BEAM-BASED ALIGNMENT OF SEXTUPOLES AT THE APS *

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Abstract

Sextupole magnet offsets play a large role in modern storage ring coupling control. Due to the non-linear field of sextupoles, their beam-based alignment becomes more difficult and often requires a sophisticated post-data process. A simple method had been developed at the APS that measures the vertical orbit variation (orbit change at BPMs with sextupole strength) versus beam trajectory through a sextupole in one plane while keeping the trajectory in the other plane fixed. This method converts the non-linear problem into a linear one, and experiment results show very good reproducibility and accuracy.

INTRODUCTION

Given the strong sextupoles used in modern storage rings, such as light sources with emittance for producing x-rays near the diffraction limits and/or colliders (B-Factory or damping ring) with very low vertical emittance, misaligned sextupoles tend to be the main sources of large coupling and optics perturbation. It affects the ability to model the machine, and correct orbit, tune and coupling, often resulting in a reduced dynamic aperture and beam lifetime.

For a sextupole installed next to a quadruple, the alignment is as simple as aligning its magnet center to the next quadrupole, and then performing a commonly used beam-based alignment (BBA) technique on the quadrupole. At the APS, however, the majority of sextupoles (four of seven per cell) are on "dipole" girders that do not have quadrupoles, thus we cannot rely on BBA of quadrupoles. Other means of measuring the sextupole magnet offsets need to be developed.

In a previous paper [1], we presented a matrix fitting method to fit all sextupole offset errors together with other machine errors, so that the fitted model agrees with the response matrix measurement. The advantage of this method is that one can quickly get results. The disadvantage is that results are obtained in an "indirect" way and could be mixed up with other effects.

Similar to the beam-based quadrupole offset measurement method, a "direct" beam-based sextupole offset measurement method has been developed since then. This method measures the vertical orbit variation (orbit change at BPM with variation of sextupole strength) versus beam trajectory through a sextupole in one plane while keeping the trajectory in the other plane fixed. The small change of data acquisition and manipulation converts the non-linear problem into a linear one, and experiment results show very good reproducibility and accuracy. Details of the method, simulation, and experiment results are discussed in this paper.

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PRINCIPLE

The closed orbit displacement (COD) at position s, rising from a kick error θ at position s_0, is given by

$$u(s) = \frac{\sqrt{\beta_{u,s_0}\beta_{u,s}}}{2\sin\pi\nu_u}\theta\cos[\pi\nu_u - (\phi_{u,s} - \phi_{u,s_0})] = A\cdot\theta, \quad (1)$$

where $u(s)$ represents x or y; β and ϕ are the β-function and the betatron phase; and ν is the betatron tune. For a sextupole with misalignment of x and y, the kick angle is given by

$$\theta_x = \frac{1}{2}\cdot K2L\cdot(x^2 - y^2),$$
$$\theta_y = K2L\cdot x\cdot y, \quad (2)$$

where $K2L = \frac{e}{cp}\partial^2 By/\partial x^2 \cdot L$ is the integrated sextupole strength. The corresponding kick angle from a misaligned quadrupole is given by

$$\theta_x = K1L\cdot x \qquad \theta_y = K1L\cdot y. \quad (3)$$

Equations (2) and (3) have different character, one is linear and the other is non-linear. However, if we keep either x or y unchanged during the measurement, i.e., $\theta_y = (K2L\cdot x)\cdot y$ or $\theta_y = (K2L\cdot y)\cdot x$, Eq. (2) becomes as linear as Eq. (3). In other words, by fixing x while varying y and the sextupole strength, we are doing the vertical offset measurement of a quadrupole with strength $K1L = K2L\cdot x$. Similarly, by fixing y while varying x and the sextupole strength, we are doing the horizontal offset measurement of a quadrupole with strength $K1L = K2L\cdot y$. The only difference in this case is that we measure the vertical orbit variation instead of the horizontal orbit variation for a real quadrupole offset measurement.

SIMULATION STUDY

The principle of the method is simple and straightforward. However, other effects, such as coupling from misaligned sextupole etc., need to be considered, too. We studied different misalignment scenarios through simulations before testing with beam. The calibrated lattice model obtained from LOCO fit [2] (includes normal- and skew-quad errors) is used for simulation. One sextupole (S17B:S3) is misaligned intentionally in three different sets: $DX = 2$ mm, $DY = 1$ mm; $DX = 1$ mm, $DY = 1$ mm; and $DX = 0$ mm, $DY = 0$ mm. Sextupoles within the measurement bump are kept on or turned off.

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Similar to the BBA of quadrupoles, the simulation (and, later, measurement) is done in the following steps:

- Generate a local orbit bump at the BPM next to the sextupole, and scan the bump amplitude with $u_A = \pm 2$ mm in 1-mm steps (total $5 \times 5 = 25$ orbit sets).
- At each orbit bump, vary sextupole settings I between 0 and its maximum value in 4 steps. Record vertical orbit y at all BPMs.
- Calculate dy/dI (the slope of vertical orbit variation vs sextupole settings) at each BPM over the ring (Fig. 1).
- For the same x orbit, plot dy/dI over y; the crossing point is the sextupole's vertical offset (Fig. 2).
- For the same y orbit, plot dy/dI over x; the crossing point is the sextupole's horizontal offset (Fig. 3).

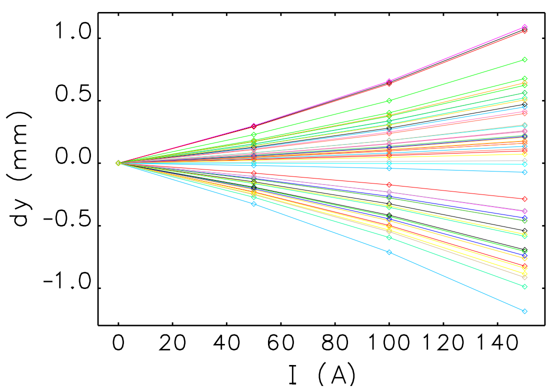


Figure 1: Vertical orbit variation dy vs. sextupole current change (symbols). Case for $DX = 2$ mm and $DY = 1$ mm. Data from the same BPM are connected; likewise for following figures.

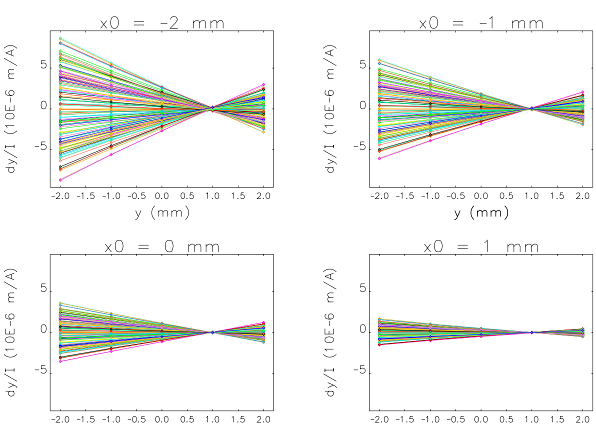


Figure 2: Calculated dy/dI vs. vertical beam orbit y (symbols). Results for different horizontal beam offsets (shown on top). Lines crossing at $y = 1.0$ mm indicate that the vertical sextupole offset is $y = 1$ mm.

Sextupole offset is determined where $dy/dI = 0$. The histogram distribution of $dy/dI = 0$ from all BPMs is

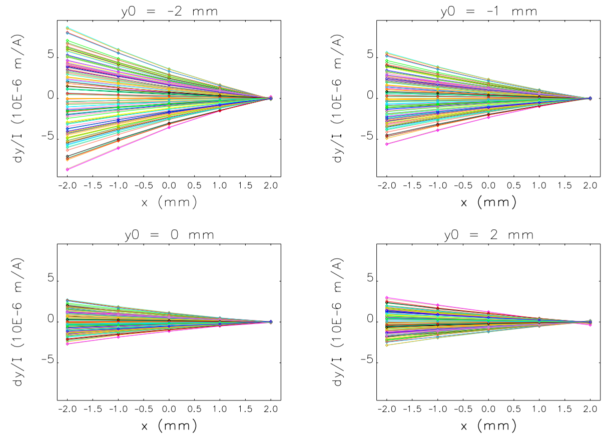
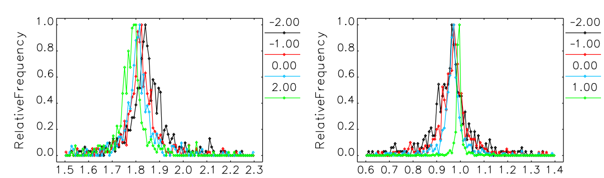


Figure 3: Calculated dy/dI vs. horizontal beam orbit x (dots). Results are grouped with the same vertical beam offsets (shown on top). Lines crossing at $x = 2.0$ indicate the horizontal sextupole offset is $x = 2$ mm.

shown in Figure 4. The average derived x and y offsets using this method are 1.83 mm and 0.98 mm, respectively. Compared with our initial assumption in simulation (2 mm in x and 1 mm in y), the agreement on vertical offset measurement is very good (better than 50 μ m), while the horizontal result seems to have a significant systematic error. Further simulations with different sextupole offsets or in cases when other sextupoles are turned off inside the bump all give similar results, i.e., good agreement on vertical offset prediction but large systematic errors for horizontal results.



(a) (b)

Figure 4: Histogram distribution of $dy/dI = 0$ vs. x (a) and vs y (b). Legend shows beam orbit in the other plane.

Further investigation of the method reveals that the linear dependence on x requires a fixed vertical orbit y inside the sextupole, while the strength change of the sextupole also causes y variation and leads to an additional vertical kick. This second-order effect has been ignored up to now. To include this effect we fit dy/I vs. $x(y)$ to the second order, and calculate the value to give $dy/I = 0$. Results including this second-order correction from the same data set are shown in Figure 5. The offset determined this way is closer to the input sextupole offset ($DX = 2$ mm).

The sensitivity of measurement depends on the product of beam offset "xy". As shown in Figure 5, a larger beam offset $y = -2$ mm gives more precise results. If either x or y are actually close to the sextupole offset (beam going through the sextupole center), the results become noisy, as

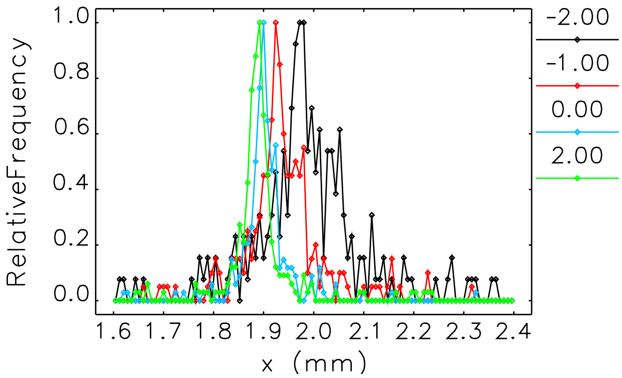
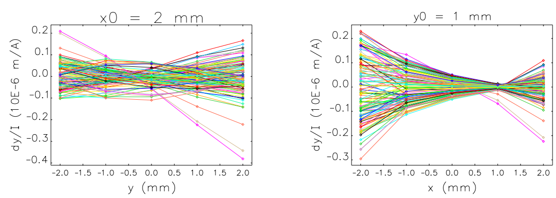


Figure 5: Histogram distribution of $dy/dI = 0$ vs x using second-order correction. Legend shows the beam orbit in y-plane.

can be seen in Figure 6. To have meaningful measurement results, two sextupole settings (to obtain dy/I) at each $3 \times 3 = 9$ orbit offset are needed.

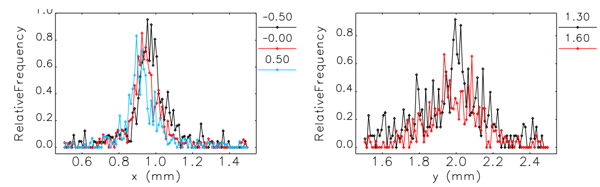


(a) (b)

Figure 6: Noisy results when beam is going through the sextupole center: $x0 = DX$ (a), and $y0 = DY$ (b).

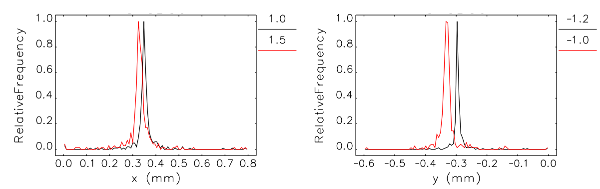
EXPERIMENT RESULTS

The method has been tested at the APS storage ring with beam. In preparing for the superconducting undulator (SCU) commissioning [3], we measured the sextupole offsets next to the 6BM (S6B:S2 and S6B:S3). Three x orbit offsets with $x = 1.0$, 1.3, and 1.6 mm and three y orbit offsets with $y = -0.5$, 0, and 0.5 mm were used in the measurement. Histogram distributions of $dy/dI = 0$ vs. beam orbit are shown in Figure 7. The predicted sextupole offsets are $DX = 0.95$ mm and $DY = 2$ mm. For DX measurement, all y orbits are moved away from the predicted sextupole center DY, so all measurement results are valid. We learned from simulation that the systematic error does exist and is reduced as y moves away from DY, as can be seen from both Figures 5 and 7. In this case, results from $y = -0.5$ mm should be taken as DX; the measurement error is believed to be within 50 μm. For DY measurement, the measurement made at $x = 1.0$ mm is too close to the sextupole center and gives noisy data similar to an example shown in Figure 6, and was discarded from the plot. Two other measurements predict the same DY results, agreeing with simulation. The accuracy of DY measurement is better than 50 μm. Similar results have been found with another sextupole (S18B:S3). Results are shown in Figure 8.



(a) (b)

Figure 7: S6B:S2 offset measurement results. Legend shows beam orbit in the other plane.



(a) (b)

Figure 8: S18B:S3 offset measurement results. Legend shows beam orbit in the other plane.

CONCLUSIONS

A direct beam-based sextupole offset measurement method has been developed at APS. This method converts the sextupole field from nonlinear to linear by keeping the beam orbit in the X plane unchanged while measuring the vertical beam orbit variation as a function of sextupole strength. The validity of the method had been tested through simulation and beam experiment. The second-order effect from orbit variation in the unmeasured plane was noticed and fixed through a second-order polynomial fit. The accuracy of this method is of the order of 50 μm.

The direct sextupole offset measurement takes more time compared with the "LOCO" fit method we originally reported in a previous paper [1]. Nevertheless, this is a suitable method if a direct measurement is required.

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