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Abstract

LOCO is a computer code for analysis of the linear optics in a storage ring based on the closed orbit response to steering magnets. The analysis provides information on focusing errors, BPM gain and rotation errors, and local coupling. Here, we discuss the details of the LOCO implementation at the KEK-ATF Damping Ring, and report the initial results. Some of the information obtained, for example on the BPM gain and coupling errors, has not previously been determined. We discuss the possibility of using the data provided by the LOCO analysis to reduce the vertical emittance of the ATF beam.

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ANALYSIS OF KEK-ATF OPTICS AND COUPLING USING LOCO*

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Abstract
LOCO is a computer code for analysis of the linear optics in a storage ring based on the closed orbit response to steering magnets. The analysis provides information on focusing errors, BPM gain and rotation errors, and local coupling. Here, we discuss the details of the LOCO implementation at the KEK-ATF Damping Ring and report the initial results. Some of the information obtained, for example on the BPM gain and coupling errors, had not previously been determined. We discuss the possibility of using the data provided by the LOCO analysis to reduce the vertical emittance of the ATF beam.

INTRODUCTION

The ATF has recently reported a vertical emittance of below 5 pm [1]. Although this meets the specification for the damping rings for an X-band linear collider, detailed studies of potentially limiting effects in beam dynamics and the development of high performance diagnostics, motivate efforts to reduce the vertical emittance to even smaller values. This would require very precise correction of betatron coupling and vertical dispersion. Simulation studies have shown that it may be possible to achieve a vertical emittance close to 1 pm [2]. The Advanced Light Source (ALS) at LBNL has also achieved a vertical emittance of around 5 pm [3]. In this case, the coupling correction was achieved in a reasonably straightforward manner using the optics analysis code LOCO [4].

In using LOCO, one first measures the closed-orbit response matrix (i.e. the measured change in orbit at each BPM resulting from a change in strength of each orbit corrector), and the horizontal and vertical dispersion. LOCO then automatically adjusts parameters in a lattice model to reproduce the measured data.

Here we report the results of a first attempt to use LOCO at the ATF. Our goals were: to obtain information on the optics of the ATF, in particular to identify any focusing errors; to estimate BPM gains and coupling errors; and to reduce the vertical emittance of the ATF by determining appropriate settings for the skew quadrupoles in a manner similar to that used at the ALS.

MEASUREMENT PROCEDURE

The ATF contains 47 horizontal orbit correctors, and 50 vertical orbit correctors. There are 96 BPMs in each plane. Data collection was semi-automatic, with each orbit corrector varied in steps, with a number of orbit measurements made at each step. The data are preprocessed to give the orbit variation at each BPM with respect to the variation of each corrector – the closed orbit response matrix.

We note that the BPM resolution is typically a few microns. Thus, averaging over a number of orbits provides data with good resolution for the LOCO analysis. The resolution of each BPM is estimated from the collected data and is used by LOCO in weighting the fit to the data provided by each BPM.

The horizontal and vertical dispersion were also provided as input data for the LOCO analysis. This breaks a degeneracy that otherwise occurs between the corrector strengths and the BPM gains. We discuss the significance of the vertical dispersion in the analysis below.

ANALYSIS OF FOCUSING ERRORS, BPM GAINS, AND CORRECTOR STRENGTHS

Here, we present the results of the analysis of data collected during December 2003. The parameters varied in fitting the model to the measured response matrix were:

- BPM gains and couplings;
- corrector magnet kicks and couplings;
- strengths of all quadrupoles;
- strengths of skew quadrupoles.

Note that skew quadrupoles in the ATF are provided by trim windings on the sextupoles. For maximum flexibility in correcting the coupling, every skew quadrupole is independently adjustable.

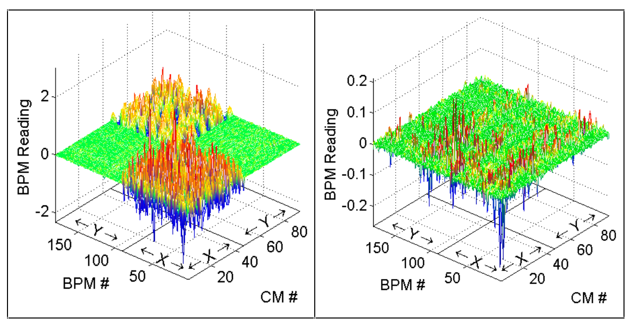

Figure 1: Terms in the measured response matrix (left) and difference between the measured response matrix and the modeled response matrix after fitting with LOCO (right).

Figure 1 shows the measured response matrix, and the difference between the measured response matrix and the modeled response matrix, after the model is fitted to the response matrix using LOCO. Note the different scales on the two plots, and that the cross-plane sectors of the response matrix are much smaller than the in-plane sectors. The residuals of the coupling components after the fit are significant.

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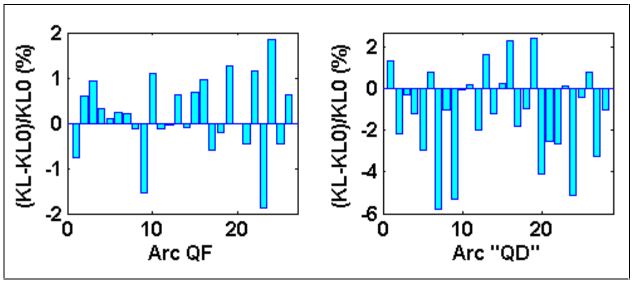

Figure 2: Relative integrated gradient errors fitted by LOCO for arc QF quadrupoles (left) and arc "QD" quadrupoles (right).

Figure 2 shows the errors on the integrated quadrupole gradients in the arcs. Note that the vertical focusing in the arcs is provided by a gradient in the dipoles; variation in the dipole focusing is not fitted directly in LOCO, but instead projected onto adjacent weak quadrupoles (the arc "QD" magnets) that are used for tune adjustments. Note that the errors represent differences between the magnet strengths found by LOCO from the machine measurements, and the magnet strengths in a nominal design model. The magnets are generally tuned slightly away from their nominal values to optimize machine performance.

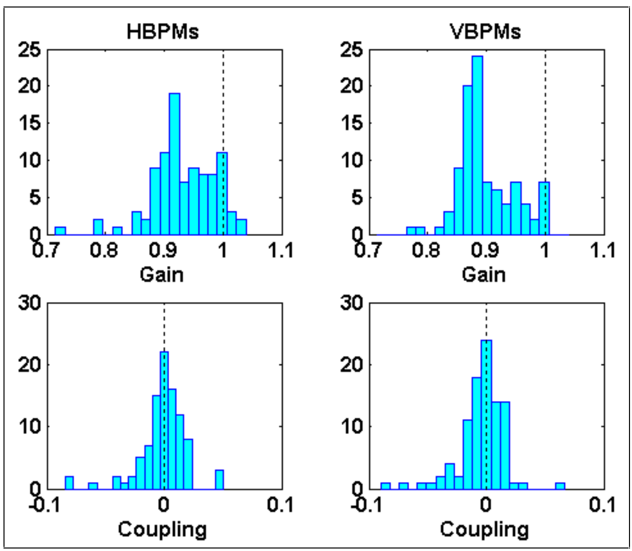

Figure 3: BPM gains (top) and BPM couplings (bottom) fitted by LOCO.

The fitted BPM gains are shown in the top two histograms in Figure 3. We note that there seems to be a systematic gain error in both the horizontal and vertical BPMs. This may be real, or an artifact from an error in the dispersion data provided. The fitted BPM couplings are shown in the bottom two histograms in Figure 3. The coupling is defined as the *measured* beam motion in one plane resulting from a *real* unit beam motion in the other plane. If the source of coupling is BPM rotation, then the horizontal and vertical coupling will be equal; however, there may be other sources of coupling, and in LOCO, the horizontal and vertical couplings are independent parameters.

ANALYSIS OF SKEW QUAD STRENGTHS AND COUPLING CORRECTION

The expected dominant sources of coupling in the machine are rotations of the quadrupoles about the beam axis and vertical offset of the beam in the sextupoles. Coupling correction involves determining the optimum settings for the skew quadrupole trims to compensate the quadrupole rotations and sextupole offsets. The procedure we adopted was as follows:

1. Collect data for LOCO and carry out an analysis assuming that all coupling comes from skew quadrupoles superposed on the sextupoles.
2. Adjust the strengths of the skew quadrupole trim windings to cancel the skew quadrupole strengths found from step 1.
3. Repeat the above steps until no further changes to the skew quadrupole strengths are needed.

A key indication of the ability of LOCO to correct the coupling is the change in the skew quadrupole strengths found by LOCO between two iterations, compared with the known changes applied to the currents in the skew quadrupole trim windings on the sextupoles. Such a comparison is shown in Figure 4. The data are taken from the machine in its initial condition and after the first applied correction.

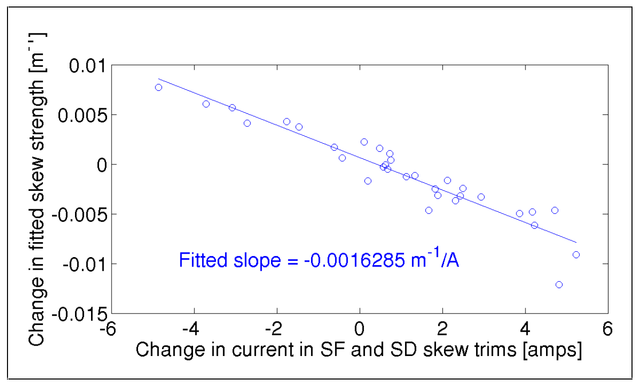

Figure 4: Change in fitted skew quadrupole strengths as determined by LOCO analysis, compared with known changes in current in the skew quadrupole trim windings on the sextupoles.

We observe that the fitted changes in skew quadrupole strengths are well correlated with the known changes in the current in the trim windings. The slope of the linear fit is in reasonable agreement with the known calibration of the skew quadrupoles. This gives us confidence that LOCO is providing meaningful results.

Two iterations of coupling correction were performed. The distributions of components in the coupling sectors of the response matrix before and after the first iteration are shown in Figure 5. We observe that after the first coupling correction, there is some reduction in the width of the distribution, with an increase in the peak at zero. This implies that there has been a general reduction in the size of the coupling components in the response matrix.

Analysis of the skew quadrupole strengths found by LOCO before and after the skew correction suggested that the first correction was successful in reducing the strengths of the skew quadrupoles. However, after the second iteration the coupling elements in the response matrix appeared to *increase*, and there was no further reduction in the skew quadrupole strengths.

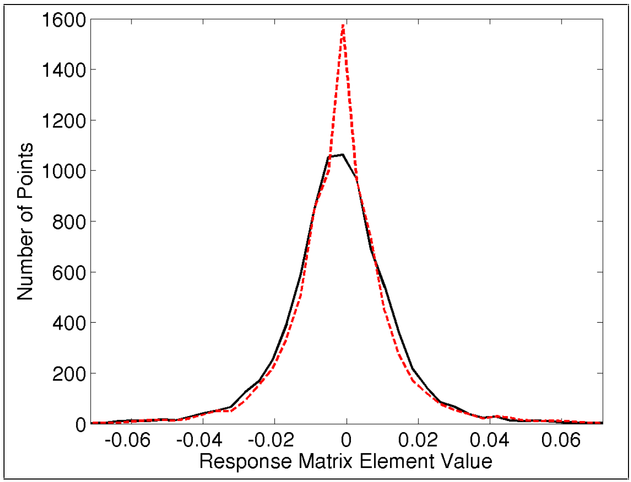

Figure 5: Distribution of elements in coupling sectors of measured response matrix before (solid line) and after (broken line) coupling correction.

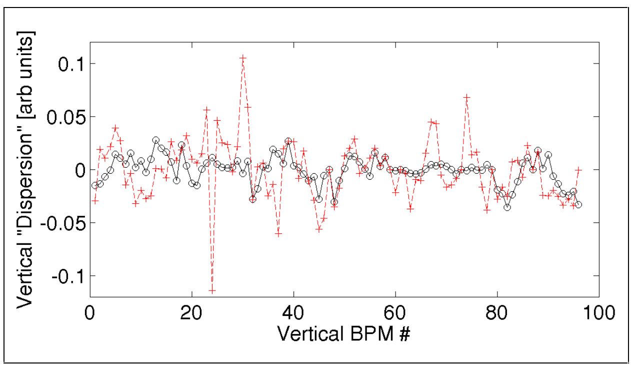

Figure 6: Residual vertical dispersion before (solid line) and after (broken line) coupling correction.

Figure 6 shows the measured change in vertical orbit resulting from a change in the RF frequency, before and after skew correction. We refer to this as the dispersion although more correctly, the dispersion is a change in orbit with respect to beam energy (also, the measured orbit change will differ from that expected from the dispersion because of BPM gain and coupling errors). The skew correction appears to *increase* the vertical dispersion. It is possible that this is consistent with a *reduction* in the skew coupling if the orbit has large vertical steering, in which case the skew coupling might compensate the dispersion from steering.

The results from the response matrix measurement and the fit to the skew quadrupole strengths are consistent in indicating a reduction in the coupling following the first skew correction, and no further reduction (and possibly some increase) after the second skew correction. The reasons for the failure of the second skew correction are unclear. Figure 4 suggests that the skew quadrupole strengths being found are meaningful, but the scatter in this correlation plot indicated that a resolution limit might have been reached after the first correction. Another possibility is an incorrect weight on the vertical dispersion in the fit. Steier has observed in studies of the ALS [5], that in correcting the coupling, it is important to set the weight for the vertical dispersion correctly: if the weight is too low, then the vertical dispersion remains large after the correction and dominates the emittance; if the weight is too high, then the fitted skew quadrupole strengths are incorrect because of the effects of vertical steering.

CONCLUSIONS

Application of LOCO to the ATF provided some new information about the lattice and the BPMs. The results shown in Figure 4 do indicate that the analysis is able to identify real changes to magnet strengths. Nevertheless, our attempts to reduce the vertical emittance by applying a coupling correction with skew quadrupole strengths determined from the LOCO analysis were not successful. A possible reason for this is our inattention to the weight applied to the vertical dispersion in fitting the model to the measured data.

We would also remark that the vertical emittance of the ATF is already very small. Depending on the exact errors present in the machine, it is possible that the optimum skew quadrupole settings for low vertical emittance, providing a balance between vertical dispersion and betatron coupling, had already been found. Changes to the skew quadrupole strengths would then result in reducing the betatron coupling at the expense of increasing the vertical dispersion, or vice-versa. In this case, it would be important to reduce the vertical dispersion generated by vertical steering, for example by using the results of beam-based alignment, before applying LOCO to determine changes in the skew quadrupole strengths needed to correct the coupling.

ACKNOWLEDGEMENTS

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