SIMULATION OF LINEAR LATTICE CORRECTION AND COUPLING CORRECTION OF AN ENERGY-RECOVERY LINAC DESIGNED FOR AN APS UPGRADE*

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Abstract

An energy recovery linac (ERL) is one of the candidates for an upgrade of the Advanced Photon Source (APS). In addition to the APS ring and full-energy linac, our design also includes a large turn-around arc that could accommodate new x-ray beamlines as well. In total, the beam trajectory length would be close to 3 km. The ERL lattice has strong focusing to limit emittance growth, and it includes strong sextupoles to keep beam energy spread under control and minimize beam losses. As in storage rings, trajectory errors in sextupoles will result in lattice perturbations that would affect delivered x-ray beam properties. In storage rings, the response matrix fit method is widely used to measure and correct linear lattice errors. Here, we explore the application of the method to the linear lattice correction and coupling correction of an ERL

INTRODUCTION

Linear optics measurement and correction using the response matrix fit method is well known and widely used on modern circular machines. The purpose of this work is to simulate the application of the same method to a non-closed beamline.

Theoretically, there is no big difference between response matrix measurement for closed and non-closed beamlines. The orbit equations are well-known and look similar (top equation is for non-closed trajectory and bottom is for closed trajectory, θ – is the kick strength):

$$x(s) = \theta \sqrt{\beta_s \beta_\theta} \sin(\psi_s - \psi_\theta),$$

$$x(s) = \frac{\theta}{2\sin(\pi\nu)} \sqrt{\beta_s \beta_\theta} \cos(\psi_s - \psi_\theta - \pi\nu) \cdot$$

The measured trajectories in both cases depend on beta functions and phase advances and therefore could be used to derive linear optics. The main practical difference is that in the case of a non-closed beamline, the response matrix is triangular with zeros in the top right triangle.

SIMULATION DETAILS

At the APS, we have been using the response matrix fit method for many years [1]. We added to our existing program an option for working with non-closed trajectories. From our experience, we know that at APS the main sources of focusing errors are non-zero orbits in sextupoles, and we also know that the focusing errors from sextupoles cannot be the precisely represented by nearest quadrupoles [2]. Therefore we decided to include sextupole displacements in the error simulation. Table 1 lists the set of errors that was used for simulations.

Table 1: Errors Used in Calculations

Quadrupole gradient error	0.1 %
Quadrupole tilt	0.001 rad
Sextupole X and Y displacement	1 mm
Corrector calibration error	5 %
Corrector tilt	0.001 rad
BPM calibration error	2 %
BPM tilt	0.001 rad
BPM measurement noise	1 μm

Sextupole displacements were chosen rather large because trajectory errors in sextupoles are defined not by the accuracy of sextupole alignment but by the accuracy of the nearest BPM offset, which could be large. The errors were generated using Gaussian distribution with 2 sigma limit.

For optics correction simulation we used only the APS portion of the ERL because the turn-around arc design has not been finalized to a level of BPM and corrector locations. The lattice of the APS portion is described in [3]. The main difference from the present APS storage ring lattice is zero dispersion in ID straight sections to decrease electron beam size dependence on energy spread.

Special attention was paid to the choice of correctors used for response matrix measurement in our simulations. The APS storage ring has 8 correctors and 11 BPMs per sectors (in most sectors). Presently, for real measurements we use only 27 correctors in each plane (out of 320) evenly distributed along the ring and all BPMs. We limit the number of correctors in order to save measurement time and also to limit the size of the fitting problem. If all the correctors were used, the size of the response matrix derivative would be 15 Gb, which would be too big. Our experience shows that with 27 correctors we still have enough data for an accurate fit. In the case of a circular machine, the location of correctors used for the response matrix measurement is not important as long as they are separated by some phase advance. However, the situation is different for a non-closed beamline where measured trajectory is affected only by elements that are located after the steering magnet. Therefore, for a non-closed beamline, different steering magnets provide a different amount of useful information. Obviously, one would want to use as many steering magnets in the beginning of the beamline as possible while keeping them at some phase-space distance. For our simulations, we used 27 correctors

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in each plane spread over the first six sectors (out of forty) and none after that.

The following procedure was used to simulate the entire process of measurement and optics correction (`elegant` [4] was used for all beta function and trajectory calculations):

- `elegant` parameter file is generated with element errors;
- trajectory is corrected using two correctors per sector (because sextupole displacements can cause large orbit errors);
- "measured" response matrix and dispersion are calculated on the corrected orbit;
- response matrix fit is calculated (dispersion included);
- quadrupole gradient errors opposite to those found in the response matrix fit are applied to correct the optics, and the resulting beta functions are compared with the ideal beta functions

The entire process was run 100 times with different error seeds. Figure 1 shows typical beta functions and dispersion before beta function correction. For each case, we have calculated the relative beta function difference between actual and ideal beta functions and its rms value (the rms value is calculated using all beta function points along the beamline). Figure 2 shows a histogram of the rms values of relative beta function errors before correction. The histogram is calculated over the set of 100 different error seeds. For every seed, the relative beta function error was calculated, and then the rms was calculated using all beta function points along the beamline. Average rms values of the relative beta function difference over all cases is 0.71 for the horizontal and 0.47 for the vertical plane.

CORRECTION RESULTS

Each APS quadrupole magnet has separate power supply. Therefore, the straightforward way to correct the optics is to apply opposite quadrupole gradients. However, this method has some drawbacks that prevent us from using it in real life. To achieve the best possible response matrix fit, we use as many singular values in the matrix inversion as possible. This might lead to the appearance of large quadrupole errors in the solution. After we calculated the beta functions using quadrupole errors from the response matrix fit, we use the inverse beta function response matrix to correct the difference between measured and ideal beta functions. We also adjust the number of singular values in this inversion until we get satisfactory correction accuracy while still keeping quadrupole changes small. This allows us to minimize real quadrupole changes during optics correction at the APS storage ring. However, these arguments are not important for the optics correction simulation here, so we used the straightforward approach to keep our simulations simple. Figure 3 shows a histogram of the rms of relative beta function errors after correction. Average rms of the relative beta function difference over all cases is 0.03 for the horizontal and 0.02 for the vertical plane. Figure 4 shows typical lattice functions after correction.

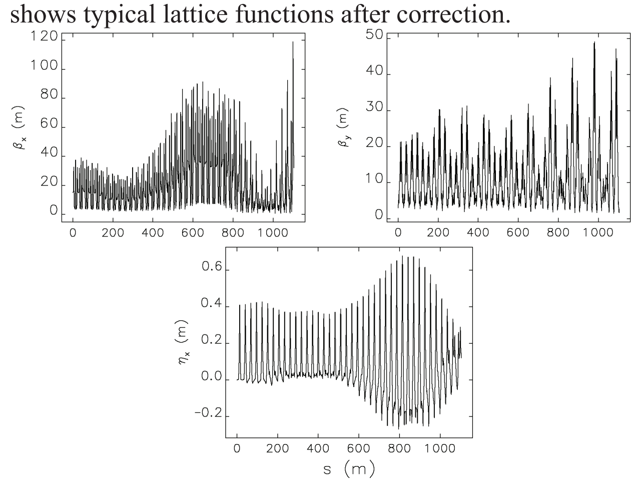

Figure 1: Typical beta functions before beta function correction. Top left – horizontal, top right – vertical, bottom – dispersion.

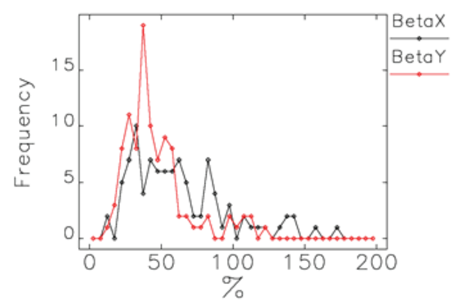

Figure 2: Histogram of the relative beta function error rms before beta function correction.

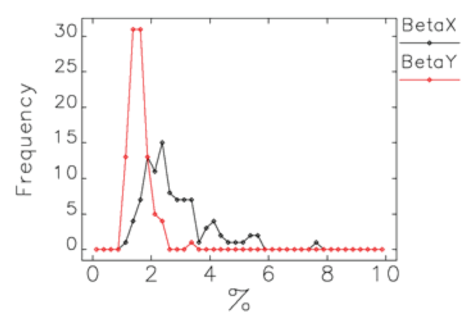

Figure 3: Histogram of the relative beta function error rms after beta function correction.

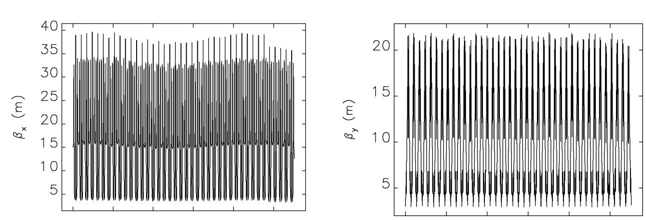

Figure 4: Typical beta functions after beta function correction.

One can ask why the correction is not perfect. Two reasons are obvious – due to BPM noise the response matrix measurement is not accurate and due to the fact that the focusing errors come from sextupoles but are corrected using quadrupoles in different locations. These reasons are likely to explain short-scale perturbations in beta functions. But we can also see a long-scale smooth variation in the horizontal beta function in Figure 4. The reason for that is inaccurate determination of focusing errors in the very beginning of the lattice because the first quadrupoles and sextupoles have only a few trajectories going through them. We have confirmed that argument by adjusting initial beta functions at the entrance of the lattice. A small change in initial beta function conditions allows correcting the long smooth variation seen on top of the left plot of Figure 4. To improve accuracy for the first elements of the measured beamline, one might use several correctors upstream of the measured portion of the beamline.

During our simulations, we have also found that if the focusing errors of the lattice are large enough, sometimes the response matrix fit does not converge because the initial approximation (ideal lattice) is too far from the lattice with errors. We have tested the following procedure, which helps in the case of a convergence problem: split the lattice into pieces, perform a response matrix fit piece by piece (not necessarily to be done to a very accurate level) and apply corrections from piece-by-piece solutions. After this step, the new lattice with errors is closer to the initial lattice and therefore can be solved without problems. This piece-by-piece approach will probably have to be used anyway when correcting optics of the entire ERL just to avoid long measurements and huge matrices. We have tested and confirmed that one can measure and correct only a part of the non-closed beamline.

Coupling Correction

APS has only 19 dedicated skew quadrupole correctors. This number is adequate for the purpose of coupling correction to a level of 1% for the storage ring operation mode. However, this turns out to be insufficient for coupling correction of the small ERL beam – spurious vertical dispersion could not be corrected well enough, and that increases vertical beam size and effective vertical emittance. Figure 5 shows vertical dispersion before and after correction; one can see little improvement after the correction. The effect of not fully compensated coupling on the beam size and effective emittance can be seen in the histograms in Figure 6 (black curve). These histograms are calculated using beam parameters at locations of all insertion devices for all simulated cases. The average vertical beam size is increased by almost a factor of 3.

Such a beam size increase is unacceptable. We repeated the simulations with an increased number of skew quadrupoles from 20 to 80 (two skew quadrupole correctors per sector). Results are presented as red curves in Figure 6. For this case, the average increase in vertical beam size is only 7%.

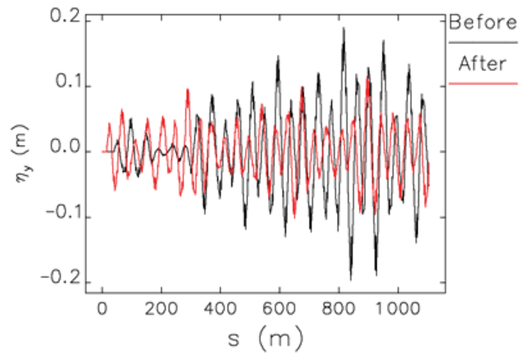

Figure 5: An example of vertical dispersion before and after correction.

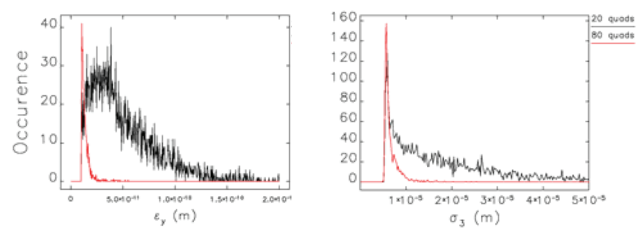

Figure 6: Left – histogram of effective vertical emittance at ID locations; right – histogram of vertical beam sizes at the same points. Black curve corresponds to correction with 20 skew quadrupoles, red curve – with 80 skew quads.

CONCLUSION

We have simulated optics correction for a non-closed beamline using the response matrix fit. As example, we used the suggested APS lattice in ERL mode. We have found that the response matrix fit can be used to measure and correct a linear lattice successfully. We have confirmed that one can measure and correct only a part of a non-closed beamline, which will be useful for large ERLs. We have also concluded that having only 20 skew quadrupole correctors (as there are presently at APS) is not enough for coupling correction. Simulations with 80 skew quads showed good correction results.

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