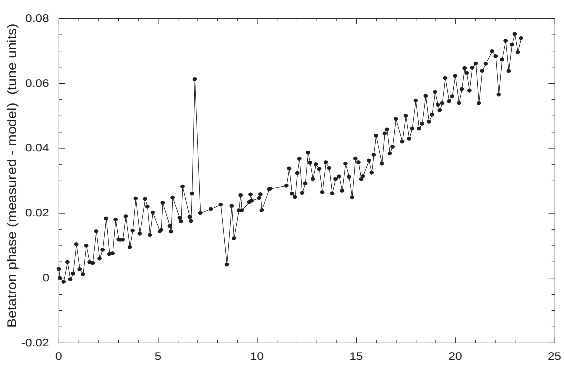

Figure 5: Error in the vertical betatron phase. The phase error (measured - model) is plotted as a function of vertical phase advance. The phase is in tune units i.e. $\mu/2\pi$.

Figures 6 and 7 are phase differences between the same measured data and a "new" model with fitted values for quadrupole strengths in the interaction region and the main QD,QF strings.

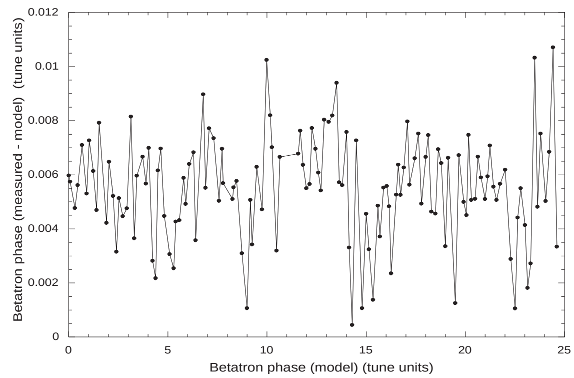

Figure 6: Error in the horizontal betatron phase. The phase error (measured - model) is plotted as a function of horizontal phase advance. The phase is in tune units i.e. $\mu/2\pi$.

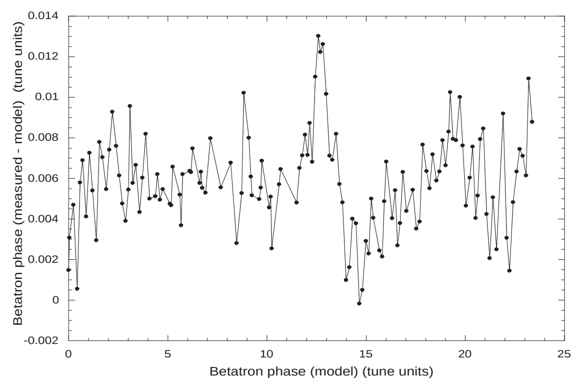

Figure 7: Error in the vertical betatron phase. The phase error (measured - model) is plotted as a function of vertical phase advance. The phase is in tune units i.e. $\mu/2\pi$.

4 ACKNOWLEDGMENTS

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