A NEW METHOD TO TUNE THE NONLINEAR LATTICE ONLINE *

W. Guo†, Y. Hidaka, X. Yang, Brookhaven National Laboratory, Upton, NY, USA

Abstract

Most nonlinear lattice tuning methods use only part of the optimization constraints, for example, part of the driving terms, nonlinear detuning, lifetime or injection efficiency. Even though some of the nonlinear properties can be improved, it is not guaranteed the nonlinear lattice is fully optimized. In this paper we propose to characterize the nonlinear lattice by correcting the betatron phase advance and detuning of the off-orbit lattices. It is shown that all the leading order optimization constraints are restored in this approach. One advantage of this new method is that the measurement is independent of BPM calibration errors. We succeed in both simulation and experiment in identifying the intentionally added sextupole errors to a precision of 0.1%.

INTRODUCTION

There are many ways to fine-tune the linear lattice; however, the online nonlinear characterization has always been a challenge. The reason is two fold. First the multipole (>4 poles) effects are small in comparison to the quadrupole focusing effect. For example, the parasitic oscillation induced by the sextupole driving terms is 2-3 orders smaller than the betatron oscillation amplitude [1]. In such a situation it is difficult to resolve the magnet setting error, which is on the order of 10^{-4} to 10^{-3}. The second obstacle is the complexity of the nonlinear constraints. So far most of the nonlinear tuning methods have focused on part of the nonlinear constraints, such as the driving terms [2, 3], the tune dependence on the amplitude [4], and either the lifetime [5] or the injection efficiency [6]. We learned from dynamic aperture optimization that the completeness of the nonlinear constraints are necessary; therefore partial correction does not guarantee the lattice is optimized.

In this paper we propose to use the betatron phase advance as a measure for the nonlinear lattice characterization. The idea is to correct the focusing error of the off-centered sextupoles in a lattice with perturbed orbit. This phase measurement is fast, precise, and independent of the BPM calibration. We show that the proposed scheme treats the complete set of the nonlinear constraints, i.e., all the driving terms and the detuning terms.

There are two ways to offset the beam in the sextupoles. One way is to create an orbit wave by powering a horizontal orbit corrector. However some of the sextupoles might have close-to-zero offset in this case; hence at least two correctors separated by $\pi/2$ phase advance must be used. Similar to the LOCO [7] approach, adding more correctors improves precision and minimizes degeneracy. The second way is to run the beam at off-momentum. It can be shown that in the first case phase advances are functions of the geometric driving terms, and in the second case they depend on the chromatic driving terms. Therefore both setups are needed for a complete nonlinear characterization. The peak orbit deviation must be large enough to excite measurable focusing effects. The bending angle or the momentum offset can be precisely determined from fitting the orbit change at all the BPM.

A study lattice can be created with the applied bending angle or the momentum offset. The phase difference between the original model and the study lattice can be calculated. Comparing the phase difference to the measurement gives the phase error. The response matrix of the sextupoles can be calculated from the study lattice. When the setup changes, such as switching to another corrector or run the beam at a different momentum, another study lattice must be created. The response matrices and the phase error vectors must be assembled together. Similar to the linear correction, the error phase vector is multiplied by the inverse response matrix and the correction is obtained.

Dynamic aperture optimization requires the necessary nonlinear constraints be: the leading order driving terms, the amplitude dependent tune shift terms, and the linear and nonlinear chromaticity. The leading order driving terms are constrained by the phase error correction. For completeness the following terms are included into the penalty vector:

$$\frac{d\nu_x}{dJ_x}, \frac{d\nu_x}{dJ_y}, \frac{d\nu_y}{dJ_y}, \xi_x^{(1)}, \xi_y^{(1)}, \xi_x^{(2)}, \xi_y^{(2)} \tag{1}$$

The response matrix for these terms should be obtained from the original lattice. We have tried including the higher order terms, such as $\frac{d^2\nu_x}{dJ_x^2}$ and $\xi_y^{(3)}$, however they are not linear functions of the sextupole strength and therefore it is ineffective to use a matrix to correct them.

APPLYING TO NSLS-II

In the following text NSLS-II is used as an example to illustrate the method. The first step is to create orbit bumps. The phase vector must be measured with or without the bump so the difference caused by the sextupoles can be measured. Figure 1 shows the two types of orbit bumps and the fitting results. The fitted angle or the momentum offset are used to generate study lattices.

The phase difference between the study lattice and the original lattice is given by,

$$\Delta\phi_i = \psi_{i+1}^{std} - \psi_i^{std} - (\psi_{i+1}^{org} - \psi_i^{org}), \tag{2}$$

where the subscript indicates the BPM index, ψ_i is the phase advance at BPM i, the superscript stands for "study" or

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† wguo@bnl.gov

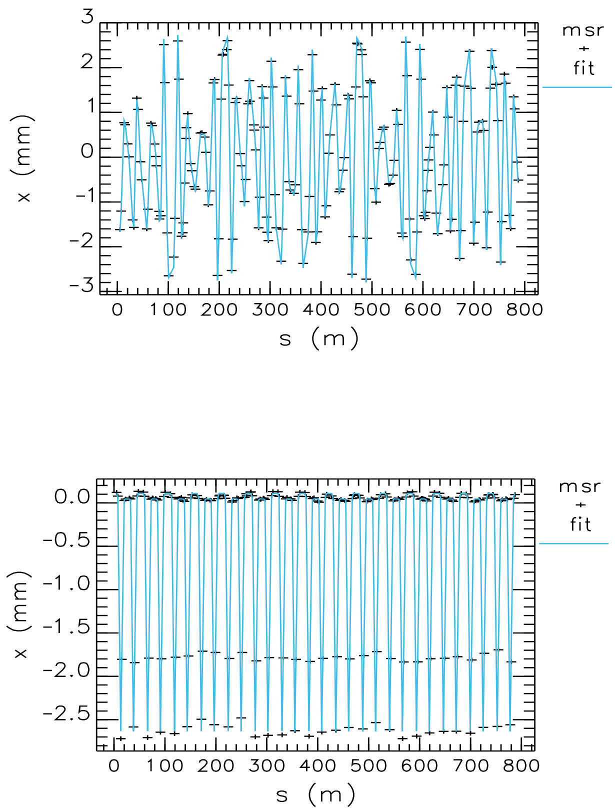

Figure 1: The measured and the fitted orbit. Top: The fitted bending angle is 0.18 mr. Bottom: The fitted momentum offset is -0.6%.

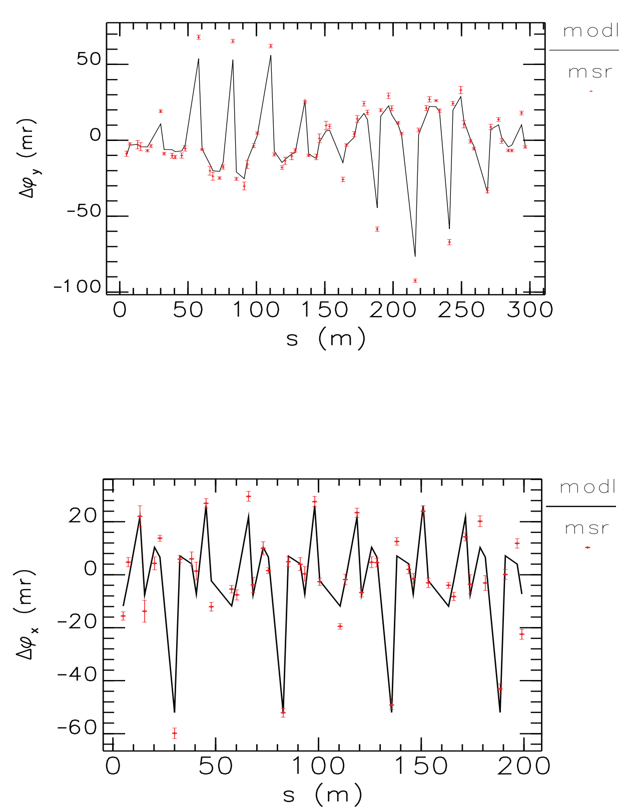

Figure 2: The measured and the calculated phase change caused by the off-centered sextupoles. Top: The corrector was changed by 0.18 mr. Bottom: The momentum offset was -0.6%. The error bar was obtained from 6 measurements. They correspond to the orbit change in Fig. 1, but only one plane is plotted. In both cases only part of the ring is shown for clear view.

"original". The above phase difference can be either measured, or calculated from the model [8]. Comparison of the two cases gives the phase error. Figure 2 shows the measured phase change caused by the orbit offsets shown in Fig. 1 and the model prediction.

Using the calculated response matrix and the phase error, the sextupole strength correction can be computed. Figure 3 shows the error before and after correction for one of the study lattices. The same measurement was repeated with 20 correctors and at 4 momentum-offsets. Sextupole response matrix was calculated for all the perturbed lattices. The assembled response matrix was used to compute the sextupole correction. The sextupole correction is shown in Fig. 4. The repeatable pattern is due to the sextupoles being powered in series in every 6 cells. The nonzero average of 0.1 $1/m^3$, or, -0.27%, is caused by either calibration error, or energy mismatch between the sextupoles and the dipoles.

The rms phase error before and after the correction are plotted in Fig. 5. The residual error is about 2.5 mr, and the amplitude shows a beta function dependence. During the experiment the applied bending angle is approximately the same for all the correctors, however the peak orbit distortion differs due to the beta function at the individual correctors. The phase deviation from the model depends on the orbit offset in the sextupole therefore the pattern emerges in

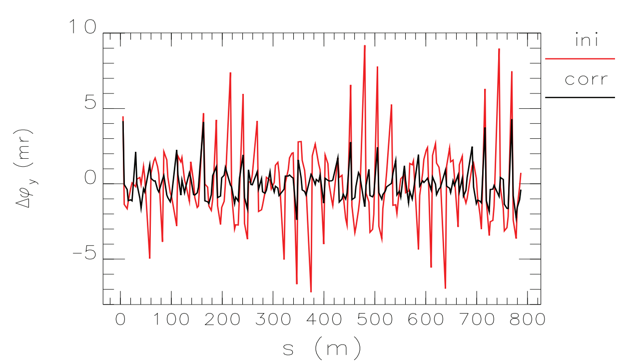

Figure 3: The initial and the residual phase error after one round of correction. One plane is shown only.

Fig. 5. The horizontal residual has similar amplitude. The off-momentum phase error reduction is small, due probably to the large dispersion deviation (shown in Fig. 1). Some of the nonlinear terms, such as $d\nu_x/dJ_x$ can be corrected in one iteration, however the other terms converge slowly.

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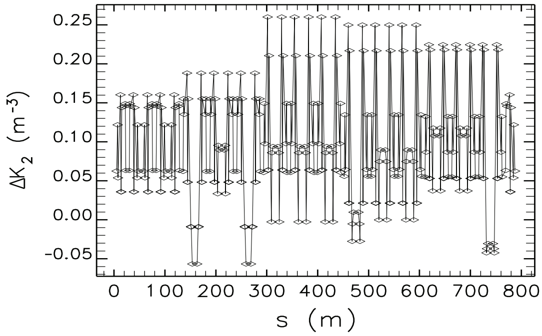

Figure 4: The sextupole strength error calculated from all the study lattices.

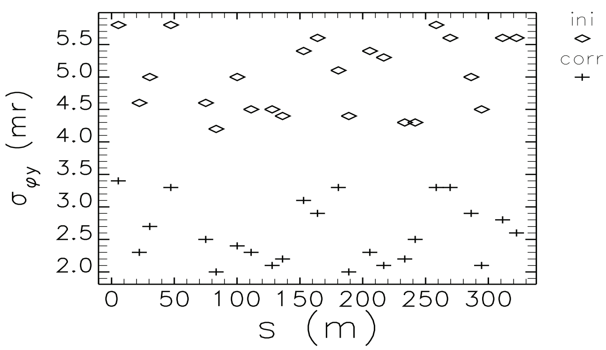

Figure 5: The vertical phase error before and after one correction. Each point corresponds to a study lattice which is perturbed by one corrector at the shown location. The bending angle is about 0.2mr for all the correctors.

CONFIRMATION OF THE APPROACH

We tested the algorithm on the NSLS-II storage ring. An error lattice was created by decreasing 10A in one of the sextupole curcuits. The corresponding strength change was $\Delta K_2 = 4.2m^{-3}$ for the group of 6 sextupoles. Then the phase vector and the nonlinear detuning terms were measured and compared to the original lattice. The algorithm was used to identify the error, and the results are plotted in Fig. 6. Among 54 power supplies the result clearly points to the changed circuit. The amplitude also agrees very well with the input value. The background error of $\Delta K_2 = 0.5m^{-3}$ can be lowered if a smaller number of eigenmodes are kept from the inversion calculation; however the amplitude at index 39 will also be smaller. This is a common problem of the inverse matrix calculation, and iteration must be performed to reduce the noise level.

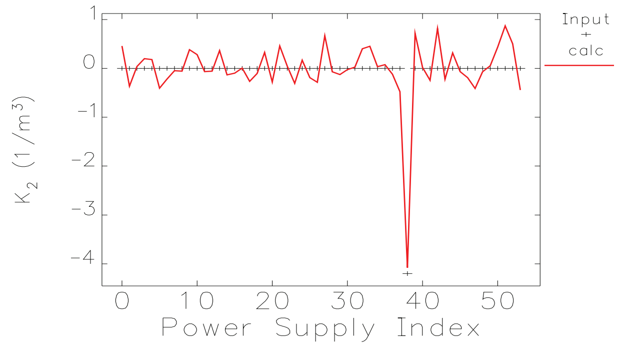

Figure 6: The cross shows the index number (39) of the altered curcuit with $\Delta K_2 = 4.2m^{-3}$, and the red curve is the error identified by the algorithm.

CONCLUSION

The nonlinear lattice can be characterized by correcting the focusing error of the sextupoles with the off-centered probing beam. The proposed approach treats the complete set of the nonlinear constraints. It was demonstrated at NSLS-II that the sextupole errors were identified to a high precision.

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