

# EFFECTS OF VERTICAL GIRDER REALIGNMENT IN THE ARGONNE APS STORAGE RING\*

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## Abstract

The effects of vertical girder misalignments on the vertical orbit of the Advanced Photon Source (APS) storage ring are studied. Partial sector-realignment is prioritized in terms of the closed-orbit distortions due to misalignments of the corresponding girders in the sectors. A virtual girder-displacement (VGD) method is developed that allows the effects of a girder realignment to be tested prior to physically moving the girder. The method can also be used to anticipate the corrector strengths needed to restore the beam orbit after a realignment. Simulation results are compared to experimental results and found to reproduce the latter quite closely. Predicted corrector strengths are also found to be close to the actual local corrector strengths after a proof-of-principle two-sector realignment was performed.

## 1 INTRODUCTION

The long-wavelength distortions induced by ground settlement are not, in general, too detrimental to beam stability, but can result in large beam-orbit corrector currents. In the APS storage ring, magnets are supported by girders that can become misaligned due to ground settlement, particularly in the vertical direction. The displaced magnet centers cause orbit distortions that require correction. We examine the effects of vertical girder misalignment in the APS storage ring closed orbit. We study changes in the user orbit due to a partial girder realignment and the corrector strengths needed to reestablish that orbit to within the required tolerance. We also introduce an analytical method that provides a mean to perform machine tests to mimic the closed-orbit distortions that would be introduced by selected girder movements, prior to the physical realignment. Comparisons are made of machine tests vs. simulations and of corrector strengths predicted by simulations vs. the actual changes in correctors after a partial realignment of the ring.

## 2 EFFECTS ON THE CLOSED ORBIT

The storage ring magnets are mounted on six distinct girders per sector, in a total of 40 similar sectors. Figure 1 shows one sector of the nominal low- $\beta_y$  lattice. Girders 1 and 5 support three quadrupoles, one sextupole, two beam position monitors (BPMs), and two combined-function vertical/horizontal correctors. Girders 2 and 4 support the bending magnets, two sextupoles, one vertical/horizontal

corrector, and two BPMs. Girder 3 holds two defocusing and two focusing quadrupoles, one sextupole, two correctors, and one BPM. The sixth girder is reserved for insertion devices. The floor settlement affects the vertical closed orbit primarily through the odd-numbered girders, due to the strong-focusing quadrupoles mounted on them.

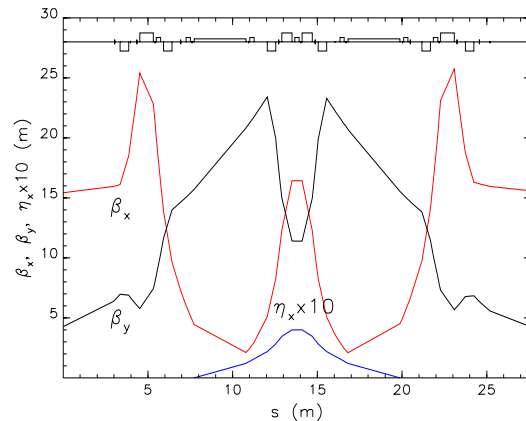


Figure 1: One sector of the APS lattice.

In 1997 the APS Survey Group performed a comprehensive vertical survey of the storage ring magnets. The data showed some displacements exceeding the  $\pm 0.15$  mm vertical displacement tolerance limit with respect to the “smoothed” orbit [1]. We used the program *elegant* [2] to simulate the effects of the displacements on the closed orbit and to establish an order of priority for partial realignment, since a complete realignment of the ring is not feasible during a single shutdown. We identified the sector or group of sectors whose misalignments contributed most to the closed-orbit distortions. In particular, the displaced girders within and around Sector 16 were responsible for almost as much orbit distortions (about 1.6 mm rms uncorrected) as the distortions caused by the displacements over the entire ring (on the order of 1.7 mm rms uncorrected). Those were the first set of girders chosen to be vertically realigned, according to the established priority.

## 3 THE VGD METHOD

A partial or whole girder realignment will introduce perturbations in the established closed orbit (“golden orbit”). In particular, the resulting perturbations in the user orbit slope need to be corrected to within  $\pm 10$   $\mu$ rad. The VGD method provides an analytical means to estimate those perturbations, quantify local corrector strengths needed to

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reestablish the orbit, and an experimental means to test the realignment effects.

The method calculates the deflection (kick) at a corrector on a girder that is equivalent, in the rms sense, to the displacement of quadrupoles supported by the same girder. If we equate the rms of the distortions caused by a kick  $\delta y'$  in a corrector V on a girder G, to the rms of the distortions caused by a displacement  $\delta y$  of the quadrupoles on the same girder, we obtain [3]:

$$(\delta y')_V = \frac{(\delta y)_Q}{(\langle \sqrt{\beta} \rangle)_V} (R_1^2 + R_2^2 + 2R_1 R_2 \cos(\Delta\phi_1 - \Delta\phi_2))^{1/2}, \quad (1)$$

where  $\beta$  denotes the vertical betatron function at the corrector and  $R_i = (\sqrt{\beta_i} K_i l_i)$ , with  $K_i, l_i$  and  $\Delta\phi_i$ , the strength, length and incremental phase advance of the  $i^{\text{th}}$  quadrupole, respectively. We assumed two quadrupoles on the girder, for illustration.

Table 1 lists the VGD equivalent kicks for the lattice model used in the simulations. Verification of the VGD

Table 1: VGD equivalent kicks

Girder	Corrector	Equivalent Kick $\delta y' / \delta y$ (mrad/mm)
1, 5	A:V2, B:V2	0.1111
3	A:V4 and B:V4	0.0568

method is shown in Fig. 2 where we plot the differences between a real girder displacement near the 420-m mark and a VGD at the same location. For the latter, a 1-mm girder displacement is replaced by a 0.1-mrad kick. As shown in the figure, the residuals are less than  $50 \mu\text{m}$ , whereas either alone produces an rms orbit distortion of about eight times that or 0.40 mm.

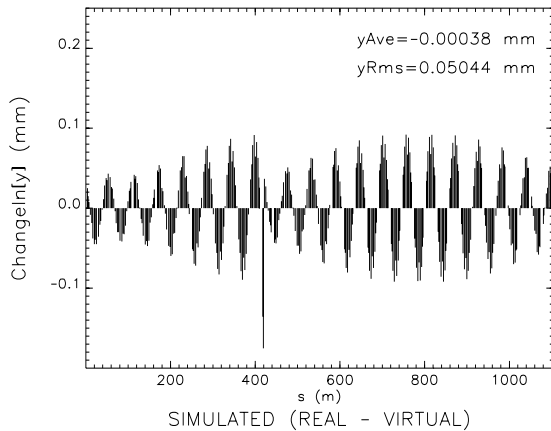


Figure 2: Residuals between real and virtual displacement.

## 4 CORRECTION OF REALIGNMENT EFFECTS

The VGD method also provides a local correction scheme. By adjusting the corrector strengths to *minus* the equivalent quadrupole displacements, we can artificially bring the girders to the correct elevation on the lattice.

Perturbations to the users' orbit, introduced by girder realignment, can be reduced by a factor of 10 by a *local* correction that uses the correctors defined by the VGD algorithm. The local correction may not be enough to bring the users' orbit to within the  $\pm 10 \mu\text{radians}$  tolerance; however, this tolerance can be easily achieved by a further "global" correction, normally done using one corrector on each Girder 1 and one corrector on each Girder 5.

In Fig. 3 we compare the simulated changes in the users' orbit after a local correction, shown in the upper plot, to simulated changes after a local plus global correction, shown in the lower plot. The latter correction requires a maximum corrector strength of 0.3 mrad. Although there is little improvement in the residual closed-orbit distortions when the global correction follows a local correction, as expected, the overall corrector-strength rms can be 10% lower for the "local plus global" scheme, compared to the rms from a "global-only" scheme.

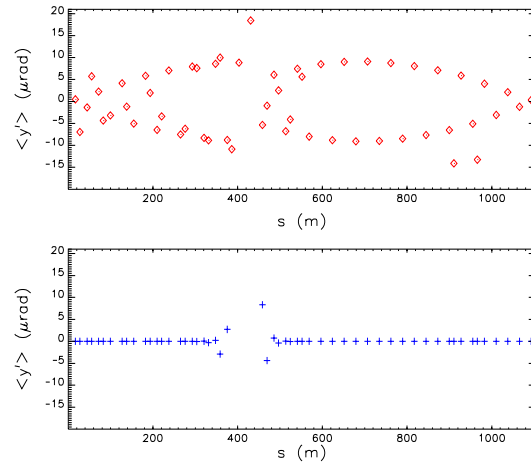


Figure 3: Users' orbit after a local correction (upper plot) and a local plus global correction (lower plot).

### 4.1 Experimental Tests

We conducted machine tests on the most misaligned girders in the ring, wherein the correctors in Table 1 were set to the values estimated by the VGD method. We tested virtually displacing individual girders and sets of girders, with and without orbit correction after the displacements. We found very good agreement between the experimental and simulated values of the uncorrected orbit at the BPMs for Girder 1 in Sector 16. For Girders 3 and 5, those values differed by less than 5% rms. This can be accounted for by

the measured differences between the simulated and actual machine  $\beta_y$ -values at the quadrupoles.

In the lower plot of Fig. 4 we show the experimental values of the orbit at the BPMs after a virtual displacement of all the quadrupole-supporting girders (1, 3, and 5) in Sector 16. The other plots in the figure show the corresponding simulation results, where “simulated real” indicates distortions obtained by displacing the quadrupoles, sextupoles, and BPMs on a girder by the survey-fitted values; and “simulated virtual” corresponds to distortions obtained by setting the correctors to their respective VGD values. As seen in the figure, the simulated virtual orbit reproduces the experimental virtual orbit to within 2% rms.

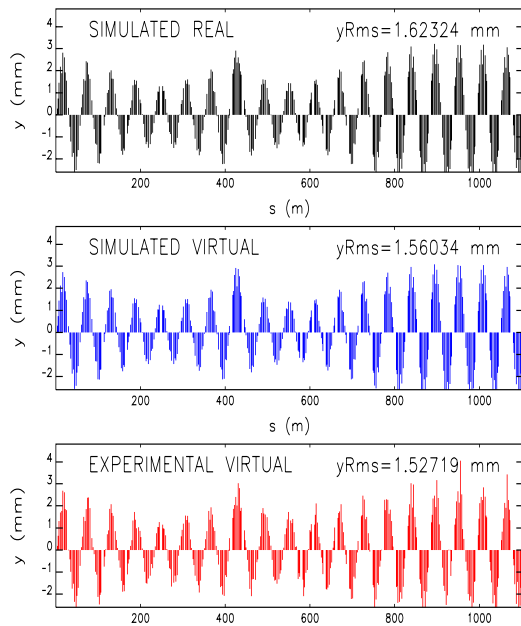


Figure 4: Closed orbit from experimental and simulated tests.

#### 4.2 Measured Effects

In December of 1998, the girders on Sectors 16 and 17 were realigned vertically. The change in the machine vertical corrector strength for the correctors in the vicinity of the realigned sectors was about +0.034 mrad rms, compared to the values held just before the realignment. When all sectors were taken into account, the changes in the vertical corrector strengths were very small, about +2  $\mu$ radians.

In Fig. 5 we compare the measured values of the correctors needed to reestablish the closed orbit to those predicted by the VGD method. Both the machine and simulation correction configuration included the local correctors, indicated in Table 1 and depicted in the figure by a continuous line, and the nominal global correctors, depicted by a dashed line. The simulated values for the global correctors agree quite well with the machine values but less so for the local correctors. This is attributed to a different, al-

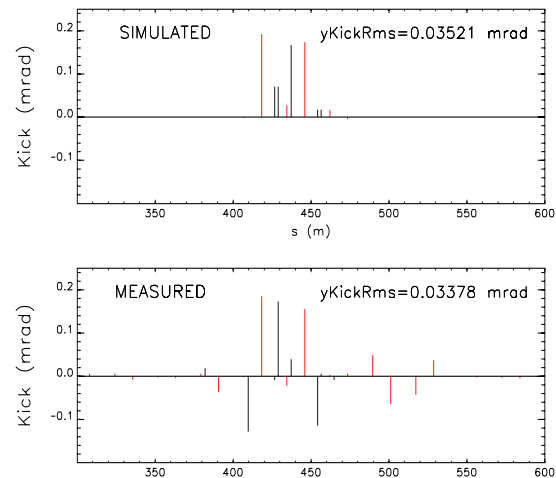


Figure 5: Corrector changes after a two-sector realignment.

beit equivalent, orbit-correction algorithm used during actual machine operation.

## 5 SUMMARY

We have simulated the effects of vertical girder realignment on the APS storage ring using both a method of “real” displacements and a method of “virtual” displacements. In the first method, the measured survey values of girder misalignments are distributed over all the relevant magnet elements on a girder and the effects on the orbit are obtained by simulation. In the second method, a girder displacement is shown to be equivalent, in the rms sense, to deflections produced by a corrector on the same girder whose strength value can be calculated analytically. This VGD method allows a machine study to be performed prior to an actual realignment. The virtual realignment, its effect on the orbit, and the corrector strength required to bring the orbit to the nominal values can then be gauged.

Machine tests prior to any physical realignment showed that the simulated results agreed quite well with the experimental values. Finally, the simulation-predicted corrector values required to restore the user orbit for a realignment of girders in Sectors 16 and 17 were close to the measured changes in vertical corrector after the physical realignment of those girders.

## 6 REFERENCES

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