BEAM-BASED MODELING AND CONTROL OF STORAGE RINGS

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Abstract

Analysis of the measured orbit response matrix is a powerful technique for debugging the linear optics of storage rings. The orbit response matrix is the change in orbit at the beam position monitors (BPMs) with changes in steering magnet excitation. Results will be presented from a computer code called LOCO (Linear Optics from Closed Orbits) [1] that has been used to analyze the response matrices from several synchrotron light sources including the ALS, NSLS VUV, NSLS X-Ray, and SRRC storage rings. The analysis accurately determines the individual quadrupole magnet gradients as well as the gains of BPMs and the calibrations of the steering magnets. The coupling terms of the response matrix such as the shift in vertical orbit from horizontal steering magnets can be included in the analysis to give the role of the quadrupoles, BPMs and steering magnets. The LOCO code can also be used to find the changes in quadrupole gradient that best compensate for gradient errors from insertion devices and sextupoles. In this way the design periodicity of the linear optics can be restored.

1 INTRODUCTION

When a storage ring is first commissioned, the resulting optics invariably differ to some extent, often significantly, from the design. Achieving maximum performance, whether it be small beam size, small coupling, maximum lifetime, or maximum dynamic aperture, requires understanding and removing or compensating the source of the optics perturbations. This is particularly important in storage rings pushing the limits of accelerator performance such as third generation light sources, damping rings, and high energy physics factories.

The orbit response matrix is a good place to start when trying to debug a storage ring optics. The response matrix contains a large number of accurate data points reflecting the magnetic gradients of the ring. For example, in the NSLS X-Ray Ring, the response matrix contains 8640 data points with a noise level better than 1 μm.

The computer code LOCO was developed using ideas from reference [2] to determine the individual magnet gradients using the measured response matrix. It has been used to calibrate several storage rings [1, 3, 4, 5, 6, 7, 8], and work is in progress with several others. The emphasis of this paper will be the improvements made to the storage rings as a result of applying LOCO, but first a brief summary of the method and accuracy of the analysis will be given.

2 METHOD

For a more detailed discussion of the method and error analysis, see [1].

2.1 Characterizing linear optics

The measured, M_{meas}, or model, M_{mod}, orbit response matrix is defined as

$$\begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{pmatrix} = M_{\mathrm{meas,mod}} \begin{pmatrix} \boldsymbol{\theta}_x \\ \boldsymbol{\theta}_y \end{pmatrix}, \tag{1}$$

where $\boldsymbol{x}, \boldsymbol{y}$ is the shift in orbit at the BPMs for some change in steering magnet strengths $\boldsymbol{\theta}_x, \boldsymbol{\theta}_y$.

The parameters, such as quadrupole gradients, in a model such as MAD [9] of the storage ring are varied to minimize the χ^2 difference between the model and the measured response matrices.

$$\chi^2 = \sum_{i,j} \frac{(M_{\mathrm{mod,ij}} - M_{\mathrm{meas,ij}})^2}{\sigma_i^2}, \tag{2}$$

where σ_i is the measured noise level for the i^{th} BPM.

When fitting an uncoupled model, the parameters varied include the magnet gradients, the BPM gains, the steering magnet calibrations, and the electron energy shifts from changing horizontal steering magnets. When a horizontal steering magnet strength is changed there is an electron energy shift proportional to the dispersion at the steering magnet. Because there is no direct way to measure the dispersion at the steering magnets, $\frac{\Delta E_j}{E}$ is a fit parameter.

When fitting a coupled model, the coupling parts of the response matrix (i.e. the shift in vertical orbit from horizontal steering magnets) are included in the fit data, and additional fit parameters such as quadrupole, BPM, and steering magnet role are varied.

To minimize the number of parameters fit to a measured response matrix, if possible, some magnet gradients are set to zero before measuring the first matrix. For example, the insertion devices are opened, and the sextupoles are turned off, for those storage rings where beam can be stored without sextupoles. The matrix measured without insertion devices and sextupoles is analyzed to calibrate the gradients in the quadrupoles. After measuring this matrix, the sextupoles are turned on and the response matrix is remeasured. For fitting this second matrix, the quadrupole gradients are fixed at the values arrived at from analyzing the first matrix, and the gradients in the sextupoles are fit. Then a third matrix is measured with the insertion devices closed. In this way an accurate model of the full storage ring is derived.

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2.2 Error analysis

Once LOCO has arrived at a set of magnet gradients for a storage ring, it is natural to ask how accurately these gradients represent the real gradients in the storage ring. The error bars on the fit gradients due to the propagation of random orbit measurement error are fairly straightforward to calculate. Simply measure many consecutive response matrices, analyze each independently, and see how much the fit gradients vary from matrix to matrix. This was done for the NSLS X-Ray Ring analysis, and the variation in the quadrupole gradients for different response matrices was only .04% rms.

This, however, is only a lower bound on the uncertainty in the fit gradients, because it does not include systematic error. With effort, it is possible to reduce the systematic error to the point that, after fitting, the measured and model response matrices agree to very nearly the noise level of the BPMs, but with a system as complex as a storage ring it is practically impossible to completely eliminate systematic error.

With the inevitable and unpredictable systematic error, it is necessary to make additional independent measurements of the fit parameters and of other optics parameters such as tunes, beta functions and dispersion to confirm that the fit model does accurately represent the storage ring. Many such measurements have been made [1, 4], and the results indicate that the LOCO analysis can produce a model that does represent the actual storage ring to very nearly the accuracy determined by random error alone.

2.3 Restoring design periodicity

Section 2.1 described a method of applying LOCO to determine the gradient errors in each magnet. This section will describe applying LOCO to find those quadrupole power supply settings that best compensate for these errors and restore the design periodicity.

First, use LOCO as described in section 2.1 to generate a model with the correct BPM gains, steering magnet calibrations, and energy shifts. Then set all the model gradient errors such as gradients in insertion devices and sextupoles to zero. Refit the response matrix varying only those gradients that can be varied independently in the storage ring. For example, if some set of quadrupoles are powered by a single power supply, then gang the model gradient for that set in the fitting. The resulting gradients will show some break in periodicity that best reproduces the break in periodicity of the real ring. If opposite changes are applied to the storage ring, a periodic lattice is restored as close as possible. In essence, the storage ring is adjusted to maximize the periodicity of the response matrix.

3 APPLICATIONS

3.1 X-Ray Ring horizontal emittance reduction

LOCO was originally written in order to understand the distortion of the measured horizontal dispersion, η_x, in the NSLS X-Ray Ring [1, 3]. The dispersion in the dipole magnets is critical in determining the horizontal emittance. A synchrotron light source requires minimum emittance to maximize the source brightness, so it was important to understand and correct the η_x distortions.

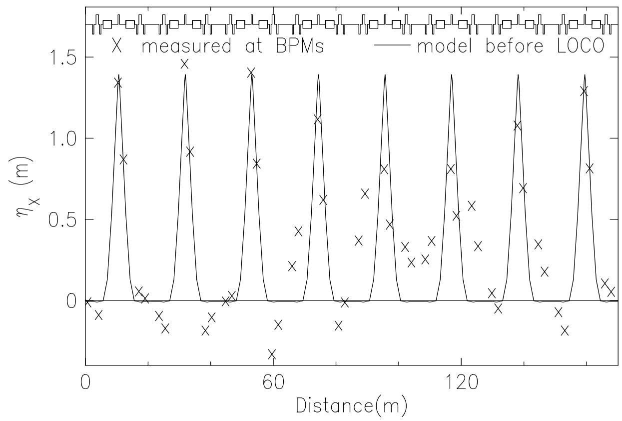

Figure 1: Before applying LOCO in the X-Ray Ring, the measured η_x differed significantly from the model.

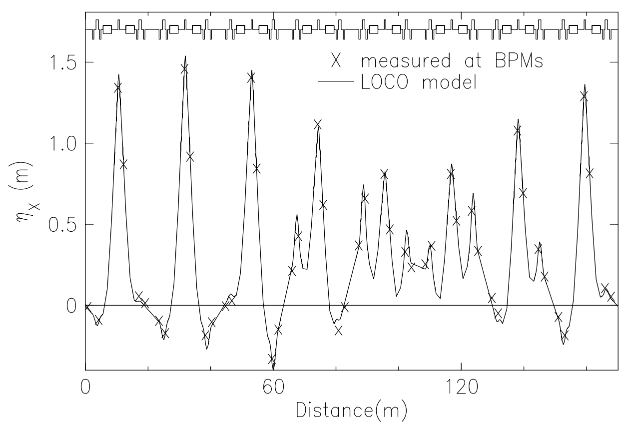

Figure 2: After the model was fit to the measured response matrix, the model also accurately predicted the measured η_x.

Fig. 1 compares the measured horizontal emittance compared to the model prior to applying LOCO. Clearly η_x differed significantly from the design 8-fold periodicity. Fig. 2 shows the measurement compared with the model fit by LOCO to the response matrix. The fit model revealed that the source of the η_x distortion was primarily gradients in the sextupoles due to horizontal offsets of the closed orbit from the sextupole magnetic centers. The sextupoles are located on either side of the single quadrupole between the dipoles. In order to correct for the gradient errors from the sextupoles, trim supplies were installed on the single quadrupoles in each of the eight superperiods. (Changing the orbit in the sextupoles was not an viable option, because it would have required realigning the synchrotron radiation beamlines.)

With the quadrupole trim supplies powered to restore the periodicity of η_x and using LOCO as a guide in setting the quadrupole family gradients, we were able to implement a new low emittance lattice design in the X-Ray Ring [10]. Fig. 3 illustrates the performance improvement achieved. The smaller horizontal profile resulted in increased source brightness.

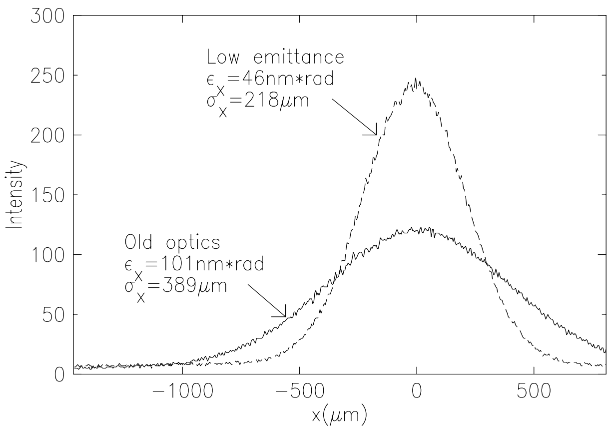

Figure 3: The reduction in X-Ray Ring horizontal beam profile as measured by an x-ray pinhole camera.

3.2 *ALS injection improvement*

LOCO was used to analyze the optics at the ALS to determine the source of the large vertical beta-beating that had been observed even with all insertion devices open. For detailed discussion of the work at ALS, see [4] and [6]. The fit model showed the expected beta-beats (see Fig. 4), and indicated that large variations in the gradients of the vertically focusing quadrupole family was the cause of the optics distortion. This quadrupole family has separate power supplies for each of the 24 magnets. Subsequent measurement of the currents from each power supply confirmed that the supplies were not regulating to specification and that LOCO had accurately predicted the variation from magnet to magnet (see Fig. 5).

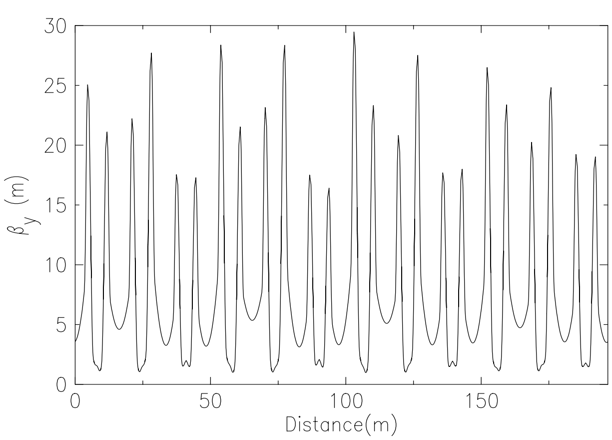

Figure 4: ALS vertical beta before correction with LOCO.

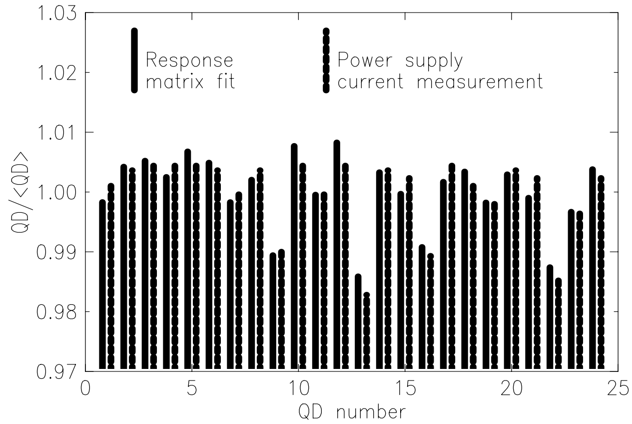

Figure 5: The variation in the fit gradients in the 24 QD quadrupoles agreed with the subsequent measurement of the current to each QD.

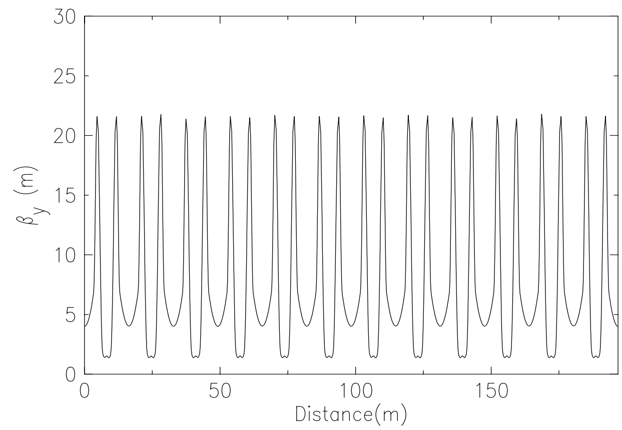

Figure 6: ALS vertical beta after correction with LOCO.

LOCO was then used as described in section 2.3 to restore the periodicity of the optics. Fig. 6 shows β_y of the model fit to the measured response matrix after restoring periodicity. Injection efficiency with the new optics improved by about a factor of two, presumably due to increased dynamic aperture with the periodic optics.

3.3 *VUV Ring lifetime improvement[5]*

The VUV Ring had also been known for some time to have large errors in both β_x and β_y. Two of the four dispersion-free straight sections in the VUV Ring have insertion devices. The vertical focusing of the insertion devices breaks the design four-fold periodicity, so the quadrupoles in the insertion device straights were put on separate power supplies to provide the capability of restoring the periodicity of the β-functions. Nonetheless, measurements indicated large beating of the β-functions. LOCO was used to find the gradient in each quadrupole, each sextupole, and the vertical focusing strength of each insertion device. The resulting model showed that the optics that had been used for operations had distortions of the β-functions of as much as

±35 and ±25 percent horizontally and vertically (see Fig. 7).

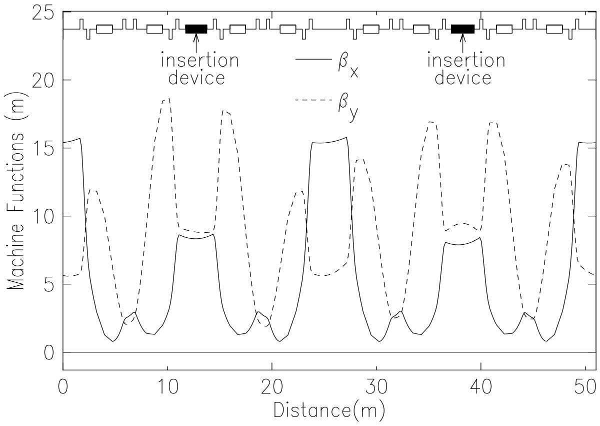

Figure 7: The β-functions in the NSLS VUV Ring did not have the design four-fold periodicity.

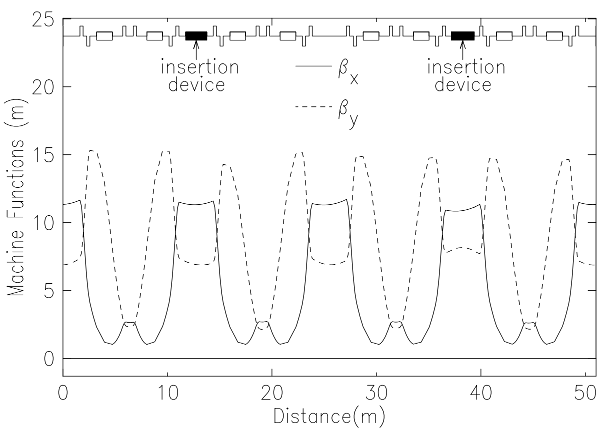

Figure 8: LOCO was able to find a set of quadrupole strengths that very nearly restored the design periodicity of the VUV Ring despite the strong vertical focusing of the insertion devices.

LOCO was then used as described in section 2.3 to restore the periodicity of the optics. Fig. 8 shows the β-functions of the model fit to the measured response matrix after restoring periodicity. The strong vertical focusing effect of the second insertion device is evident from the negative second derivative of β_y in that insertion device straight section. Despite this strong perturbation to the optics, a solution was found which very nearly restored the design four-fold periodicity of the β-functions. When this solution was implemented, the measured beam lifetime increased by 18% while both the measured horizontal and vertical emittances decreased by a few percent.

3.4 *SRRC orbit steering improvement*

The LOCO analysis of the SRRC showed that the storage ring optics is quite close to design with no large gradient errors [7]. The analysis, however, did reveal large variations in the gains of the BPMs as well as some mis-wiring of steering magnets (two magnets were wired backwards and two others had their power supplies swapped). The BPM gains varied from BPM to BPM by a factor of 3 horizontally and 2 vertically. Figs. 9 and 10 show the measured horizontal dispersion before and after correcting for the BPM gain errors derived by LOCO. Much of the apparent distortion in the measured dispersion in Fig. 9 was caused by gain errors in the BPMs.

Both the steering magnet mis-wiring and BPM gain errors were subsequently corrected, resulting in improved orbit control.

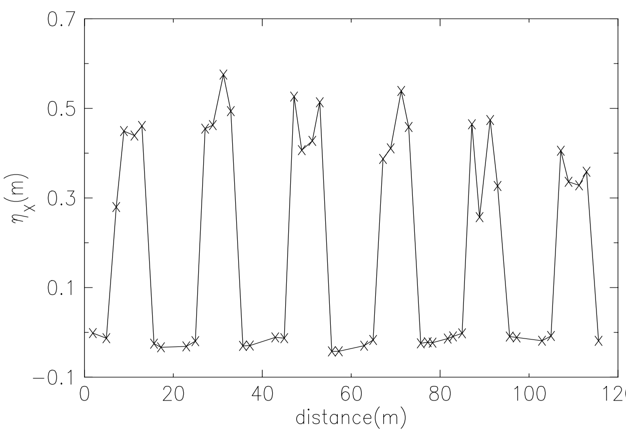

Figure 9: Measured η_x at SRRC without BPM gain error correction.

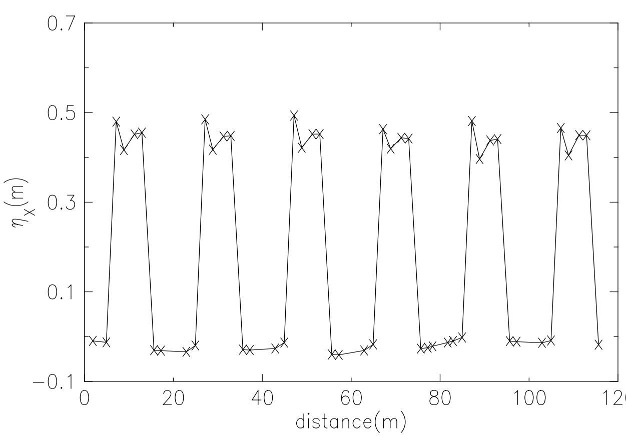

Figure 10: Measured η_x at SRRC after correcting for the BPM gain errors derived by analyzing the response matrix.

3.5 *X-Ray Ring coupling correction*

The coupling terms (i.e. the shift in vertical orbit with horizontal steering magnets) were included in the analysis of the X-Ray Ring response matrix. The result was fitted values for the skew gradients in each quadrupole and sextupole as well as the rotational alignment of each steering magnet and BPM. The steering magnet and BPM alignment data has been used to improve the X-Ray Ring coupling correction algorithm. The coupling correction algorithm uses the shift in vertical closed orbit with horizontal steering magnets as a measure of the horizontal to vertical betatron coupling [11]. The skew quadrupoles are adjusted to simultaneously minimize these orbit shifts as well as the vertical dispersion. This algorithm proved quite successful, but it suffered from the limitation that some of the measured vertical orbit shift was not due to coupling, but was a result of steering magnet and BPM roles. Once these roles were determined by LOCO, that part of the measured vertical orbit shift could be removed. In this way the skew quadrupoles were set to only remove the part of the orbit shifts associated with skew gradient errors.

Fig. 11 shows the measured vertical profile before and after applying this coupling correction technique.

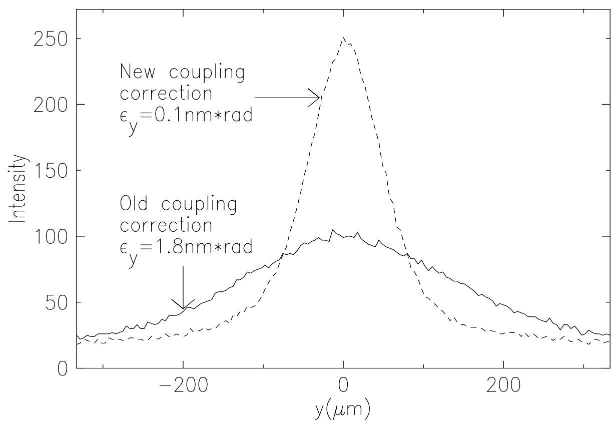

Figure 11: The reduction in X-Ray Ring vertical beam profile as measured by an x-ray pinhole camera.

4 CONCLUSION

Results from NSLS, ALS, and SRRC have shown that the accurate optics model that can be derived from analyzing the measured orbit response matrix can be a valuable tool for maximizing storage ring performance.

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