Alignment of the Dipole Magnets in the Cornell Electron-Positron Storage Ring

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Introduction

There are 84 dipole magnets in the Cornell Electron-Positron Storage Ring (CESR) which bend the electron and positron bunches in a circular path. The roll of the dipole magnets is critical to the performance of CESR. If a dipole is rotated about the vacuum chamber (figure 1) the bunches traveling around the accelerator receive an unwanted vertical kick. The purpose of aligning the dipole magnets is to reduce the overall vertical kick and thus reduce the dependence on the steering magnets needed for orbit corrections. Presented in this paper is the technique used to measure the rotation (or roll) of the dipole magnets and results of simulation and measurements of corrections to the vertical orbit in CESR.

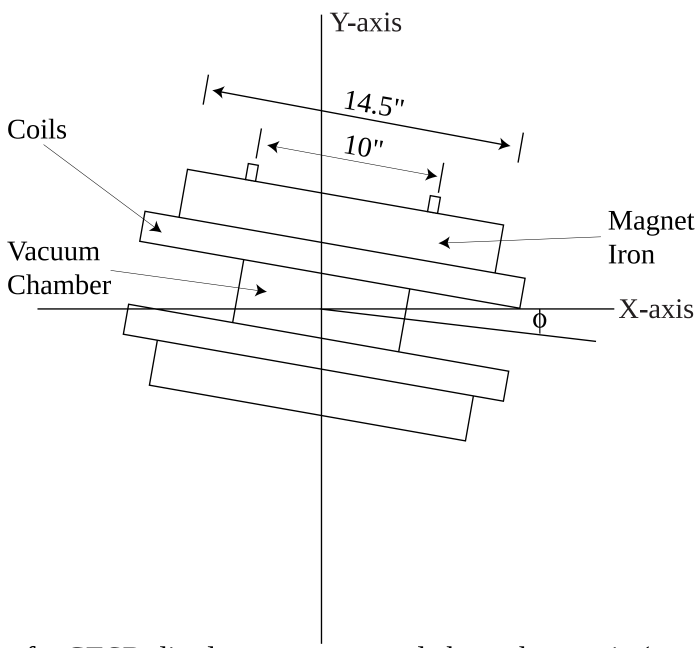

Figure 1. The geometry of a CESR dipole magnet rotated about the z-axis (out of the paper) by an angle ϕ. There are several types of dipole magnets in CESR. The two most common types of dipoles are the hard bend magnets near the interaction point and the arc dipoles (chevrons).

CESR Dipole Survey and Analysis

The dipole magnets are surveyed to determine their radial positions, vertical positions, and roll and compare the misalignments with their ideal location. The radial and vertical misalignments of the dipole magnets, to first order, will not effect the performance of CESR, nonetheless, the magnets when moved are aligned radially and vertically. The rotation of the dipole magnets is the primary concern in regard to degradation to the performance of the CESR. The method of measurement of the dipole magnets rotation is discussed in this section.

The rotation of the dipole magnets is measured by comparing two of the reference drill bushings mounted on top of the magnets. The two drill bushings are placed at each end of the dipole magnets and difference in height between the drill bushings determines the rotation of the magnet. Figure 2 and 3 are drawings of the bushing locations of two such magnets in CESR.

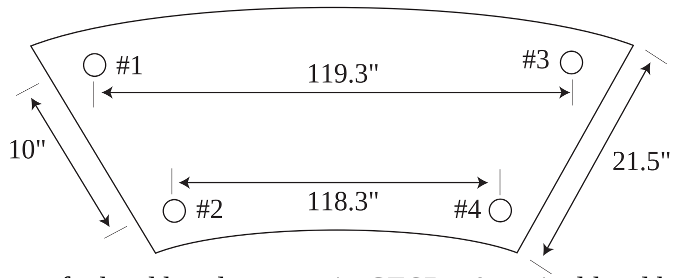

Figure 2. This is a top view of a hard bend magnet in CESR. A typical hard bend magnet has four drill bushings. The level of the magnet is determined by taking the difference in height between bushing #1 and #2 on the left side and bushing #3 and #4. A typical hard bend magnet has a bend angle of 5.86 degrees. There are 8 hard bend magnets located near the interaction region in CESR and two near the North symmetry point.

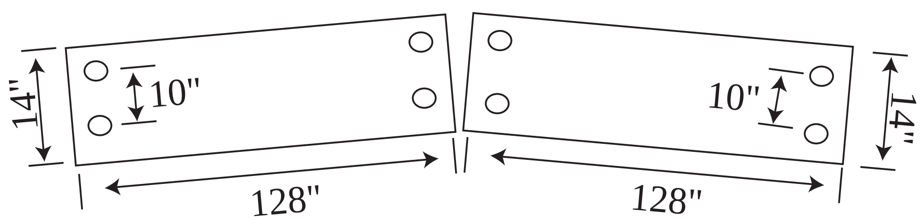

Figure 3. This is a top view of an arc dipole magnet in CESR. A typical arc dipole magnet has two sections where each section has four drill bushings. The level of the arc dipole is determined by taking the average between the two sections (each section’s level is calculated in the same manner as the hard bend magnet). A typical arc dipole magnet has a bend angle of 4.28 degrees. There are 62 arc dipole magnets located in CESR.

The height of the drill bushings is measured with a bubble level and digital dial gauges mounted on bar-level. The bar level consists of two bars hinged at one end with a bubble level mounted on the top bar (figure 4). The bar level is placed across the two left or right drill bushings. The top bar is adjusted to be level by a vertical screw then the opening distance of the two bars is measured with a electronic digital dial gauge mounted 10" from the pivot.

The roll of the dipole is determined by measuring the difference between the heights of the inside and outside bushings using the bar level. The calibration of the bar level is done by placing the bar level on a leveling plate. The calibration of the bar level is confirmed by taking forward and reverse measurements on the same set of bushings. In principle if the bar level is properly calibrated a sign flip should be measured on the reverse measurement. Half of the difference of the two measurements is used in the analysis.

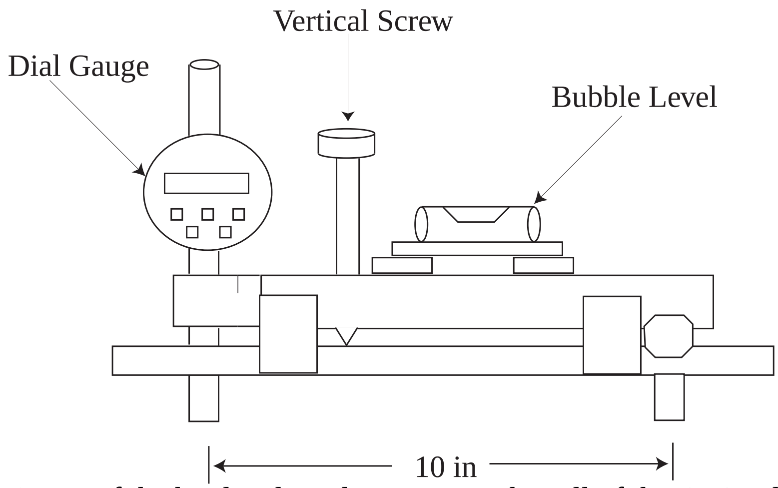

Figure 4. A detailed picture of the bar level used to measure the roll of the CESR dipole magnets. The bar level sits on top of the drill bushings and measures the relative height difference between the two bushings.

A complete dipole level survey was done in 1989, and at that time, the vertical kick induced from the dipole magnets rotation was thought to be a small effect on the vertical orbit. During January of 1998, the dipole magnet's rotation was measured again and it was evident that some of the dipole magnets had rotated substantially and were adversely effecting the vertical orbit. Two comments can be made about the survey of the dipole magnets: 1) There was almost a factor of two increase in rms. kick between the two survey dates (figure 5). 2) The dipole magnets in the west side of CESR have a larger misalignment problem than the dipole magnets in the east side (figure 6). The larger misalignments of the magnets in the west region also applies to the quadrupole magnets as well.

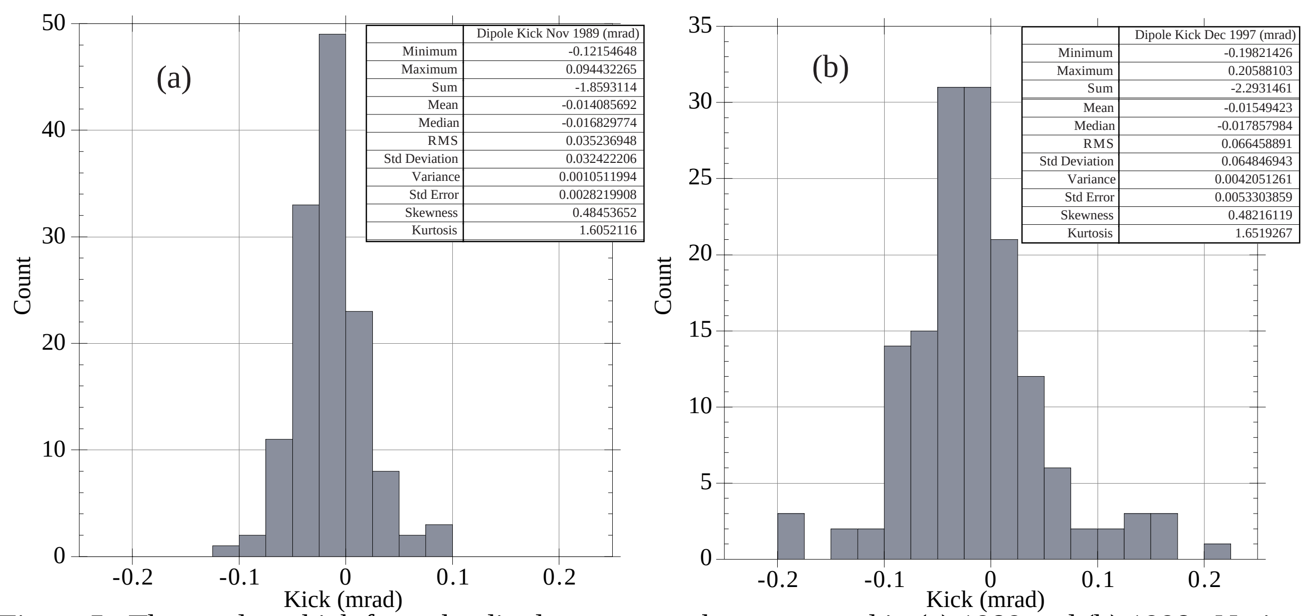

Figure 5. The resultant kick from the dipole magnets when measured in (a) 1989 and (b) 1998. Notice that the rms. has increased by a factor of two between the two surveys.

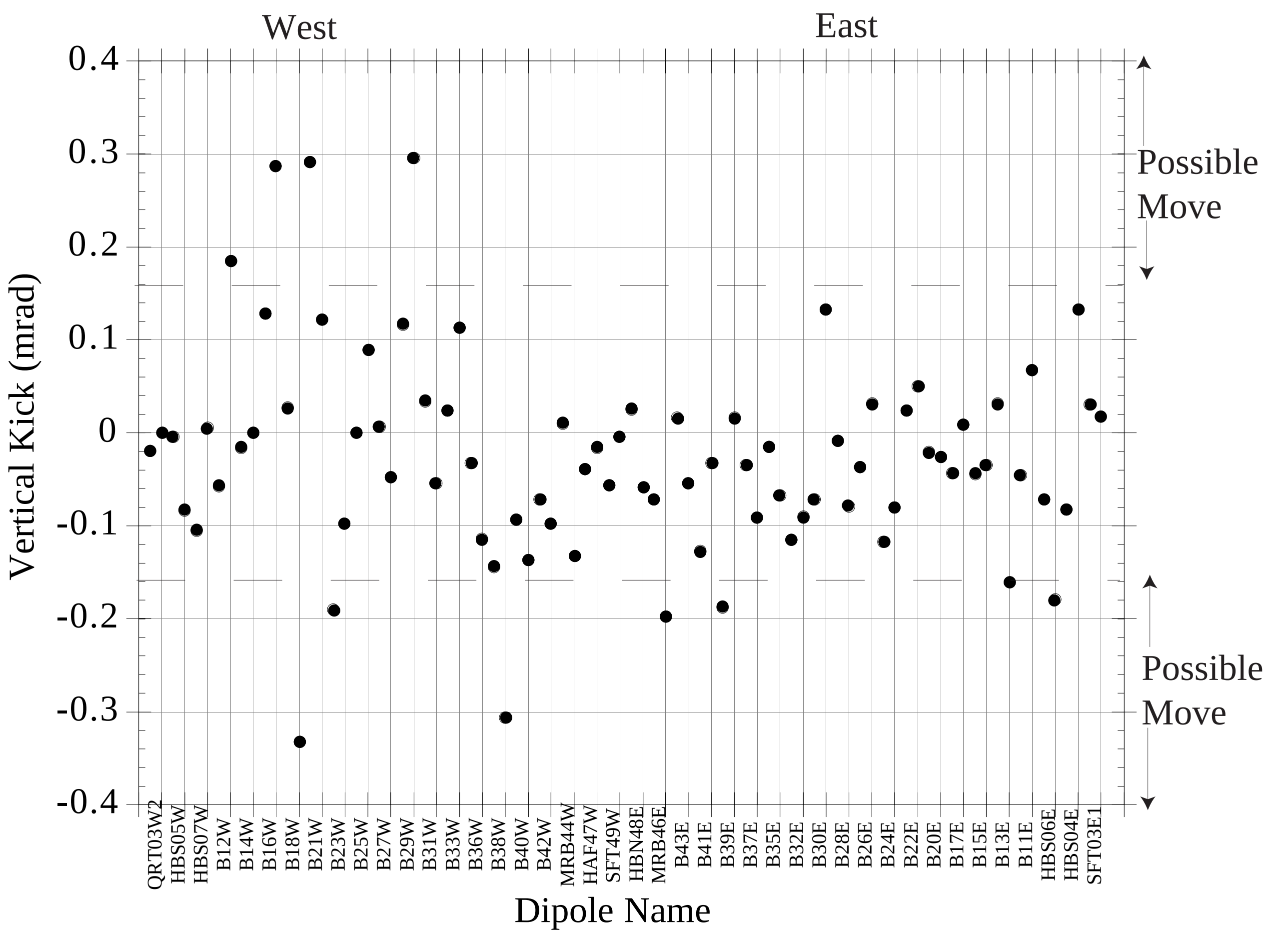

Figure 6. The result of the dipole magnet survey in 1998 as a function of location in CESR. The dipole magnets in the west are denoted with a W at the end of their label. The dipole magnets to be possibly moved have a vertical kick of greater than ± 0.16 mrad. There are eleven such magnets-seven in the west side of the tunnel and four in the east side of the tunnel.

Simulation of Dipole Misalignments

As a particle orbits in a circular accelerator it will encounter a number of kicks from dipole magnet misalignments. The equilibrium (closed) orbit is the result of a superposition of all the kicks distributed around the storage ring and is given by

$$y(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi\nu)} \sum_i \sqrt{\beta_i}\,\theta_i \cos\left[\left(\varphi(s) - \varphi_i\right)\nu + \pi\nu\right]$$

where the index i indicates the location of the kicks, β is the betatron function, θ is the kick provided by each dipole, φ is the phase advance, and ν is the tune. Simulating the closed orbit due to all the misalignment errors in CESR is a rather difficult job due to the vast number of elements in CESR. A simpler method is to use the beam orbit to determine which magnets to move. In order to use the beam as a diagnostic tool, a closed orbit was measured before leveling the dipole magnets with all the steering correctors turned off. This closed orbit is called the zero corrector orbit (figure 7). The zero corrector orbit is the beam's orbit resulting from all the magnet misalignments and field errors in the CESR ring.

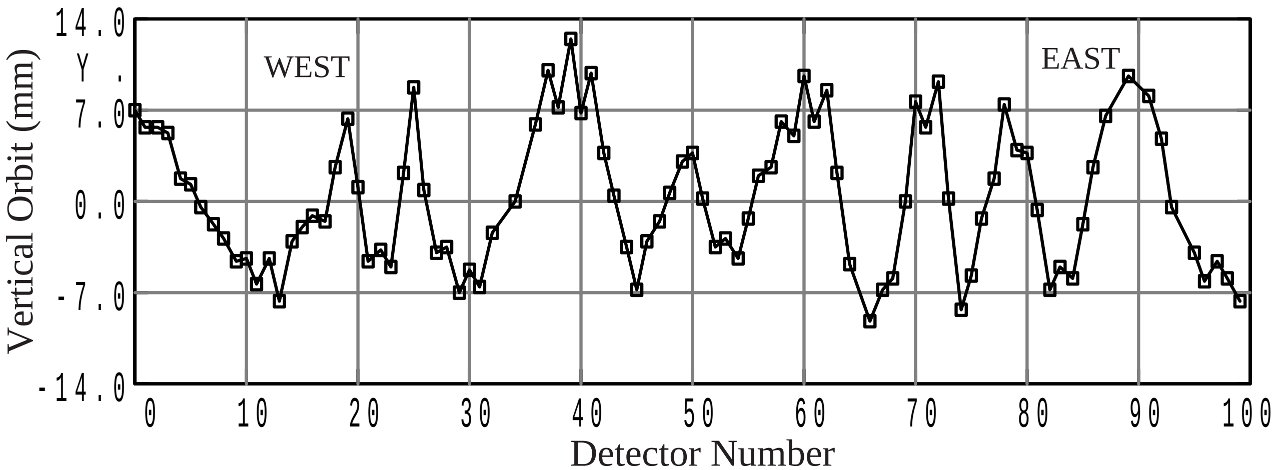

Figure 7. The zero corrector orbit before the dipole magnets are leveled. The interaction region is located between detector 100 and 1, which wraps around the figure.

The zero corrector orbit is a starting point for simulating the effects of leveling the dipole magnets. We then subtract the negated orbit due to a combination of misaligned dipoles from the measured zero corrector orbit to give a new zero corrector orbit, hopefully with a reduced orbit oscillation. Because there are 84 dipole magnets in CESR and leveling the dipoles is not an easy process, a selection process of dipole magnets to be moved was made. Eleven dipole magnets were selected as candidates to be leveled. The criteria for selection is that the magnets must have a vertical kick ± 0.16 mrad or greater to be considered a suspect to level. We decided that the dipole magnets near the interaction region were not to be moved for two reasons: 1) the steering correctors in the interaction region are strong and have good linear properties so local corrections can be easily done with these correctors. 2) The dipoles near the interaction region are not easily moved due to the interference with the Cornell High Energy Synchrotron Source (CHESS) beamlines.

The closed orbit simulation of leveling the four dipoles was done in the following manner: The measured roll of each magnet was computed for each set of bushings. Each set of bushings, or each end of the dipole magnet, was given a vertical kick due to the roll in the magnet. The vertical kick was given by

$$y' \cong \theta \times \phi$$

where θ is the dipole magnet bend angle and ϕ is the roll of the magnet. The closed orbit due to the vertical kicks from the rotated dipole magnets is determined by DIMAT[1]. Every permutation of the eleven dipole magnets is used in the simulation. The goal is to reduce the rms. zero corrector orbit. The minimized rms. orbit as a function of the dipole magnets moved is plotted in figure 8. It is evident from figure 8 that little is gained by moving more than four dipole magnets. Leveling the four dipole magnets

B12W, B16W, B38W, and B46E produced the minimum rms. zero corrector orbit allowed when moving four magnets.

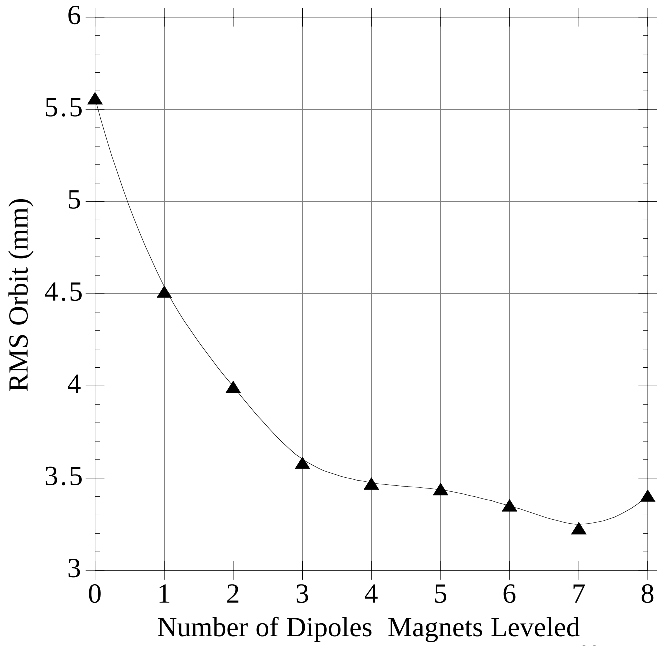

Figure 8. The rms. zero corrector orbit simulated by subtracting the effect of zeroing the dipole magnets and subtracting it from the zero corrector orbit.

The change in the zero corrector orbit due to the leveling dipole magnets B12W, B16W, B38W, and B46E is shown in figure 9.

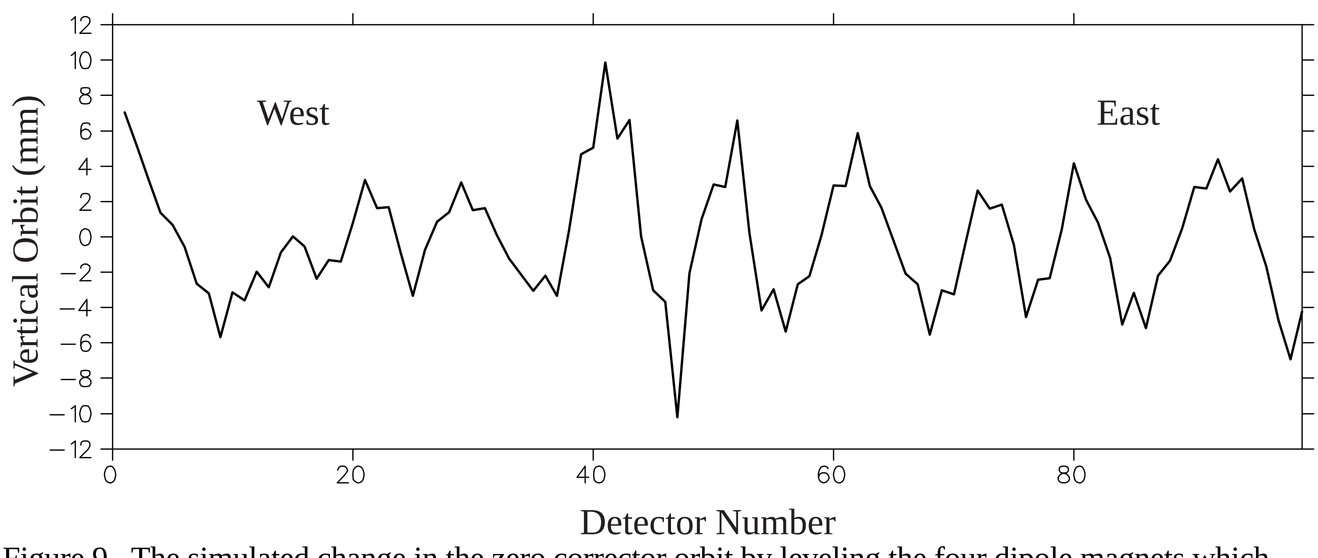

Figure 9. The simulated change in the zero corrector orbit by leveling the four dipole magnets which make the largest change in the zero corrector orbit. The change has a mean of -0.18 mm and an rms. of 3.44 mm.

After the dipole magnets were moved, their levels were re-measured and a new zero corrector orbit was measured on CESR. A comparison between the measured zero corrector orbit and the simulated new zero corrector orbit after moves is shown in figure 10. There is good agreement between the simulated and measured zero corrector orbits.

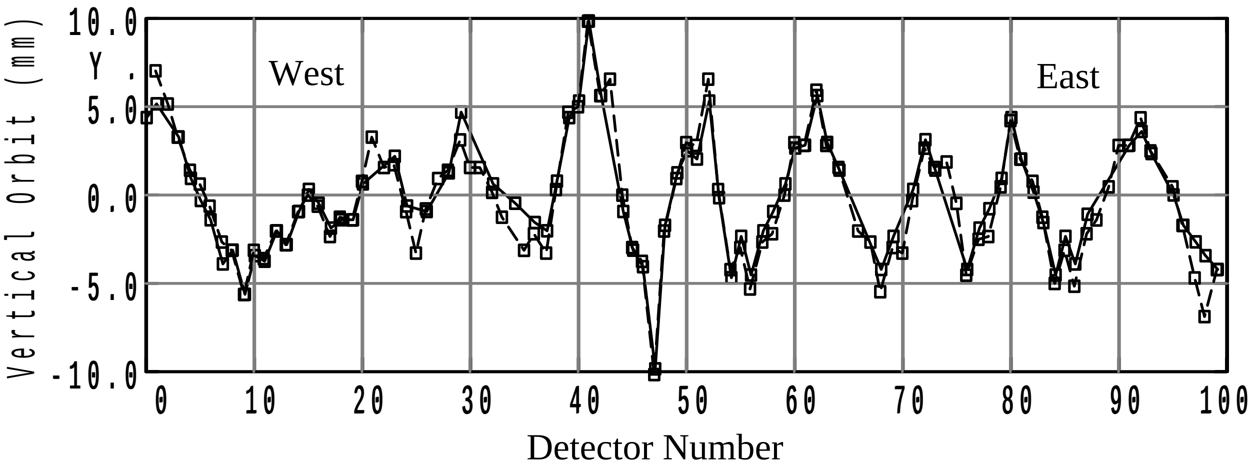

Figure 10. The measured and simulated zero corrector orbit after the four dipole magnets have been leveled. The measured orbit is the solid line and the simulated orbit is the dashed line.

The residual between the measured and simulated zero corrector orbit is displayed in figure 11. The residual may be due to constant movement of all the magnets in CESR. The time difference between the zero corrector orbit measurements was approximately a month and the magnets have moved during this period.

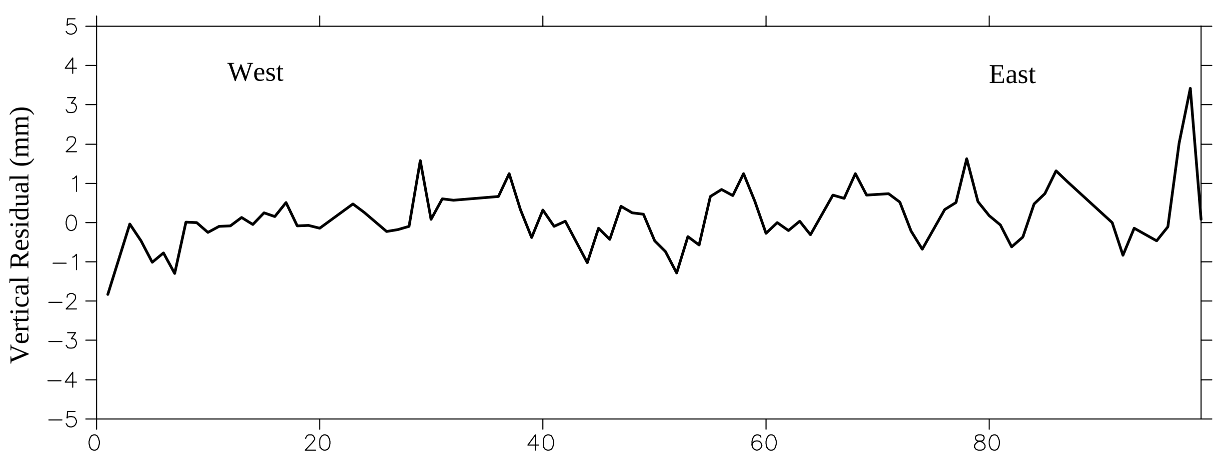

Figure 11. The residual between the measured and simulated zero corrector orbit. The residual has a mean of 0.15 mm and an rms. of 0.76 mm.

Conclusions

In CESR, a typical vertically focusing quadrupole which is misaligned by 20 mils vertically gives a kick of 0.077 mrad. For a dipole magnet that has a 20 mil roll the typical kick resulting is 0.149 mrad. The last time the quadrupoles were measured, their rms. vertical misalignment (not including the interaction region magnets) was 9.5 mils which corresponds to a 0.037 mrad vertical kick. The dipole magnets, before leveling, had an rms. vertical misalignment of 14.6 mils and an rms. vertical kick of 0.11 mrad. After the dipoles were leveled, the rms. vertical kick was reduced to 0.096 mils. It is evident that the alignment issues of the dipole magnets in CESR need to be addressed in the same manner as the quadrupole magnets due to their effect on the vertical orbit.

Using the zero corrector orbit as a diagnostic tool to improve the alignment of CESR has been beneficial and the accuracy of the simulation has eased the concern and uncertainty of moving magnets and has pointed out the tremendous gain in reducing the errors and enhancing the performance of the machine.

The performance of CESR is highly dependent on the alignment of the CESR magnets, especially in the vertical plane due to the vertical emittance being many times smaller than the horizontal emittance. By constantly monitoring and realigning the dipole magnets the performance of CESR will not be limited by the alignment of CESR dipole magnets.

Acknowledgments

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References

[1] Servranckx R. V. and Brown, K. L, ”Users Guide to the Program DIMAT”, SLAC Report 270 UC-28, March 1984.