SIMULTANEOUS MEASUREMENT OF ALL SEXTUPOLE OFFSETS USING THE RESPONSE MATRIX FIT [*]

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Abstract

The APS linear model is defined by the quadrupole and skew quadrupole errors that are determined using the response matrix fit. What was missing until now were the sextupole offsets relative to the beam orbit. At APS the orbit is routinely steered according to user requests, and at some locations the steering has accumulated to rather large values. That is why the usual sextupole changes that are performed during operation mode switches lead to optics and coupling changes. Knowledge of the sextupole offsets would allow us to predict and control those changes. There are a number of ways to measure sextupole offsets, but most of them utilize an element-by-element approach. This would take a very long time for the 280 sextupoles at APS. Here we describe a method that determines the beam offsets of all sextupoles based on fitted values of local optics and coupling changes at each sextupole. We perform a response matrix measurement, fit several lattices with different sextupoles, and derive the sextupole offsets. The results are included in the linear model of the APS storage ring.

INTRODUCTION

From the start of APS operations, it has been the policy to allow for user-requested beam steering. Over time the storage ring and beamlines have settled, and at many locations the steering has accumulated to several millimeters of orbit distortion. This orbit is called "user orbit" and deviates from the centers of magnets significantly. This would have been a big problem for the storage ring optics, but fortunately the APS has separate power supplies for all quadrupoles (and sextupoles). So the optics is regularly corrected, and there seems to be no significant negative effects from operating on the non-zero orbit.

The main consequence of such operation is the focusing errors that come from a non-zero orbit in the sextupoles. The exact knowledge of the orbit inside the sextupoles is not necessary for operation since the optics is corrected based on the response matrix fit on the user orbit. However, for the purpose of better understanding the machine's behavior, it would have been useful to know the orbit inside the sextupoles, which we will call here sextupole offsets. Unfortunately we cannot just read the beam position monitors (BPMs) next to the sextupoles. BPMs have offsets that might change with time, and due to large number of BPMs at the APS (more than 400 in each plane), not all offsets are regularly measured. Also 160 sextupoles out of a total number of 280 are located on the dipole girders where there are no quadrupoles nearby to measure the BPM offsets. That is why we have to measure sextupole offsets using the electron beam.

There are various methods to measure an orbit offset in the individual sextupole – using its effect on the orbit or on the betatron tunes and coupling. However, when you have 280 sextupoles and each individual measurement takes a few minutes, then the total measurement could take many hours. Here we present the method that allows for simultaneous measurement of all (or many) sextupole offsets using the response matrix fit.

METHOD DESCRIPTION

When orbit goes off center in a sextupole with strength $K2 = \frac{e}{cp}\ \partial^2 By/\partial x^2$, the following quadrupole and skew quadrupole components are generated [1]:

$$\begin{aligned} K1_{\text{quad}} &= x_0 \cdot K2, \\ K1_{\text{skew}} &= -y_0 \cdot K2, \end{aligned} \qquad (1)$$

where x_0 and y_0 are the horizontal and vertical orbits inside the sextupole, respectively. Therefore, when one has quadrupole and skew quadrupole errors as a function of the sextupole strength, the slopes of these functions give the horizontal and vertical orbits in the sextupole. In our case, we perform a scan of a group of sextupoles and measure the response matrix at each point. From the response matrix fit [2] we obtain local quadrupole and skew quadrupole errors as functions of each sextupole's strength, and then calculate the sextupole offsets.

To correctly analyze the response matrix, one has to have three elements presented at the location of the sextupole: the sextupole itself (not absolutely required for the response matrix fit, but it improves the fit accuracy because nonlinear sextupole fields exist in the real measurement), the quadrupole to represent horizontal displacement of the sextupole, and the skew quadrupole to represent the vertical displacement of the sextupole. We note here that usually the tilts of real quadrupoles are used in the response matrix fit to represent the skew quadrupole errors. However, it would not work in our case because the initial strength of the quadrupole inside the sextupole is zero. So we really have to use two different elements – quadrupole and skew quadrupole. For this work, we had to create a new lattice file where every sextupole was split into two elements: a combined element with quadrupole and sextupole gradients and a skew quadrupole.

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[*] Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357

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Measurements

The APS has 40 nearly identical sectors each containing seven sextupoles split into four families – two focusing (named S1 and S4) and two defocusing (S2 and S3) families. Sextupoles within each family are located symmetrically around the center of the sector and one sextupole (S4) is located right in the middle of the sector. The sextupole scan has to be performed in a way that keeps the chromaticity approximately constant to avoid beam losses due to instabilities. For our measurements, we performed two scans: a scan of the S1 family with families S3 and S4 used for chromaticity correction, and a scan of S2 family again with families S3 and S4 correcting the chromaticity. It turns out that for each scan, the sextupoles of one sign are changed approximately equally in opposite directions and the sextupole family of the opposite sign is barely changed at all. Also, for every step of the scan we had to correct betatron tunes – the effect of the user orbit on the optics indeed was quite large.

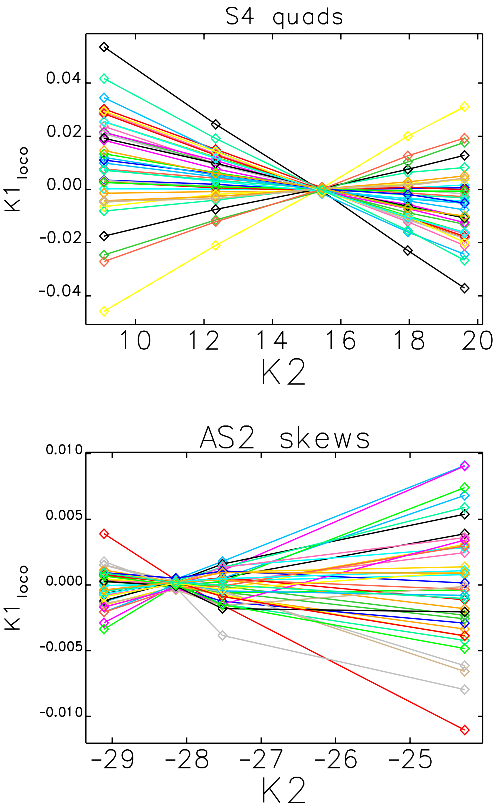

Figure 1: Individual fit data for some of the sextupoles: top, quadrupoles; bottom, skew quadrupoles.

Every scan represents a sequence of response matrix measurements. As a first step, the measurement with initial sextupoles was fitted using all the variables we usually use for the response matrix fit: all quadrupole gradient errors and tilts, all corrector calibration errors and tilts, and all BPM gain errors and tilts. The full set of variables is used for the fit to obtain the best possible initial storage ring model, and that model is used as the initial model for all later fits. Then all response matrix measurements are fitted using a different set of variables – instead of gradient errors in real quadrupoles and their tilts we use quadrupoles and skew quadrupoles located inside sextupoles (correctors and BPMs are also used in the fit). When the fits for all measurements are done, we get quadrupole and skew quadrupole errors for every sextupole as a function of the sextupole strength.

Changing sextupoles during the scan would change nonlinear dynamics significantly. Therefore, the measurements were always performed with a 324-bunch fill pattern – the bunch pattern with the longest lifetime (about 60 hours) – and the reinjection during the scan was not needed. First, we planned to split sextupoles into two scans as mentioned above: S1-S4 and S2-S3 pairs. It turned out that due to the proximity of the S2s and S3s to each other, the response matrix fit was not able to distinguish between those two sextupoles with enough certainty. To deal with this problem, we split the S2-S3 measurement into two: A:S2-B:S3 and B:S2-A:S3 pairs, where A and B stand for the first and second halves of each sector.

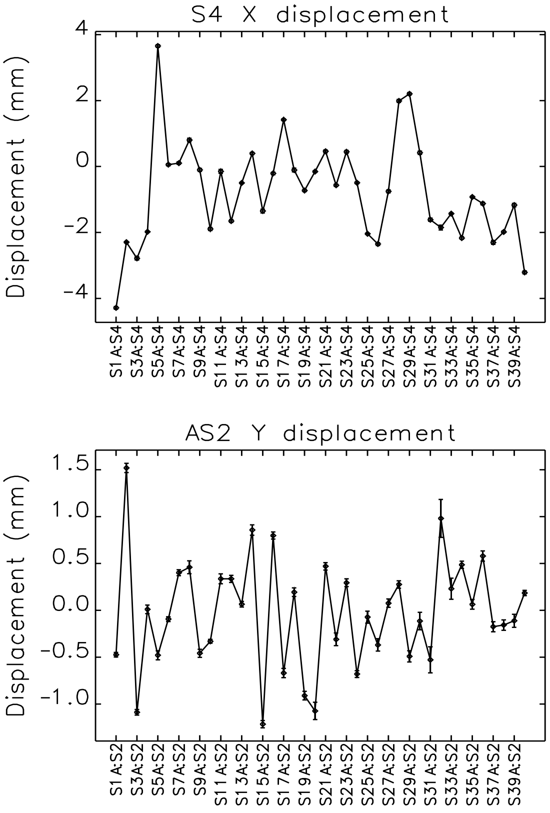

Figure 2: Sextupole offsets for some of the sextupoles with error bars corresponding to the data in Fig. 1.

Figure 1 shows individual fits for different sextupoles. The top plot is the fit of quadrupoles located at the S4 sextupoles. Every line represents a separate sextupole. This plot shows the best set of data; most of the sextupoles

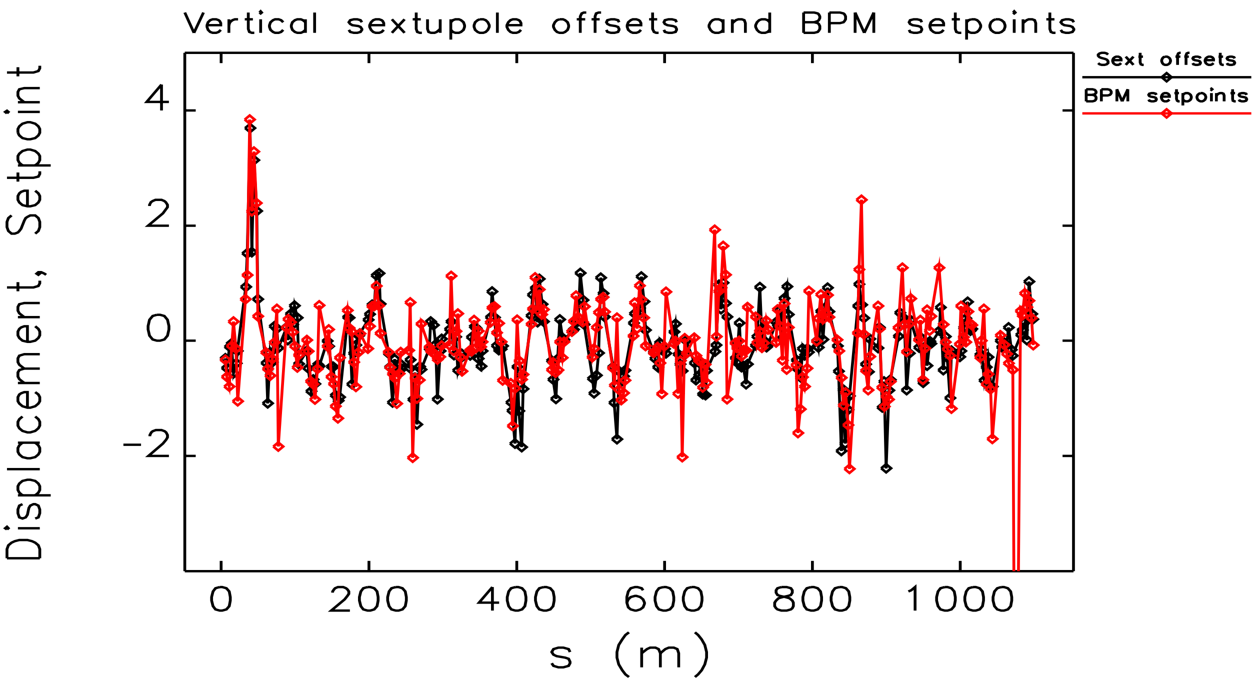

Figure 3: Vertical sextupole offsets (black line) and BPM setpoints (red line).

give good linear dependences with little deviation from the straight line. The bottom plot is the fit of skew quadrupoles located at the A:S2 sextupoles. This plot shows a typical set of data with some curves not as straight as in the top plot. Deviations from the straight line illustrate the accuracy of the offset determination. For each sextupole, error bars were calculated based on the residual errors of the linear fit. Figure 2 shows the sextupole offsets calculated from the slopes of Fig. 1 with error bars.

To check the reality of the sextupole offsets obtained above, we compared the offsets with BPM setpoints. BPM setpoints show where the orbit needs to be relative to the zero orbit. In an ideal world, the BPM setpoints should be exactly the same as the measured sextupole offsets. Figure 3 shows the comparison of the vertical sextupole offsets and BPM setpoints. One can see that the two curves follow each other approximately. The differences between the curves can be attributed to both the accuracy of the sextupole offset measurements and to BPM setpoint uncertainty.

Model

The sextupole offsets calculated above were included in the storage ring model as sextupole displacements. The orbit generated by the sextupole displacements was corrected, and the betatron tunes had to be adjusted. The model with sextupole offsets showed large beta function beating, which probably indicates that quadrupole errors in the quadrupoles itself also contribute to the optics distortion (which could have been expected). We hoped, however, that the vertical sextupole offsets would be the main source of the vertical dispersion in the storage ring. We have found that the vertical dispersion in the model had comparable amplitude to the real vertical dispersion in the storage ring, but the perturbation pattern was different. It could mean that the quadrupole tilts and/or dipole tilts contribute significantly to the dispersion or that the accuracy of our sextupole offset measurements are not good enough. We will continue investigating the correspondence of the model to the real storage ring.

CONCLUSIONS

We used orbit response matrix analysis to measure orbit offsets in sextupoles. We scanned groups of sextupoles and measured the response matrix at every step. Then from the response matrix analysis we obtained quadrupole and skew quadrupole errors at the location of each sextupole as a function of the sextupole strength. This allowed us to obtain orbit offsets in many sextupoles simultaneously. We have found that the measured offsets in general are close to the BPM setpoints, as expected.

REFERENCES

[1] S.Y. Lee, *Accelerator Physics*, 2nd ed. (Singapore: World Scientific, 2004), 101.

[2] J. Safranek, “Experimental Determination of Storage Ring Optics using Orbit Response Measurements,” Nucl. Instrum. Methods A 388 (1997), 27.