LINEAR LATTICE MODELING OF THE RECYCLER RING AT FERMILAB*

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Abstract

Substantial differences are found in tunes and beta functions between the existing linear model and the real storage ring. They result in difficulties when tuning the machine to new lattice conditions. We are trying to correct the errors by matching the model into the real machine using Orbit Response Matrix (*ORM*) Fit method. The challenges with *ORM* particularly in the Recycler ring and the results are presented in this paper.

INTRODUCTION

The Recycler Ring at Fernilab is a fixed 8 GeV kinetic energy storage ring. One distinguishing feature of the Recycler ring is that most of its magnetic elements are made of permanent magnets. It is a strong focusing FODO lattice made up of either two gradient magnets or two quadrupoles (in dispersion free straight sections). The magnetic properties of all magnets were measured before installation and surveyed in place to minimize possible errors. Nevertheless, substantial differences are found in tunes and beta functions between the existing linear model and the real storage ring. The magnetic harmonic errors of the Recycler Ring were examined using circulating beam data taken with closed local orbit 3-bumps [1]. We have identified several rolled quadrupoles which resulted in strong coupling. However, the data taking procedures were long, and analysis was tedious. The studies were only limited to several locations. To obtain the linear model of the entire storage ring, we have used the Orbit Response Matrix Fit technique [2] for fully coupled motion based on the measurement and the analysis of many differential orbits.

SRLOCOFITTING SOFTWARE AND *OPTIM* LATTICE

Orbit Response Matrix (*ORM*) Fit method has been successfully used to calibrate linear optics at many storage rings. For Recycler analysis, we used program SRLOCOFitting developed at Advanced Photon Source (APS) at ANL [3]. The program has an extensive graphical user interface that allows user to choose any set of fit variables and to change a lot of fit parameters. The program is written in Tcl/tk. For accelerator related calculations (response matrix, beta functions, etc.) the program uses code Elegant [4] or OptiM [5]. All other processing is performed using SDDS toolkit [6]. Initially, the program SRLOCOFitting was written for analysis of APS storage ring which has very small coupling between horizontal and vertical planes. Therefore the program could only fit non-coupled matrices. In order to apply the program to Fermilab accelerators, it was upgraded to include analysis of fully coupled response matrix. Dispersion fit was also added at that time. The program was successfully used to derive the linear model of Tevatron [7] and Accumulator. In order to apply the software to Recycler, a few changes to GUI has been made to accommodate for Recycler's complicated element naming convention. The software is run on a 32-node linux cluster Heimdall. The program can run in parallel to speed up calculations of response matrices and response matrix derivatives. Based on the design MAD bare lattice of the Recycler ring, the corresponding *OptiM* lattice has been prepared, and tunes and beta functions were cross-checked.

MEASUREMENTS AND ANALYSIS

An application program, Differential Orbit BPM Measurement, is used to perform differential closed orbit measurements and provide the data in SDDS format for *SRLOCO Fitting* program. The corrector excitation currents are limited to 1 Amp to keep the orbit responses within the linear region. Each corrector is excited first to positive current and then to negative. At each current, the orbit is measured 5 times. The total response to the steering magnet excitation is the average positive orbit minus average negative orbit.

The measurement was taken on Feb 25, 2006. For all 105 horizontal and 104 vertical correctors, the orbit response data on all 111 horizontal and 110 vertical BPMs were collected. The dispersion was also measured by scanning *rf* frequency in five steps, measuring the orbit each step, and then fitting a straight line at each BPM.

The following variables were used in the response matrix fit: quadrupole strength errors, corrector calibration errors, BPM gains, energy shift due to corrector changes, and quadrupole, BPM and corrector rolls. To reduce the response matrix size and achieve high-precision fit, we divided measurements into 3 subsets each containing approximately one third of correctors and all BPMs. The correctors for the subsets were chosen in such a way so that to provide for the phase advance between correctors of roughly 90^{o}. For a typical fit, the size of the full response matrix derivative is about 180MB with 1116 variables.

The fit is converged approximately to the same value for 3 sets of data, the residual *rms* errors are listed in table 1. Those values correspond to the present accuracy of Recycler BPMs. It indicates the fitting is done to the best

*Work supported by U.S. Department of Energy under contract No. DE-AC02-76CH03000.
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and is limited by BPM accuracy. Figure 1 shows typical measured and calculated vertical responses to a horizontal excitation before and after the fit. Figure 2 gives horizontal and vertical dispersions before and after the fit.

Table 1 RMS Difference between calculated and measured response matrix before and after the fit for different parts of the response matrix (*x-x* means horizontal-to-horizontal response, and so on).

	Before fit	After fit		
		Set 1	Set 2	Set 3
x-x(μm)	571	16	19	17
x-y(μm)	184	17	17	17
y-x(μm)	60	8	8	8
y-y(μm)	150	10	4	10
H-dis.(mm)	267	12	14	15
V-Dis.(mm)	60	12	12	13

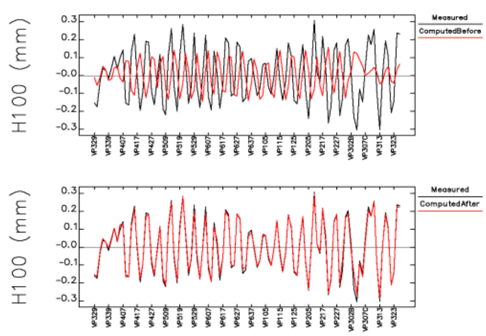


Figure 1: Typical measured and calculated vertical responses to a horizontal excitation before (Top) and after the fit (bottom).

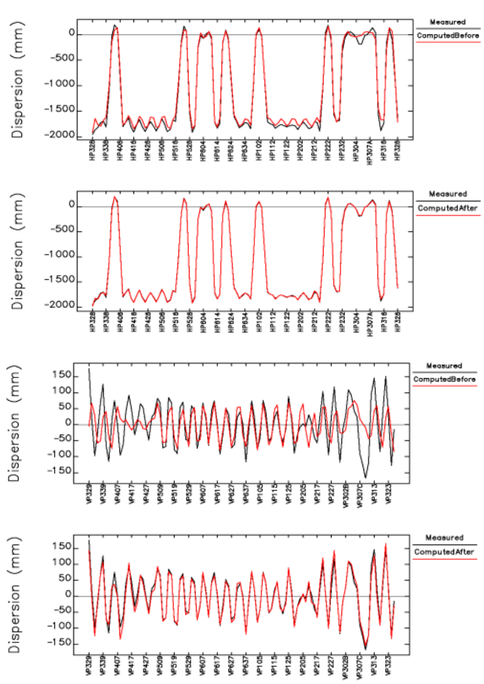


Figure 2: Measured and fitted dispersion in both horizontal (Top) and vertical planes (Bottom)

The solution of the fit is only one set of the possible variables that makes model response matrix coincide with the measured response matrix within the accuracy of the measurements. Among them, quadrupole gradient errors and rolls define beta functions and coupling of the machine. With 3 sets of the solutions, we may not be able to determine the unique model that resembles the real machine, but we can find something in common, that indicates something real in the machine. Figure 3 shows the errors of quadrupole gradient in percentage (Top)and the errors of integrated skew quads strength in kG/cm (bottom), obtained by the fitting from 3 different data sets. We can see some significant differences between 3 solutions. However, most of the quadrupole gradient errors are randomly distributed in the range of 2%, and the errors of integrated skew quad strength are around ±0.2 kG/cm. All three data sets show larger errors at the same magnets, and these results are also similar to those obtained with local 3-bump method [2]. Further investigations will be done for these magnets.

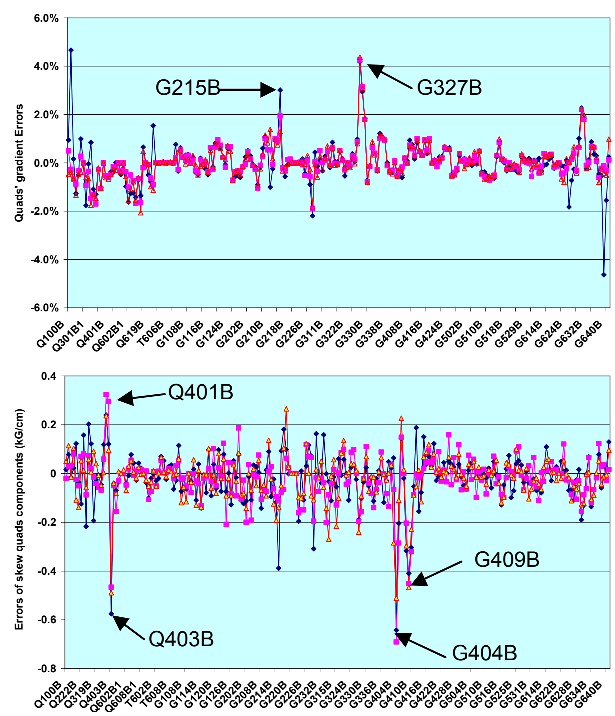
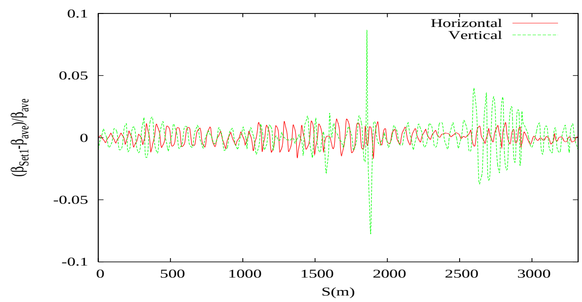


Figure 3: Top: quadrupole gradient errors; bottom: errors of integrated skew quads strength.

We obtained the model beta-functions by inserting quadruple errors into the designed lattice. All 3 different sets of solutions give the beta-functions with very little differences. Figure 4 (Top) gives the relative differences of one of the solutions from the average of all the three solutions, the total RMS difference are 1.6% in horizontal and 1.4% in vertical planes without taking the spikes into considerations. Spikes shown are around G640M, and needs further investigation. Figure 4 (bottom) shows the relative beta function errors compared to the designed lattice. The difference is up to 40% in horizontal, and 20% in vertical planes.

Unlike quadrupole errors, BPM calibrations and rolls have to be unique for all three data sets. Figure 5 gives calibration of horizontal BPMs for all three solutions. It tells us that most of BPMs calibrations are within 2% gain error, except some large aperture BPMs from 303 to 307 and from 601 to 610, up to 8%. Again, 3 sets of solutions show little difference.



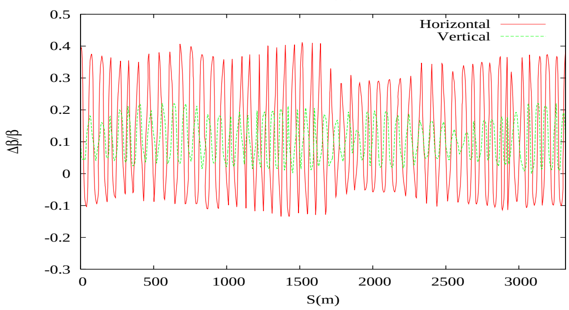
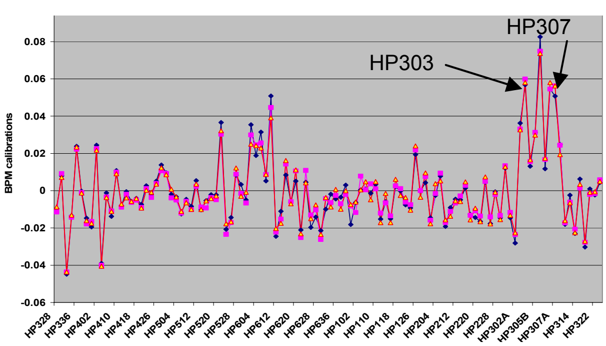


Figure 4: Top: Relative differences of beta-functions of one set of solutions from the average of all the three solutions;
Bottom: Relative beta-function of measured value to designed value.



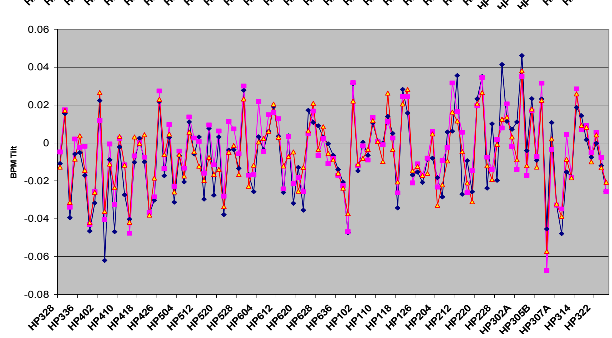


Figure 5: Top: Horizontal BPMs' gain errors; Bottom: Horizontal BPM Tilt

CONCLUSION

The Orbit Response Matrix Fit technique for fully coupled motion based on the measurement and the analysis of many differential orbits was applied to Recycler. We have significantly improved the linear model of the Recycler ring. We have found some large quadrupole and skew quadrupole errors at some magnets, further studies with local three bumps will follow. We have obtained model beta-functions with estimated accuracy of 1.5%. Independent measurements with turn-by-turn data confirmed the results. We have also certified gain errors of all BPMs.

This better knowledge of the lattice model will help us to improve the operation of the Recycler ring. We drove the coefficients for tune control (Tune Mult) based on this model, and it gives the prediction within 2% of expected.

Already, the new model was used to calculate the growth rate of the instability of the cooled beam in the machine and showed very good agreement with the real machine limit [8].

ACKNOLOWDGEMENT

One author (Meiqin Xiao) would like to thank Cons Gattuso for his operation support in orbit measurement. She would also like to thank Sergei Nagaishev for his support to the studies. This work has also been supported by Kathy Harkay from APS, ANL.

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