MODEL CALIBRATION AND SYMMETRY RESTORATION OF THE ADVANCED LIGHT SOURCE*

D. Robin, G. Portmann, H. Nishimura, LBNL, Berkeley, CA 94720 USA
J. Safranek, BNL, Upton, NY 11973 USA

Abstract

The symmetry of the ALS magnetic lattice is crucial in suppressing nonlinear structural resonances. Breaking the symmetry of the lattice can lead to a reduction in the dynamic aperture. The degree of symmetry breaking can be determined by fitting a magnetic lattice model to the measured orbit response matrix. This reveals a large beating of the vertical beta-function caused mainly by gradient errors in the QD quadrupole magnets. When the quadrupole field strengths are adjusted to compensate for the gradient errors, the symmetry of the lattice is restored. The new lattice has a larger dynamic aperture and an improved injection efficiency.

1 INTRODUCTION

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is a third generation light source. As in other third generation light sources, the lattice of the ALS is designed with strong focusing quadrupole magnets that are necessary to generate small beam emittances. These quadrupoles produce large chromatic aberrations that need to be corrected with strong sextupole magnets. The sextupole magnets in turn generate geometric aberrations that can lead to resonance excitation. Resonance excitation can lead to a reduction in the dynamic aperture that may result in poor injection rates as well as a reduction in beam lifetime from gas and intrabeam scattering.

To reduce the resonant excitation, the ALS was designed with 12-fold symmetry [1]. For perfect symmetry the only betatron resonances that can be excited obey the following relationship:

$$N_x \nu_x + N_y \nu_y = 12 \times M \tag{1}$$

where ν_x and ν_y are the horizontal and vertical tunes and N_x, N_y, and M are integers. If the symmetry of the ALS lattice is broken, then 12 goes to 1 in equation (1) and the number of resonances dramatically increases. This makes the ALS performance very sensitive to linear focusing errors from mispowered quadrupoles, insertion devices, and orbit errors in sextupoles [2,3]. In a previous study, increased resonance excitation was observed when the symmetry of the lattice was intentionally broken [4]. The degree to which the symmetry is broken will determine how strongly these new resonances become excited. Therefore, it is important to identify and compensate for focusing errors in the ALS.

*This work is supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Sciences Division of the U.S. Dept. of Energy, under Contract Number DE-AC03-76SF00098.

2 METHOD

The orbit response matrix (sometimes called the sensitivity matrix) relates changes in steerer magnet currents to changes in the orbit at the beam position monitors (BPMs). Previous work [5-7] has shown that it is possible to derive the gradient distribution in a storage ring by analyzing the orbit response matrix. The first analysis of ALS orbit response matrices was made in 1994 shortly after commissioning the storage ring [6].

At the ALS there are 96 BPMs in each plane as well as 94 horizontal and 70 vertical steering magnets. This results in 94 x 96 + 70 x 96 = 15744 elements for an uncoupled response matrix. Analyzing the orbit response matrix is done in the following way. First, a response matrix (M_{meas}) is measured. Next, the COMFORT accelerator optics modeling program [8] is used to calculate the modeled response matrix (M_{mod}). Parameters in the model such as quadrupole strengths and steerer magnet strengths are adjusted to minimize the difference between the measured and modeled response matrices. In particular, the following quantity is minimized:

$$\chi^2 = \sum_i \frac{(M_{meas,i} - M_{mod,i})^2}{\sigma_i^2} \tag{2}$$

where the σ_i are the measured noise levels for the BPMs. The technique is described in detail in reference [7].

The parameters varied to fit the data are: the quadrupole field strengths (both in quadrupoles (73) and in sextupoles (48), the BPM gains (192) and the steerer magnet gains (164). In addition, there is another set of parameters used in the fit—the energy shifts associated with changes in a steerer magnets. This energy shift occurs when a steerer magnet is changed in a region of dispersion [6]

$$\frac{\Delta E}{E} = \frac{\theta \eta_x}{\alpha L_0} \tag{3}$$

where θ is the change in steerer magnet strength, η_x is the dispersion at the location of the steerer magnet, α is the momentum compaction, and L_0 is the circumference of the ring. This energy change results in an orbit change in regions of dispersion. Using the measured dispersion it is possible to fit the energy change associated with each horizontal steerer magnet (94). Therefore, in the full fit there are 571 parameters.

3 QUADRUPOLE FIELD ERRORS

A gradient field is created in a sextupole if the beam is not steered through the center of the sextupole. To eliminate this effect the initial response matrices are measured with the sextupoles turned off. This isolates the gradient errors to the quadrupoles and reduces the total number of parameters in the fit. Removing the sextupoles from the fit reduces the total number of parameters to 523.

To generate the measured response matrix the magnitude of the steerer magnet changes are chosen to produce approximately 1 mm rms change in the orbit at the BPMs. After fitting, the agreement between the measured and modeled orbit changes are 13 µm horizontally and 12 µm vertically. The measured rms. BPM noise is approximately 4 µm. Hence, the modeled response matrices did not converge down to the noise of the BPMs.

Measurements of the BPM noise revealed occasional "jumps" in the beam position that were as large as 100 µm in some BPMs. These fictitious "jumps" create outlying points that are partly responsible for the fits not converging to the noise. In addition to these outlying points there may be some systematic errors remaining in the system—either in the data and/or the model that limit the convergence of the fit. Therefore the degree of confidence in identifying individual magnet errors is in question.

Although the accuracy of the method is difficult to determine, there is only a 0.1% rms. variation in the fit quadrupole gradients from data set to data set. The results show that of the three families of quadrupoles in the ring, QF, QD and QFA, the QD family has significantly larger variation in field than quadrupoles in the other two families (see Table 1). The specified quadrupole design tolerances were that the field variation from quadrupoles in a family should lie within a band of ±0.2%[1].

Quadrupole Family	rms variation
QF	0.28%
QD	0.63%
QFA	0.22%

Table 1: Measured variation in quadrupole fields within the three quadrupole families.

Two of the three quadrupoles families, QF and QD, have individual power supplies. The QFA family is powered in series off a single supply. The magnets are built with very tight tolerances for magnet-to-magnet variation. It was hypothesized that the non uniformity in the field strengths may be linked to the non uniformity in the power supplies. Using a current monitor, the currents of the magnets were measured. The precision of the monitor was 0.5%. The measurements confirm that the variation in field strengths is larger in the QD family than in the other two families.

A magnet-to-magnet comparison was made between the values for the quadrupole strengths obtained with the current meter and with the response matrix fitting. The agreement is within the precision of the current monitor and the results are shown in figure 1. Since these two independent measurement methods produced consistent results, it gave us confidence that the two methods are capable of pinpointing individual magnet field strength errors to a precision better than 0.5%. In particular, both measurements showed that 4 of the 24 QD magnets were more than 1% lower than the average. Using the calibrated model it is possible to compute the beta functions. The rms perturbation of the beta function is 3% horizontally and 15% vertically. The vertical beta function is displayed in figure 2.

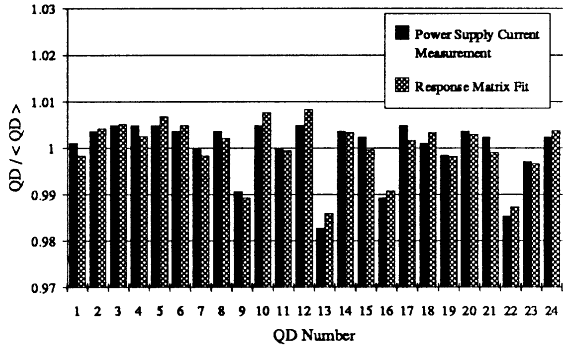

Figure 1: Variation in the 24 QD quadrupole gradients.

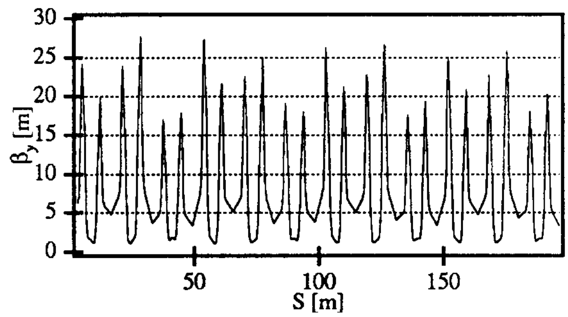

Figure 2: Vertical beta-function in the original lattice without sextupoles.

4 FULL LATTICE

The next step is to determine the quadrupole gradients in the sextupoles due to beam offset in the sextupoles. Since the quadrupole gradients in the quadrupoles are known, their values are kept fixed in the model. Using a measured response matrix with sextupoles, the model is fit by adjusting the quadrupole gradients in the sextupoles. The rms perturbation of the beta function is 6% horizontally and 19% vertically. The vertical beta function is displayed in figure 3. There is some increase in the overall beating due to sextupoles however most of the beating is due to the variation in the QD strength.

Using the calibrated model as a guide, quadrupoles in the QF and QD families are adjusted to restore the lattice symmetry. By measuring a new response matrix, the beta-functions of this new lattice are found. The resulting horizontal and vertical beta-beating is less than 1% (see figure 4).

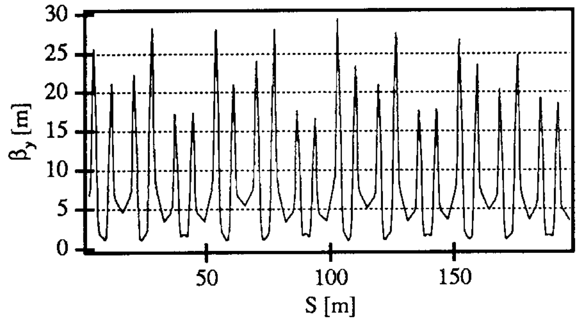

Figure 3: Vertical beta-function in the original lattice with sextupoles.

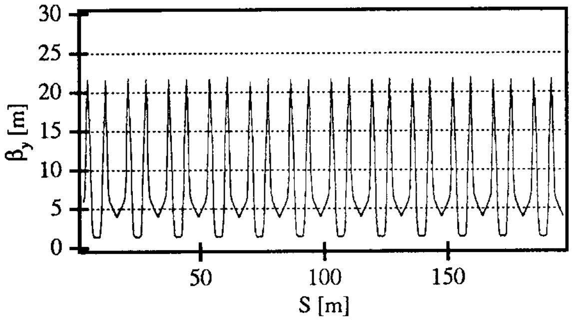

Figure 4: Vertical beta-function in a lattice with sextupoles after the symmetry is restored.

5 INJECTION EFFICIENCY

A comparison was made between the original lattice and the new more symmetric lattice by looking at the injection efficiency. Without changing the injector, the injection rate was measured as a function of the relative distance between the stored beam and the injected beam. This is done by incrementally shifting the stored beam further from the injected beam using a closed orbit bump. The measured injection efficiency of the new lattice is significantly better. The results are shown in figure 5.

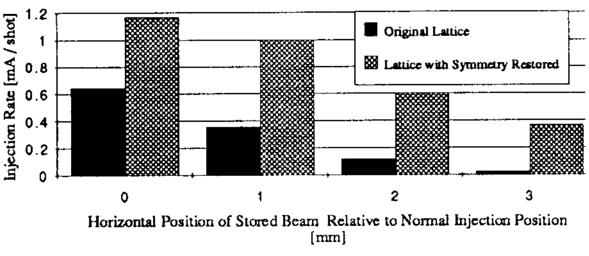

Figure 5: Comparison of injection rates of the original lattice and the lattice with restored symmetry.

6 DYNAMIC APERTURE

The improvement in injection rate may be due to an increase in the dynamic aperture. Figure 6 shows the dynamic aperture for the original and the lattice with restored symmetry. The only errors included in the lattices are the measured gradient errors. There are no higher-order mulipole errors included. Particles are tracked on energy and without synchrotron oscillations for 512 turns or until lost. The dynamic aperture is substantially larger for the lattice with restored symmetry.

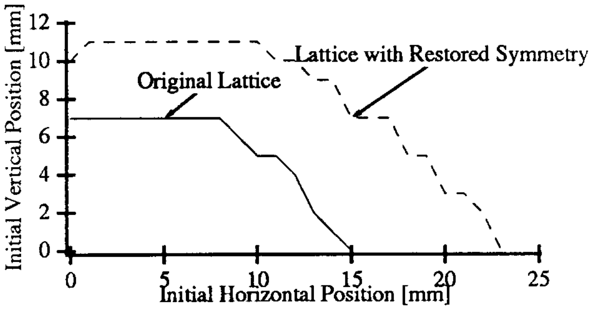

Figure 6: Comparison of dynamic aperture for the original and restored symmetry lattices.

6 CONCLUSION

By fitting measured response matrices to an optics model it is possible to determine individual quadrupole gradients. This method revealed gradient errors in the QD quadrupole magnets of greater than 1.5% which was verified by measurements of the power supply currents. The quadrupole field strengths were adjusted to compensate for the gradient errors which restored the symmetry of the lattice. The new symmetric lattice has a larger dynamic aperture and an improved injection efficiency.

7 ACKNOWLEDGMENTS

The authors would like to thank the staff at the ALS and particularly Alan Jackson for making the high precision power supply measurements and Jim Hinkson and Jim Johnston for reducing the noise levels of the BPMs. We also would like to thank Martin Lee and Jeff Corbett at SLAC and Phong Tran at BNL for interesting discussions.

8 REFERENCES

[1] ALS Conceptual Design Report, LBL Note PUB-5172 Rev. (1986)

[2] A. Jackson, et. al., Proceedings of the 1989 Particle Accelerator Conference, 1752-1754 (1989)

[3] J. Bengtsson and E. Forest, AIP Conference Proceedings No. 255, 339-233 (1991)

[4] D. Robin, et. al., AIP Conference Proceedings 344, 170-175 (1994)

[5] W.J. Corbett, M.J. Lee and V. Ziemann, SLAC-PUB 6111, May, 1993

[6] J. Bengtsson and M. Meddahi, Proceedings of the 1994 European Particle Accelerator Conference, 1021-1023 (1994)

[7] J. Safranek, Proceedings of the 1995 Particle Accelerator Conference, 2817-2819 (1995)

[8] M. P. Woodley et al, SLAC PUB Number 3086, March 1983