# PRECISION MEASUREMENT AND IMPROVEMENT OF e+, e- STORAGE RINGS *

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*Abstract*

Through horizontal and vertical excitations, we have been able to make a precision measurement of linear geometric optics parameters with a Model-Independent Analysis (MIA) [1]. We have also been able to build up a computer model that matches the real accelerator in linear geometric optics with an SVD-enhanced Least-square fitting process [2]. Recently, with the addition of longitudinal excitation, we are able to build up a computer virtual machine that matches the real accelerators in linear optics including dispersion without additional fitting variables. With this optics-matched virtual machine, we are able to find solutions that make changes of selected normal and skew quadrupoles for machine optics improvement. It has made major contributions to improve PEP-II optics and luminosity. Examples from application to PEP-II machines will be presented.

## INTRODUCTION

To improve the optics of e+, e- storages rings, it would be very helpful if one has an accurate lattice model. In some cases, the designed ideal lattice may serve such purpose to some extent. However, in most cases, real accelerator optics improvement requires accurate measurement of key or all optics parameters. In this paper we present a complete linear optics model that can match the real machine linear optics. We call such a complete model a virtual machine.

The virtual machine model starts with the ideal design lattice as its initial state. All quadrupole strengths, sextupole feed-downs, all BPM gains, and BPM cross-plane couplings are then considered as variables to fit a complete linear-optics set of well chosen quantities that are obtainable from both the computer virtual machine and the real machine measurement. To interpret the above in short, one can have a simple mathematical formulae,

$$\vec{Y}(\vec{X}) = \vec{Y}_m, \tag{1}$$

where all variables are represented by the array (a vector) $\vec{X}$; the to-be-fitted quantities obtained from the virtual model and their corresponding quantities from measurement are represented by the array $\vec{Y}$ and the array $\vec{Y}_m$ respectively. One may call that $\vec{Y}$ is the response to the $\vec{X}$ and therefore is a vector function of $\vec{X}$ as is explicitly shown in the equation.

The response quantities, we have chosen for geometric optics, are the local Green's functions and the phase advances among BPMs. The local Green's functions are simply the transfer matrix components, R12, R34, R32, R14, between any two BPMs. There are essentially unlimited of such Green's functions that help in fitting convergence and accuracy. We could also choose eigen coupling ellipses' tilt angles and axis ratios at all double-view BPMs location as response quantities. However, we usually leave these coupling quantities alone for after-fitting check to see if they automatically match between the virtual machine and the real machine measurement to make sure the virtual model is indeed accurate.

The above variables and response quantities form a complete fitting system for geometric optics. Therefore, if we include linear dispersions at BPMs as response quantities, we should add suitable bending magnet strengths and/or orbit corrector strengths as fitting variables. However, we found that once the geometric optics was fitted, the dispersion was roughly matched between the virtual model and the measurement for most cases. This encouraged us to consider adding dispersion fitting without adding bending or corrector magnet strengths as variables. Depending on each case, we may turn on more normal quadrupole skew components as variables to achieve dispersion fitting without hurting the geometric fitting.

Once the virtual accelerator is obtained, instead of comparing it to the ideal lattice model for finding and adjusting one or two magnets with noticeable differences, we would go on with this virtual accelerator to search for an easily-approachable better-optics model by pre-selecting and fitting a group of limited number of normal and skew quadrupole strengths and then create a machine operation knob for practicing the corresponding quadrupole strengths adjustment in the real accelerator. These procedures have been successfully applied for PEP-II optics improvement and have made a major contribution for PEP-II luminosity enhancement. Examples from PEP-II results will be shown.

## PRECISION MEASUREMENT

### *Geometric Orbits*

Linear geometric optics is determined if one gets 4 independent linear orbits. This can be shown by the obtainable linear mapping, $Z^b = R^{ab}Z^a$, and so $R^{ab} = Z^bZ^{a-1}$, where the 4-by-4 matrix, $Z^a = [\vec{z}_1^a, \vec{z}_2^a, \vec{z}_3^a, \vec{z}_4^a]$, represents 4 independent linear orbits at location $a$, and $R^{ab}$ is the linear map from location $a$ to location $b$. Therefore, a complete geometric set of data must be able to provide the extraction of 4 independent orbits.

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To offset radiation damping, the most economic process for such data acquisition would be through two orthogonal resonance excitations, one at the horizontal (eigen-plane 1) and the other at the vertical (eigen-plane 2) betatron tunes, and then take and store buffered BPM data. Since a betatron motion has two degrees of freedom (the phase and the amplitude), each excitation would generate a pair of conjugate (cosine- and sine-like) betatron motion orbits. They are obtained from the real and imaginary parts of tune-matched FFT respectively. Therefore, a complete set of 4 independent linear (X and Y) orbits can be extracted from the two eigen-mode excitations.

### *Dispersion*

To compliment the above linear geometric data acquisition, longitudinal oscillation at the synchrotron tune is also resonantly excited for an additional transverse BPM data acquisition. Dispersions at BPM locations are then measured by taking a longitudinal-tune-matched (zooming) FFT from such BPM turn-by-turn BPM data.

## RESPONSE QUANTITIES AND THEIR CORRESPONDING QUANTITIES FROM MEASUREMENT

Once the variables in the virtual lattice model, that is $\vec{X}$ in Eq. 1, is given, one can update the virtual lattice transfer matrices. The response quantities ($\vec{Y}$ in Eq. 1), that is, the phase advances and the Greens' functions among BPMs and the dispersions at BPM locations, are then calculated by projection of these updated transfer matrices or the concatenated one-turn linear maps. Their corresponding quantities from measurement ($\vec{Y}_m$ in Eq. 1) are described below:

### *Phase Advances*

The orbit betatron phase at each BPM location can be obtained by taking the arctangent of the ratio of the imaginary part to the real part of the resonance excitation FFT mode [2]. Phase advances between adjacent BPMs can then be calculated by subtraction. Note that the ratio of the imaginary part to the real part of the FFT will cancel the linear BPM gains but not the BPM cross couplings. Therefore the phase advances among BPMs are repeatedly calculated during the Least Square fitting process as the BPM cross couplings and BPM gains are updated to correct the linear orbits.

### *Linear Green's Functions*

The linear Green's function are simply the $R_{12}^{ab}, R_{34}^{ab}, R_{14}^{ab}, R_{32}^{ab}$ of the linear transfer matrix between any two BPMs labeled as $a$ and $b$. They are given in the data measurement space [3] and so to match these measured quantities, the variables for BPM gains and cross couplings have to be applied to the response Greens' functions from the updated virtual model for their transformation into the data measurement space.

## MEASUREMENT AND IMPROVEMENT OF PEP-II STORAGE RINGS

Once the optics-matched virtual machine is obtained through an SVD-enhanced Least-Square fitting [2], the updated transfer matrices can be concatenated into one-turn maps at the desire locations for calculating optics parameters. One can also find solutions by fitting a well selected set of normal and skew quadrupoles as well as orbit correctors for improving the optics, such as reducing the beta beating and the linear coupling, optimizing beta functions at IP, bringing the working tune to near half integer, and improving dispersion. Furthermore, this virtual model can feed to the lattice program LEGO and the beam-beam simulation [4].

Shown in Figure 1 is the PEP-II HER beta functions on Nov. 22, 2005, which shows high beta beat and was subsequently corrected through the solution from the MIA virtual model. Shown in Figure 2 is the PEP-II beta function on Mar. 16, 2006, showing that the beta beat had been much improved. From the MIA accurate virtual machine, we have been able to identify a key magnet (QF5L). This normal quadrupole along with the linear trombone quads and local and global skews are used as variables in the MIA program for finding the solution from the virtual model. The solution is then dialed into the PEP-II HER.

As mentioned above, we have been able to include dispersion measurement in the virtual model without adding new type of variables. Figure 3 compares dispersion from the virtual model and from the direct measurement for HER on Nov. 22, 2005. There is no bending magnet or orbit corrector involved in the fitting. The vertical dispersion beat was subsequently improved with the MIA virtual models.

MIA virtual model has also been applied to PEP-II LER. As an example, PEP-II LER major orbit steering usually accompanied by a much degraded linear optics due to change of sextupole feed-downs, which had been very dif-

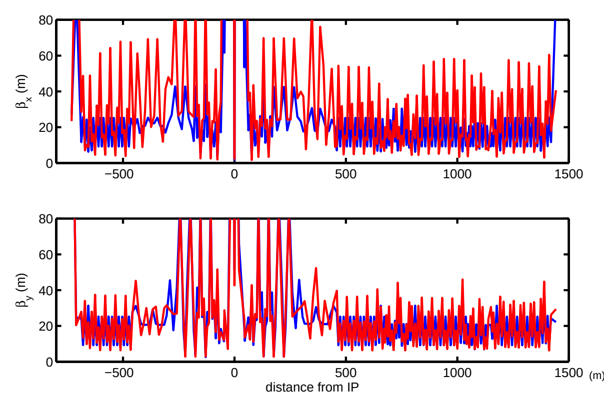


Figure 1: Comparing beta function between the ideal lattice (blue color) and the virtual machine on Nov. 22, 2005 for PEP-II HER. The PEP-II HER showed high beta beat, which were subsequently corrected through solution from the virtual model.

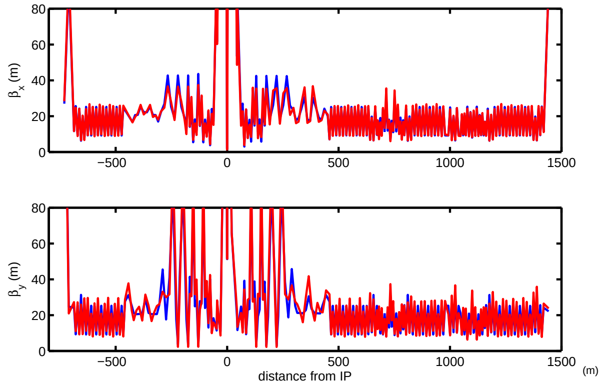


Figure 2: Comparing beta function between the ideal lattice (blue color) and the virtual machine on Mar. 16, 2006 for PEP-II HER. Beta beat shown in Fig. 1 has been much improved. From the accurate virtual machine, we have been able to identify a key magnet (QF5L). This normal quadrupole along with the linear trombone quads and local and global skews are used as variables for finding a solution from the virtual model.

ficult to correct without an accurate optics model. With the accurate MIA virtual model established for the LER right after the steering, we have been able to correct the linear optics such that the major LER orbit steering in April, 2006 is survived. Figure 5 shows the LER linear coupling characteristics after dialing in solutions right after the major orbit steering.

## CONCLUSION

We have used a model-independent analysis (MIA) for accurate orbit and phase advance measurement and then uses an SVD-enhanced Least Square fitting for building accurate virtual models for e+, e- storage rings. MIA virtual

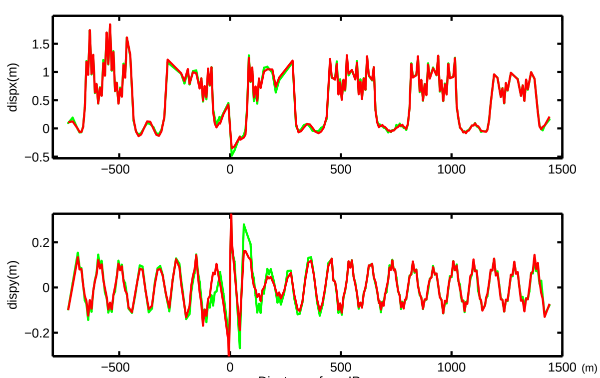


Figure 3: Comparing dispersion between the direct measurement (green color) and the virtual machine on Nov. 22, 2005 for PEP-II HER. No bending magnet or orbit corrector were added as fitting variables. The vertical dispersion beat was subsequently improved with the MIA virtual models.

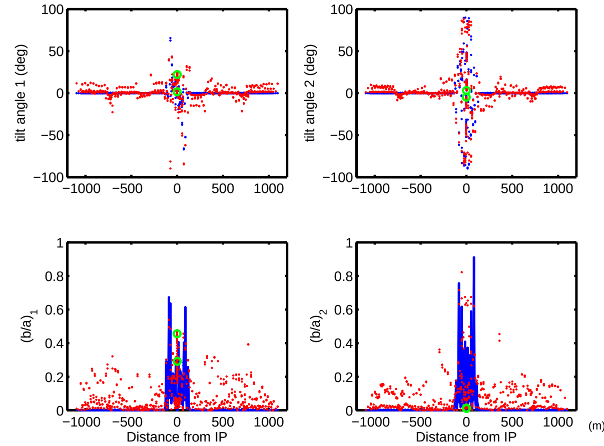


Figure 4: Comparing linear coupling between the ideal lattice (blue color) and the virtual machine on Apr. 21 for PEP-II LER after a major orbit steering that was accompanied by a MIA solution for linear optics correction. This PEP-II LER coupling is with a record low residual from the ideal lattice. Top plot shows the Eigen ellipse tilt angles while the bottom plot shows the Eigen ellipse axis ratios for Eigen plane 1 and 2 respectively.

model matches, very well, the real-machine linear optics including dispersion. It has successfully fixed PEP-II beta beat, linear coupling, half-integer working tune. The success comes from that: (a) the SVD-enhanced Least-Square fitting can avoid degeneracies and has a fairly fast convergence rate allowing for application to a fairly large system; (b) the PEP-II ring has a reasonable amount of BPMs allowing for extracting sufficient physical quantities for fitting; and (c) the linear Green's functions among BPMs can provide essentially unlimited fitting constraints that add significantly on the convergence.

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