ORBIT RESPONSE MATRIX ANALYSIS APPLIED AT PEP-II [*]

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Abstract

The analysis of orbit response matrices has been used very successfully to measure and correct the gradient and skew gradient distribution in many accelerators. It allows determination of an accurately calibrated model of the coupled machine lattice, which then can be used to calculate the corrections necessary to improve coupling, dynamic aperture and ultimately luminosity. At PEP-II, the Matlab version of LOCO has been used to analyze coupled response matrices for both the LER and the HER. The large number of elements in PEP-II and the very complicated interaction region present unique challenges to the data analysis. All necessary tools to make the analysis method useable at PEP-II have been implemented and LOCO can now be used as a routine tool for lattice diagnostic.

INTRODUCTION

PEP-II is an electron positron collider located at the Stanford Linear Accelerator Center (SLAC), which collides 3.1 GeV positrons with 9.0 GeV electrons; the two beams are stored in separate rings (the low-energy ring (LER) and high-energy ring (HER), respectively). PEP-II has a unique interaction region design, including (nearly) head on collisions, a strong asymmetrically placed detector solenoid, a permanent magnet combined-function dipole-quadrupole inside the solenoid, vertical bending interleaved with horizontal bending, sextupoles close to the interaction point, and because of all this a very complicated local coupling compensation scheme.

For a collider, especially PEP-II with its unique interaction region, beam based techniques are an essential tool to understand and correct the gradient and skew gradient distribution. The gradient distribution is important with regards to dynamic aperture, injection efficiency, detector backgrounds, beta functions at the interaction point, beam-beam performance and therefore ultimately can be one of the limiting factors for the achievable luminosity. The skew gradient distribution is very important as well, since it has (especially in the by design highly coupled LER) a strong influence on all of those effects as well, plus it directly affects the luminosity by determining the vertical emittance and the local coupling and tilt angle of the beam at the interaction point. If one uses a beam based technique to calibrate the lattice model, the calibrated model can be used to estimate important parameters, such as η_y^*, which are difficult to measure directly. A calibrated model can also improve routine tasks such as orbit correction/feedback and calculation of closed orbit bumps.

The idea behind the analysis of measured orbit response matrices [1] is to measure the response of every beam position monitor (BPM) to a small change of every corrector magnet (both in and out of plane). For the analysis, the computer code LOCO [4] was used. The tracking code used by LOCO for the PEP-II ORM analysis was the Accelerator Toolbox (AT) [2], Orbit response matrix analysis has been used very successfully at most light sources and is routinely used there to optimize the lattice symmetry and therefore the dynamic aperture, as well as the local and global coupling [3, 5, 6]. In the analysis, theoretical orbit response matrices for different settings of the fit parameters are calculated with a tracking code. For speed reasons, typically a linearized calculation of the coupled response matrix (C^{ij}) is used:

$$C^{ij}_{12} = \left[R^{ij}(1-R^{jj})^{-1}\right]_{12} - \frac{\eta_i \eta_j}{(\alpha - \frac{1}{\gamma^2})C}, \qquad (1)$$

where R^{ij} is the transfer matrix from corrector j to beam position monitor (BPM) i, R^{jj} is the one turn transfer matrix, η is the dispersion, α the momentum compaction factor, γ the Lorentz factor and C the circumference. Loco calculates a large matrix with all numerical derivatives of the model response matrix with respect to the fit parameters and the inverts that matrix (using SVD) to iteratively arrive at a solution, i.e. a calibrated machine model, which produces a calculated response matrix that best matches the measured one.

In addition to the normal and skew gradients, the scale factors and coupling factors of the correctors and BPMs are typically included as LOCO fit parameters. In the case of the PEP-II rings the number of BPM and corrector fit parameters is on the order of 1000, while the number of gradients to be fit is on the order of 100.

CHALLENGES AT PEP-II

PEP-II is one of the largest and most complex rings ever to be subject to ORM. The full orbit response matrix already contains more than 10^5 elements, which means that the matrix which needs to be inverted by SVD has several 10^8 elements leaving to memory requirements of several GByte. Since Matlab is a 32 bit application the available memory for the analysis is limited to between 1 and 4 GBytes, requiring several tricks in the analysis. First the LOCO code was optimized as part of this project to be more memory efficient. In addition, tests were conducted leaving out some of the measured data in not so interesting areas of the rings (and possibly later averaging several such data sets), as well as tests where the different fit param-

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eters (BPM and corrector gains and tilts) were iteratively fit. With those tricks, it was possible to bring the memory requirement even for the coupled analysis down to reasonable values and the results are very similar to a full analysis, however some of those tricks increase the computation time necessary.

Modelling of the Complicated Interaction Region

One of the main challenges was the complicated way the very complex PEP-II interaction region is modelled in the lattice files. The main lattice code used at PEP-II is MAD and to convert those lattice files to AT, several new integration methods, which did not exist before, had to be implemented in AT (solenoid, zero length dipoles, coordinate transformations, arbitrary Matrix elements). An automated MAD-to-AT translator was implemented. The interaction region is modelled as an interleaved set of many thin solenoid, multipole and bending magnet slices. Because most of the parameters of all those slices are related to each other, it presents a large challenge to use meaningful parameters of the magnets as fit parameters in LOCO. As a short term solution, additional multipole corrector slices have been added, implementing to first order a reasonable solution. For the long term, new integration methods for combined solenoid, dipole, quadrupole elements will be used [7]. The last challenge to be overcome is that the PEP-II lattice has a nonzero design closed orbit around the interaction region. This means that changing any fit parameters in this region will change the closed orbit, resulting in feed-down terms in sextupoles badly affecting the differentiation in the model fit. This was an effect which had not been present at other places where LOCO had been used before. It was resolved by appropriately changing the dipole kick of elements together with their gradient or skew gradient.

HIGH ENERGY RING

In the HER, the both uncoupled and coupled analyses of the orbit response matrix data provided good fit results. The χ^2 value of the fits are acceptable, indicating an rms-deviation of the the model response matrix from the measured response matrix of under 10 μm. Before the fit, the rms discrepancy is nearly 100 times as large. As fit parameters, an effective set of gradients was used, i.e. one fit parameter per power supply (not per magnet) and no feed-down terms in sextupoles. This model will not produce the best agreement between the fit and the measurement, but produces a correction to the magnet configuration which is straightforward to implement. Fig. 1 (left) shows the ratio of the fitted k-value over the k-value as calculated from the magnet setpoint at the day of the measurement.

One can see fairly large discrepancies, which were to be expected, since other measurements indicated large discrepancies relative to the design lattice. However their magnitude is not to be understood as real misscaling of magnets, but instead is partly caused by using an effective model which has a much smaller number of parameters and incorporates sextupole feeddowns (due to the existing significant orbit errors) into quadupole gradient errors.

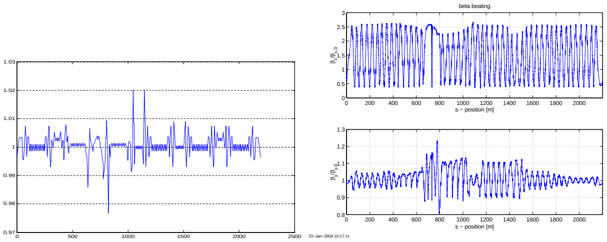

Figure 1: Left: Ratio of fitted k-values for the HER to the k-values calculated based on magnet setpoints at the day of the measurement. Right: HER betabeating of calibrated model relative to design lattice.

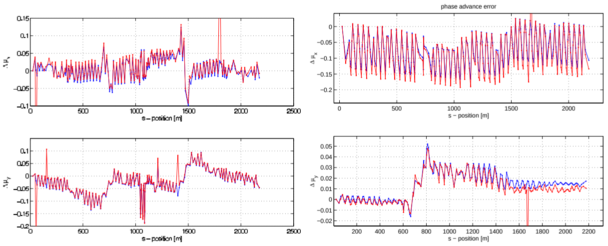

Figure 2: Comparison of the difference in LER (left), HER (right) phase advance between the calibrated model and the design lattice (blue) as well as a direct measurement of the difference to the design model using turn-by turn BPMs (red).

Fig. 1 (right) shows the beta beating of the calibrated model relative to the HER design lattice. One can see the very large beta beat in the horizontal plane as well as a significant beta beat in the vertical plane. The results of the analysis are repeatable and agree well with independent measurements (see next section).

Model Predictions and Measurements

A very good test to evaluate the quality of the calibrated model and the LOCO analysis is to compare predictions of the model with independent measurements: typically Beta functions, phase advances, betatron tunes, and local xy coupling are used for this purpose. Fig. 2 (right) shows the comparison of the phase advance error as calculated by the calibrated model (blue) as well as a direct measurement using BPMs (red). The agreement is reasonably good. In addition, the tunes of the model agree within a few $.001$, and the beta functions at the IP agree very well with independent measurements.

Fig. 3 shows the comparison of one quantity of local coupling $\bar{C}_{12}$, calculated from the calibrated HER model as well as a direct BPM measurement. Considering only a few effective skew gradient parameters were fitted, the agreement is very good and shows significant coupling errors compared to the design lattice. However, the analysis also shows that the ring is optimized to be well decoupled at the IP and have small spurious dispersion at the IP, and

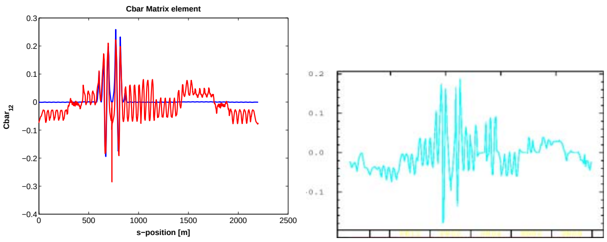

Figure 3: HER $\bar{C}_{12}$: Left: calibrated LOCO model (at all elements in lattice), Right: direct BPM measurement (at BPM locations only, shifted a bit in s-position).

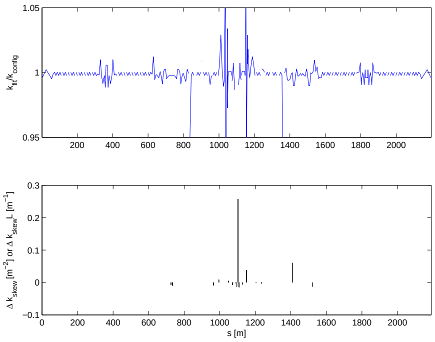

Figure 4: Ratio of fitted k-values for the LER to the k-values calculated based on magnet setpoints at the day of the measurement as well as different in (integrated) skew gradient for the local and global skew quadrupoles.

this was confirmed by other measurements.

LOW ENERGY RING

For the LER the lattice is so highly coupled that a simple uncoupled analysis of the response matrix data does not produce acceptable agreement. In addition, understanding and correcting local and global coupling as well as spurious vertical is very important to optimize the beam-beam performance. Therefore a fully coupled analysis of the response matrix was carried out the LER. In this case an “effective fit” approach was used for the skew gradients (i.e., only individual and global skew quad strengths were fit), but normal gradient feeddowns in sextupoles were permitted, leading to a better agreement between model and measurement as well as much smaller effective scaling errors of most quadrupoles (compare Fig. 4).

In general χ^2 values of the coupled model were smaller (much smaller) in the HER (LER) than in the uncoupled analysis, with final rms discrepancies between the model and the measured response matrix of well below 10 μm.

Model Predictions and Measurements

The best test to evaluate the quality of the coupled calibrated model is to again to check its predictions against independent measurements (e.g. the same values as above, plus emittance coupling, closest tune approach, local coupling, vertical dispersion, beam sizes). Fig. 2 (left) shows the comparison of the phase advance error for LER as calculated by the calibrated model (blue) as well as a direct measurement using BPMs (red). The agreement is good. In addition, the tunes of the model agree within a few $.001$, and the beta functions and beamsizes at the IP agree very well with independent measurements.

SUMMARY

All tools necessary to use the analysis of orbit response matrices for PEP-II, including conversion routines, integrators for AT, scripts for the measurements and the actual data analysis are now available. Data taking takes about an hour and the turnaround time for a full analysis of the coupled lattice is about 1 day (mostly CPU time limited). The memory limitations we originally incurred turned out to be manageable, however, a 64 Bit version of Matlab later this year will make things much easier. All analysis results (using effective fit parameters, i.e. real power supplies) look very reasonable, leading to a reasonable χ^2, and residual rms error of a few microns compared to mm size response matrices Comparison of calibrated model predictions with independent measurements look good. However, the variation from the nominal lattice is significant. The results of this analysis are therefore already being used to deduce scaling factors and thus to significantly improve the quality of the online model.

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