PEP-II Beta Beat Fixes with MIA

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We first find a virtual accelerator for the HER or the LER through determination of all quadrupole strengths and sextupole feed-downs as well as all BPM gains and BPM cross-plane couplings by an SVD-enhanced Least-squares fitting of the quantities derivable from a complete set of orbits. These quantities are the phase advances, the Green's functions, and the tilt angles and axis ratios of the coupling eigen ellipses. They are obtained by analyzing turn-by-turn Beam Position Monitor (BPM) data with a high-resolution model-independent analysis (MIA). Once the virtual accelerator is found, we select a limited number of key quadrupoles, for example, the linear trombone quadrupoles and the global skews, for Least-square fitting of their strengths to minimize the beta beat while keeping other optics characters unchanged if not improved. We then dial in these limited number of quadrupole strength changes to the real accelerator (HER or LER) to achieve a better-performance PEP-II. Noticeable achievement by this MIA technique has been that MIA has helped PEP-II achieve its breaking record peak luminosity of $6.5X10^{33}cm^{-2}s^{-1}$ in 2003 by bringing the LER working tune to near half integer and simultaneously fixing the beta beat, which would, otherwise, be difficult without MIA because of the strong LER coupling effect.

1. INTRODUCTION

With an SVD-enhanced Least Square fitting technique, we consider all quadrupole strengths and sextupole feed-downs in the lattice model as well as all BPM gains and BPM cross-plane couplings as variables to fit the Local Green's functions [1] [2], the phase advances [3] as well as the coupling ellipses among BPMs calculated from a lattice model to those derived from orbit measurement using a model-independent analysis (MIA) [4]. Once the lattice model is fitted to the orbit measurement, we call this lattice model the computer virtual accelerator which matches the real accelerator in linear optics. We then search for a better-optics model that is easy to approach from the virtual accelerator. We call this better-optics lattice model the wanted accelerator which usually requires only a limited number of quadrupole strengths adjustment from the virtual accelerator. Once the wanted accelerator is obtained, we then practice the corresponding quadrupole strengths adjustment in the real accelerator. This procedure has been repeatedly used for the PEP-II optics improvement, especially for PEP-II beta beat fixes, which, most of the time, involves only adjustment of the linear trombone quadrupole strengths and global skew strengths. Noticeable achievement has been that MIA has helped PEP-II achieve its breaking record peak luminosity above $6.5X10^{33}cm^{-2}s^{-1}$ in 2003 by bringing the LER working tune to near half integer and simultaneously fixing the beta beat, which would, otherwise, be difficult without MIA because of the strong LER coupling effect.

2. A complete set of linear orbits

The linear optics is determined if one gets 4 independent linear orbits. Taking the PEP-II Low-Energy Ring (LER) as an example, we describe, in this section, how we extract 4 independent linear orbits through massive BPM buffer data acquisition.

The PEP-II BPM system has been much upgraded by converting more single-view BPMs into double-view BPMs, particularly for the sextupole and IR locations, in the last couple of years. There were originally only 13 double-view BPMs in the LER. Now we have 118 double-view BPMs. Of the 319 BPMs in the LER, we have now a total of 222 horizontal(X)-view and 215 vertical(Y)-view BPMs. Therefore, one-turn BPM buffer data can offer a maximum of 222 X data and 215 Y data. Unlike Linacs where there is often enough incoming jitter in the beam to measure and identify betatron modes, in the rings, to offset radiation damping, the beam is resonantly excited by a shaker at the horizontal betatron (eigen) tune and then at the vertical betatron (eigen) tune, each for 1024 turns to get a complete set of data which are stored in 2 sets of matrices, one set for the horizontal and the other set for the vertical excitation. Each set has two matrices, one 1024-by-222 matrix for storing x data and one 1024-by-215 matrix for storing y data. There may be bad BPMs and so the columns are reduced accordingly.

Once the Massive BPM buffer data is stored in two matrices and the bad BPM data are removed, we perform an FFT on columns of the data to extract the resonantly excited modes. Each resonantly excited mode contains two degrees of freedom of the betatron motion; the cosine-like betatron orbit is represented by the real part and the sine-like betatron orbit is represented by the imaginary part. Therefore, a total of 4 independent linear (X and Y) orbits can be extracted from the two eigen-mode excitations. Shown in figure 1 are typical independent linear orbits for LER. Linear coupling of the LER is clear shown in these orbits especially in the IR region where BPM sequence numbers are around 160.

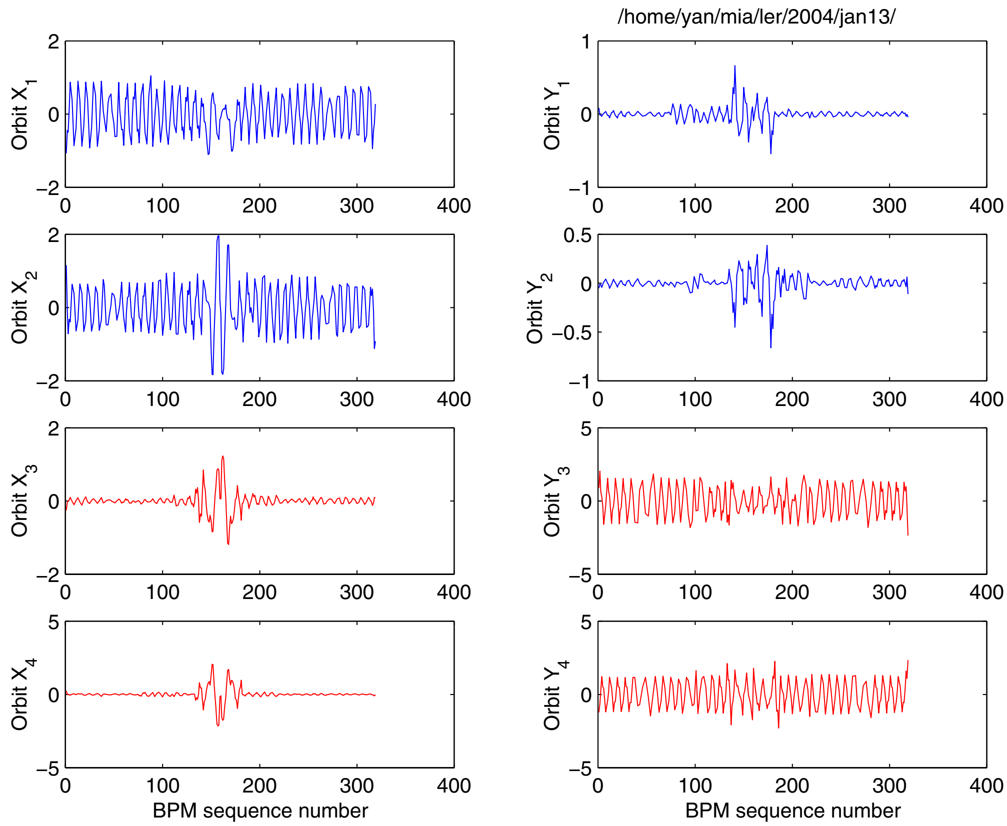

Figure 1: *Four independent orbits extracted from PEP-II LER BPM buffer data taken on January 13, 2004. The first two orbits (x1, y1) and (x2, y2) are extracted from beam orbit excitation at the horizontal tune while the other two orbits (x3, y3) and (x4, y4) are from excitation at the vertical tune.*

3. Quantities derivable from the linear orbits

3.1. Phase advances

One can calculate the orbit betatron phase at each BPM location by simply taking the arctangent of the ratio of the imaginary part to the real part of the resonance excitation FFT mode [3]. Phase advances between adjacent BPMs can then be calculated by subtraction. Note that these phase advances are independent of the BPM gains because they are cancelled in the ratio. However, they are not independent from the BPM cross coupling. Therefore the phases 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.

3.2. Linear Green's functions

Another kind of derivatives of the linear orbits are the linear Green's function, 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 as [1]

$$(x_1^a x_2^b - x_2^a x_1^b)/Q_{12} + (x_3^a x_4^b - x_4^a x_3^b)/Q_{34} = \mathcal{R}_{12}^{ab}\,, \quad (1)$$

$$(x_1^a y_2^b - x_2^a y_1^b)/Q_{12} + (x_3^a y_4^b - x_4^a y_3^b)/Q_{34} = \mathcal{R}_{32}^{ab}\,, \quad (2)$$

$$(y_1^a x_2^b - y_2^a x_1^b)/Q_{12} + (y_3^a x_4^b - y_4^a x_3^b)/Q_{34} = \mathcal{R}_{14}^{ab}\,, \quad (3)$$

$$(y_1^a y_2^b - y_2^a y_1^b)/Q_{12} + (y_3^a y_4^b - y_4^a y_3^b)/Q_{34} = \mathcal{R}_{34}^{ab}\,, \quad (4)$$

where Q_{12} and Q_{34} are the two invariants relating to the two resonance excitation amplitude, (x_1, y_1), (x_2, y_2), (x_3, y_3), (x_4, y_4) are the 4 independent linear orbits, and $\mathcal{R}_{12}$, $R_{32}, \mathcal{R}_{14}$, $\mathcal{R}_{34}$ are given as [1]

$$\mathcal{R}_{12}^{ab} = g_x^b R_{12}^{ab} g_x^a + g_x^b R_{14}^{ab} \theta_{xy}^a + \theta_{xy}^b R_{32}^{ab} g_x^a + \theta_{xy}^b R_{34}^{ab} \theta_{xy}^a,$$

$$\mathcal{R}_{32}^{ab} = g_y^b R_{32}^{ab} g_x^a + g_y^b R_{34}^{ab} \theta_{xy}^a + \theta_{yx}^b R_{12}^{ab} g_x^a + \theta_{yx}^b R_{14}^{ab} \theta_{xy}^a,$$

$$\mathcal{R}_{14}^{ab} = g_x^b R_{14}^{ab} g_y^a + g_x^b R_{12}^{ab} \theta_{yx}^a + \theta_{xy}^b R_{34}^{ab} g_y^a + \theta_{xy}^b R_{32}^{ab} \theta_{yx}^a,$$

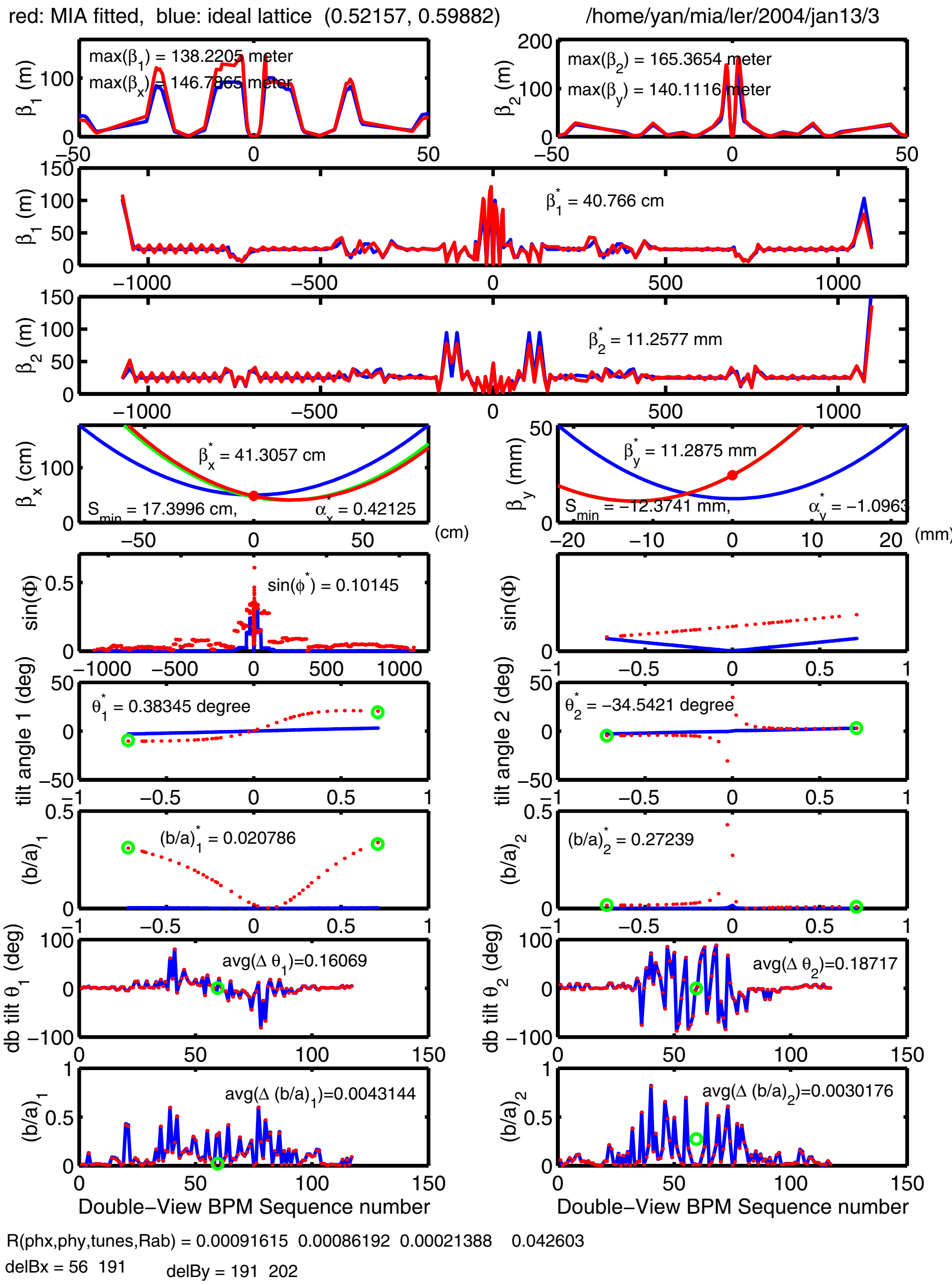

Figure 2: *A typical plot to show a virtual accelerator linear optics characteristics (red color) compared with those of the designed lattice (blue color), except the last 4 plots which compare the coupling ellispe parameters calculated from the fitted virtual accelerator to those from measurement. In this case, it is PEP-II LER on January 13, 2004. The top two plots show the two eigen beta functions in the vicinity of IP followed by two plots that show the beta functions for the whole machine and then the beta function plots at IP, which show the β^*'s and the waist. The next two plots show the phase-space coupling angles followed by 4 plots that show the coupling eigen-plane ellipse tilt angles and axis ratios at IP. The coupling ellipse parameters, the tilt angles and the axis ratios, for all double-view BPMs are compared in the last (bottom) 4 plots for those from measurement and those calculated from the virtual accelerator, which show a very good match - a necessary condition for a good fitting.*

$$\mathcal{R}_{34}^{ab} = g_y^b R_{34}^{ab} g_y^a + g_y^b R_{32}^{ab} \theta_{yx}^a + \theta_{yx}^b R_{14}^{ab} g_y^a + \theta_{yx}^b R_{12}^{ab} \theta_{yx}^a,$$

where g_x's, g_y's are the BPM gains, and θ_{xy}'s and θ_{yx}'s are the BPM cross-coupling multipliers. $R_{12}^{ab}, R_{34}^{ab}, R_{32}^{ab}, R_{14}^{ab}$ are the Green's functions between any two BPMs labeled as a and b of the machine.

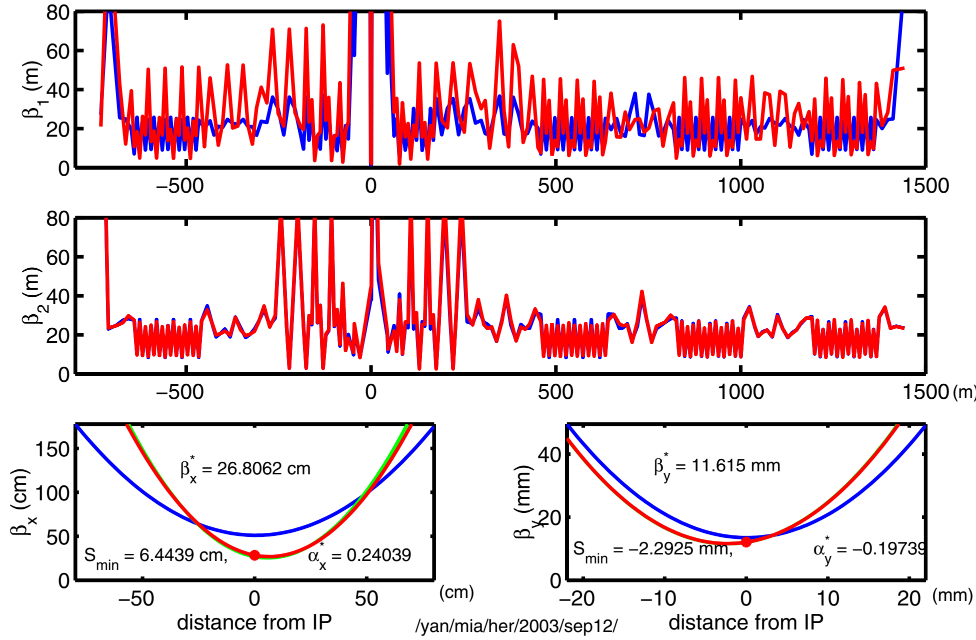

Figure 3: *HER beta functions after being adjusted to match the very strong LER. β_x at IP is reduced into about half but with a very large β_x beat. β_y at IP is kept about the same as before and with almost no beta beat.*

3.3. Coupling ellipses

For each double-view BPM, one can trace the MIA extracted high-resolution real-space orbits to obtain a coupling ellipse in real space for each resonance (eigen) excitation. Therefore, one can calculate coupling ellipse tilt angles and axis ratios for all double-view BPMs in each of the two eigen planes [5]. The tilt angle of the coupling ellipse at IP for the horizontal eigen plane is very close to the real tilt angle of the beam at IP. One can also calculate these corresponding coupling parameters from the linear map of a lattice model. Therefore, these quantities can be used as part of the fitting parameters to help obtain an accurate virtual accelerator.

4. SVD-Enhanced least-squares fitting

One can calculate, from a lattice model, the linear orbit derivatives that correspond to the above measurements. Therefore, with reasonable guessed initial value (for example, initialization with the machine configuration), one can vary the linear model variables, all quadrupole strengths and all sextupole feed-downs as well all BPM gains and BPM cross couplings, to fit the linear orbit derivatives calculated from the lattice to the corresponding measurements from buffered BPM data. We used an SVD-enhanced least-square fitting that guarantees convergence for the fitting.

We form all variables and all measured linear orbit derivatives into one-dimensional arrays, i.e. vectors, represented by $\vec{X}$ and $\vec{Y}m$ respectively. The corresponding derivatives from the model, which are implicit functions of all the fitting variables, are also formed into a vector functional form given by $\vec{Y}(\vec{X})$. Denoting the reasonably guessed variable values as $\vec{x}_o$, and letting $\vec{X} = \vec{x}_o + \vec{x}$, one has

$$\vec{Y}(\vec{x}_o + \vec{x}) = \vec{Y}(\vec{x}_o) + M\vec{x} + \vec{\eta}(\vec{x}) = \vec{Y}m,$$

where $\vec{\eta}(\vec{x})$ contains nonlinear terms of the the Taylor expansion of $\vec{Y}(\vec{x}_o + \vec{x})$, which is ignored in the iteration equation given by

$$M\vec{x} = \vec{Y}m - \vec{Y}(\vec{x}_o) = \vec{b}$$

.

Since there could be degeneracies causing the least-squares fitting solution, $\vec{x} = (M^T M)^{-1} M^T \vec{b}$, to diverge, we use an SVD-enhanced least-squares fitting which solves the above iteration equation by selecting dominant SVD modes. At each iteration, the guessed variable values, $\vec{x}_o$ is updated and so the linear derivative matrix, M, is also updated for the next iteration.

Through iterations, the corresponding phase advances and local linear Green's functions calculated from the model get much closer to those measured. Once the residuals can no longer be reduced, the iterative process stops.

In most cases, we do not fit for the coupling ellipses derivatives, but reserve them for after-fit check. They

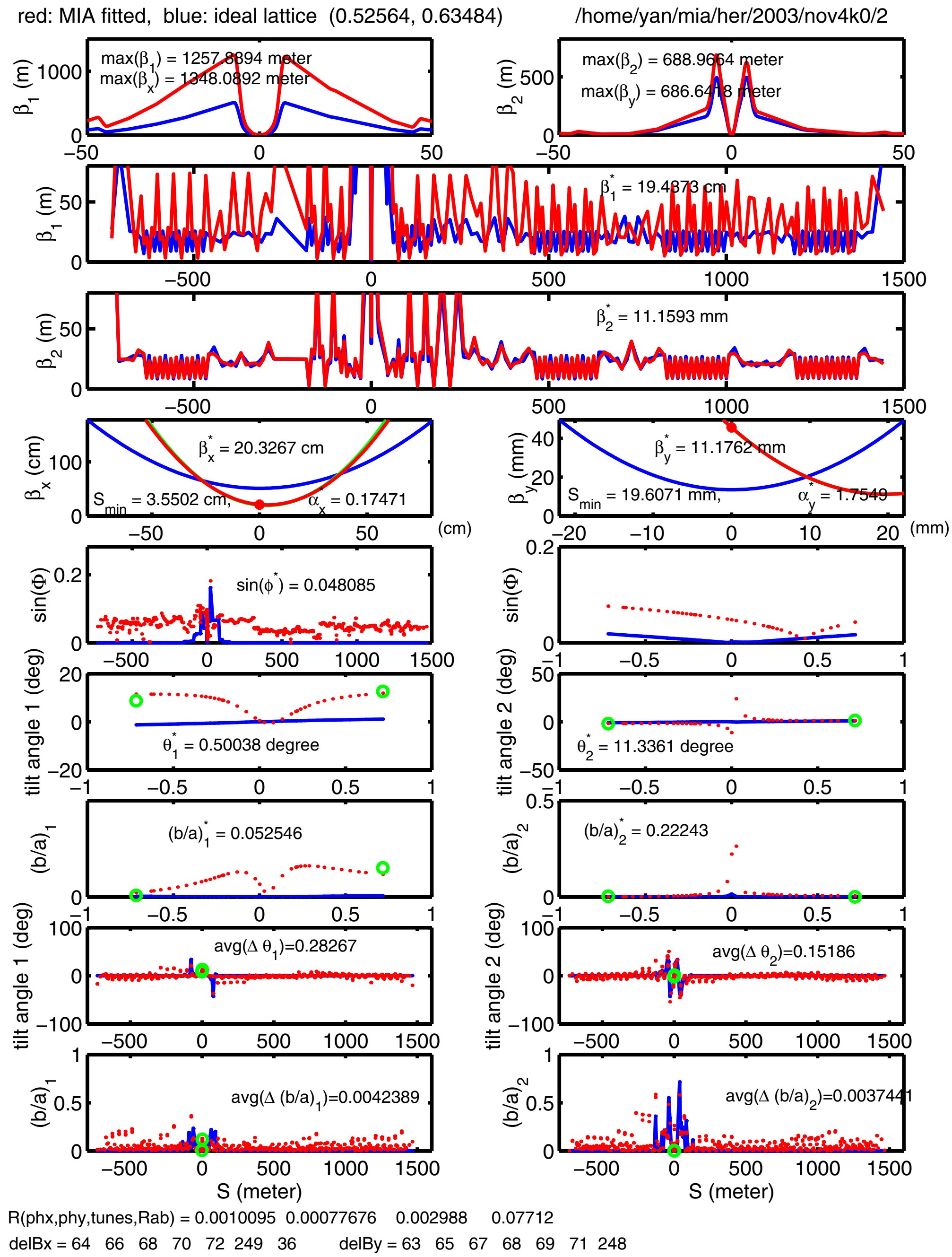

Figure 4: *HER linear optics on November 4, 2003. Plots shown are obtained from its corresponding MIA virtual accelerator.*

automatically matches - a necessary condition to make sure the fitting is all right. Shown in Figure 2 are optics characteristics plots for a well-fitted LER.

5. PEP-II LER beta beat fixes

Because of lower energy than the HER, the PEP-II LER responds much stronger to the BaBar solenoid at IP and so LER is a stronger coupled accelerator. Without dealing with the linear coupling, it is difficult to fix the LER beta beat. Before MIA was fully developed and so could be applied, without MIA, we tried several times to bring the LER horizontal working tune to near half integers but only to stop the process at each attempt because strong beta beat developed. On April 29, 2003, we successfully use MIA to bring the LER to a near half integer working tune and simultaneously fixed the beta beat by dialing in a MIA generated knob that involved adjustment of the

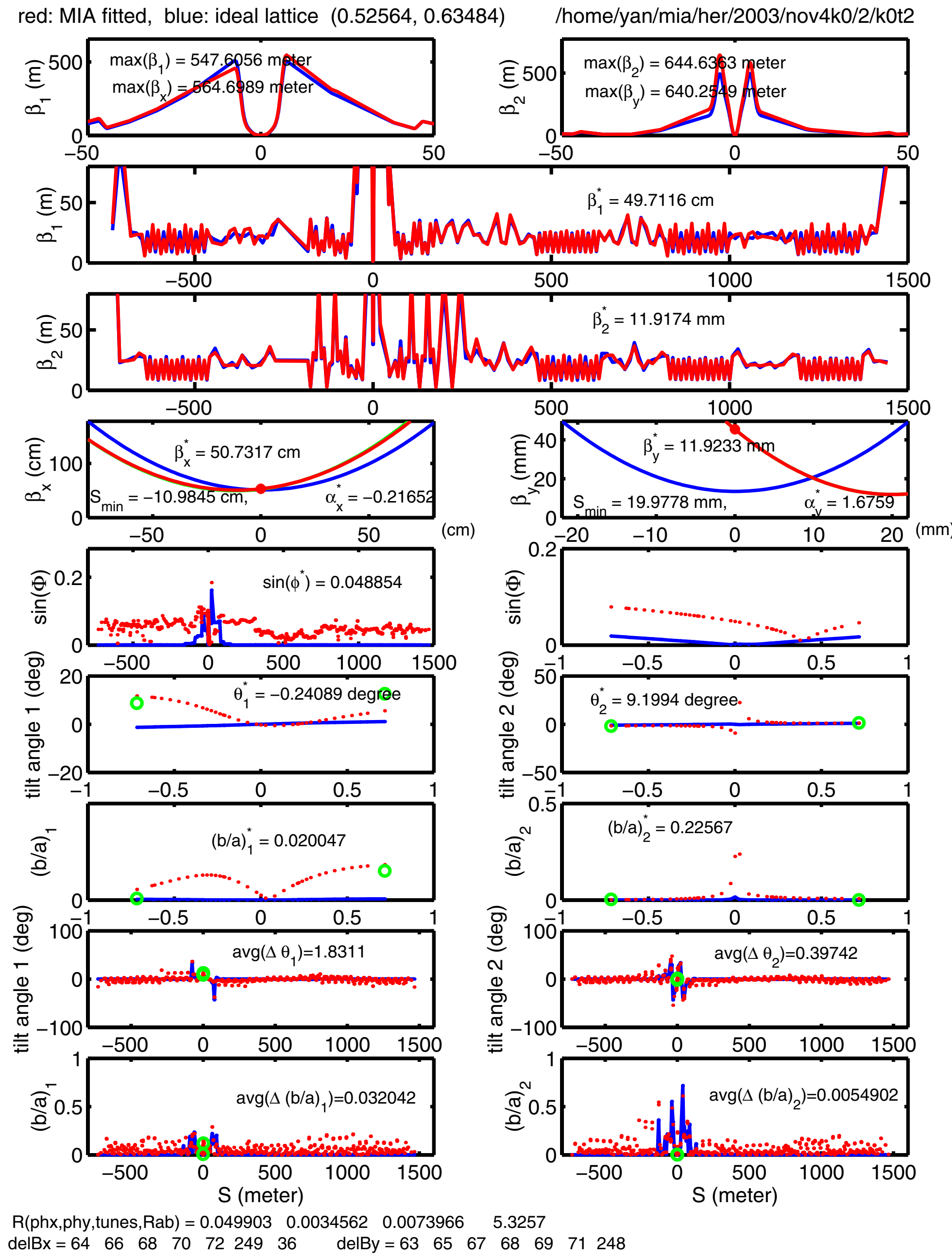

Figure 5: *Virtual HER linear optics after dialing in the beta beat fixing solution obtained with MIA, which showed that the HER could be brought back to low beta beat but restored to near the design β_x^*. Other optics characteristics, such as linear couplings and β_y^*, are not changed.*

linear trombone quadrupoles and the 4 global skews. The reason MIA was successful is because MIA takes care of the complete set of linear optics characteristics. The linear coupling is fully treated without any discount. Success of bringing PEP-II horizontal working tune to near half integer improves the beam-beam effects and subsequently, we have a breaking-record PEP-II luminosity above $6.5X10^{33}cm^{-2}s^{-1}$ after getting LER and HER matched.

6. PEP-II HER beta beat fixes

Ideally, PEP-II HER should be a simpler accelerator than the LER because weaker couplings. However, after April 29, 2003, this is not the case anymore. After MIA brought the LER to near half integer working tune and fixed the LER beta beat, the LER beam became the stronger of the two (LER and HER beams), indeed much stronger. To match the two beams for collision, subsequently, the LER β_x^* was

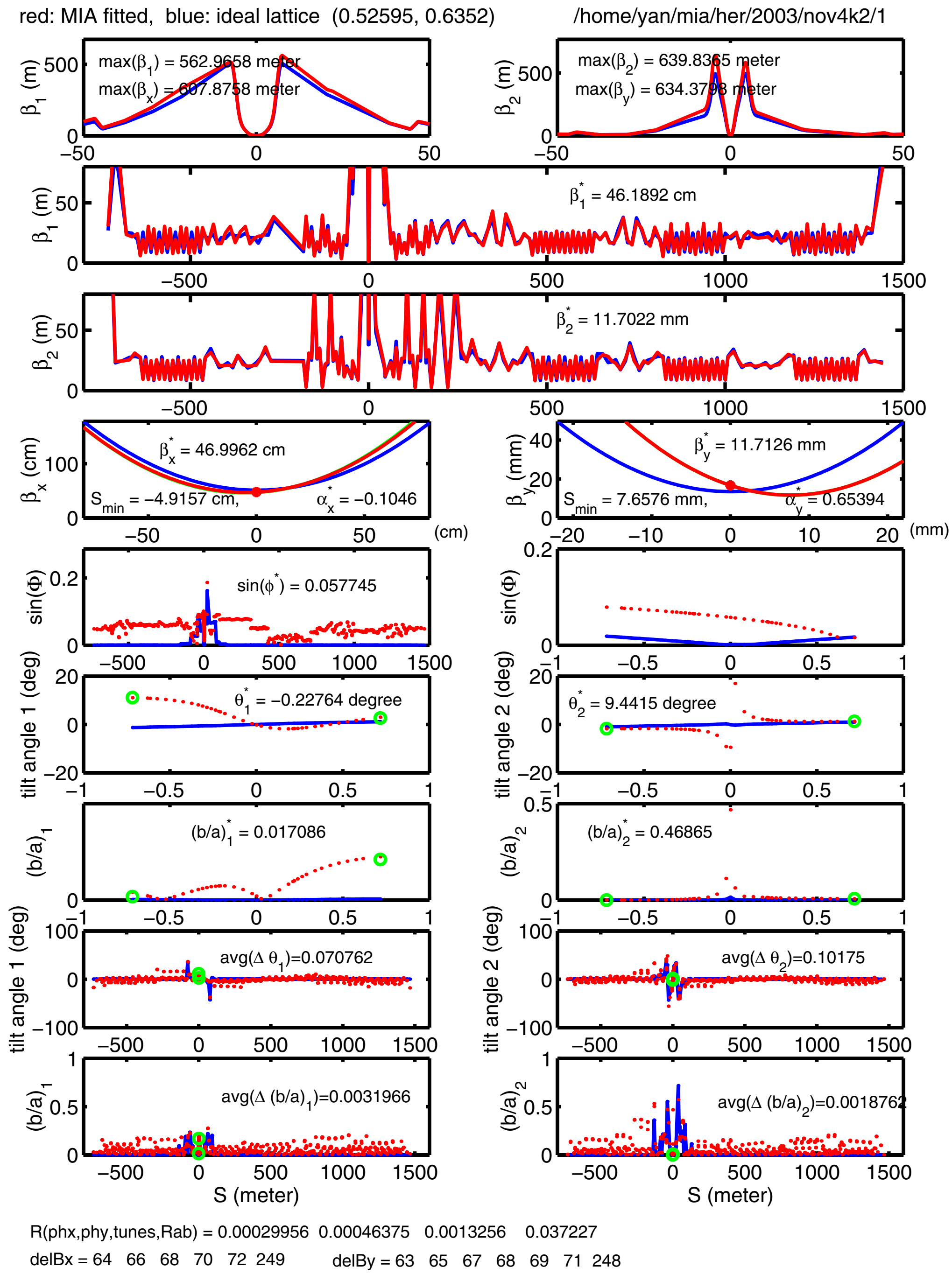

Figure 6: *HER linear optics after dialing in the beta beat fixing solution obtained with MIA into the HER. It shows very much the same as predicted by dialing the knob into the virtual HER.*

increased from about 35 cm to about 50 cm, and the HER β_x^* was reduced into about half, from about 50 cm to about 27 cm but with an above 100% beta beat while keeping the β_y^* unchaged at about 12 mm as shown in Figure 3.

Since PEP-II luminosity was much improved with the matched LER and HER at near half-integer working tune. We were not in a hurry to fixed the large HER beta beat since the HER was very much decoupled and so the second eigen (y) plane was still kept at an excellent condition. As time goes on, in November, 2003, the similar pattern was kept except that the HER was with an even large beta beat which was above 200% and even smaller β_x at IP, which is about 21 cm as shown in Figure 4.

Subsequent, with MIA, we found a solution for fixing the HER beta beat at the price of increased β_x^*. This solution only need to adjust linear trombone quadrupole and the 4 global skews. Dialing the solution knob into the virtual HER in computer we indeed found that the large beta beat was fixed and the β_x^* is increased to about 47 cm as shown in Figure 5.

We tried to dial in the MIA beta beat solution knob into the real HER, and obtained its linear optics as shown in Figure 6, which is very much the same as predicted by dialing the knob into its corresponding virtual accelerator as shown in Figure 5.

7. Summary

MIA has been developed to a mature practical stage for offering countable computer virtual accelerator that matches the real accelerator linear optics. It has been successfully applied to fix PEP-II beta beat. Noticeable contribution to PEP-II machine development has been that MIA has helped PEP-II achieve its breaking record peak luminosity above $6.5X10^{33}cm^{-2}s^{-1}$ in 2003 by bringing the LER working tune to near half integer and simultaneously fixing the beta beat, which would, otherwise, be difficult without MIA because of the strong LER coupling effect.

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