Leveling of the Quadrupole Magnets in the Cornell Electron-Positron Storage Ring

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1. Introduction

There are 102 quadrupole magnets in the Cornell Electron-Positron Storage Ring (CESR) which provide focusing of bunches in the arcs and at the interaction point. Keeping these quadrupoles level is critical to the performance of CESR. If a quadrupole magnet is rotated about the vacuum chamber (fig. 1) it introduces unwanted coupling between the beams vertical and horizontal motion. If a quadrupole is rotated about its radial axis (fig. 2) the sextupole at the end of the table is displaced vertically from the beam's ideal trajectory. The purpose of leveling the quadrupole magnets is to reduce the coupling between the transverse planes and eliminate the focusing/defocusing effects of the sextupoles. Presented in this paper is the technique used to measure the rotation (or roll) of the quadrupole magnets and results of measurements of the coupling errors in CESR.

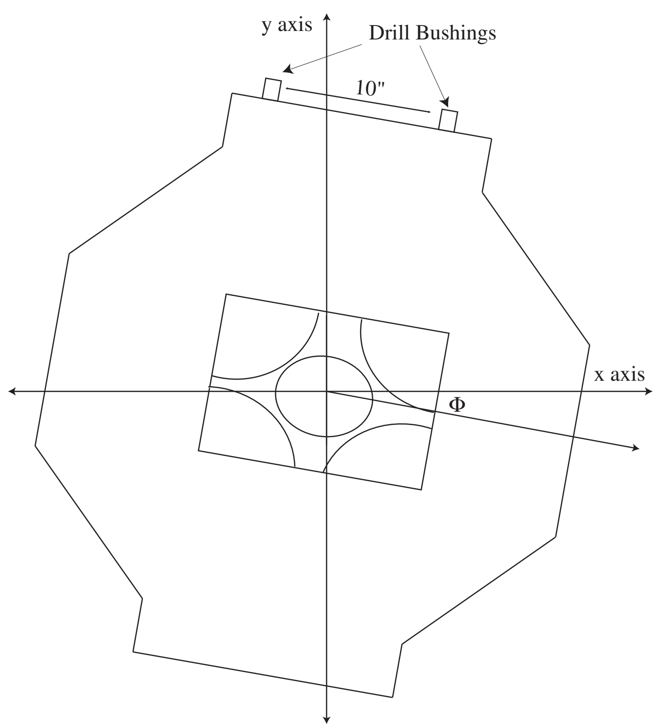

FIG. 1. The geometry of a CESR quadrupole magnet rotated about the z-axis (out of the paper) by an angle ϕ. This rotation is referred to as the roll of the quadrupole.

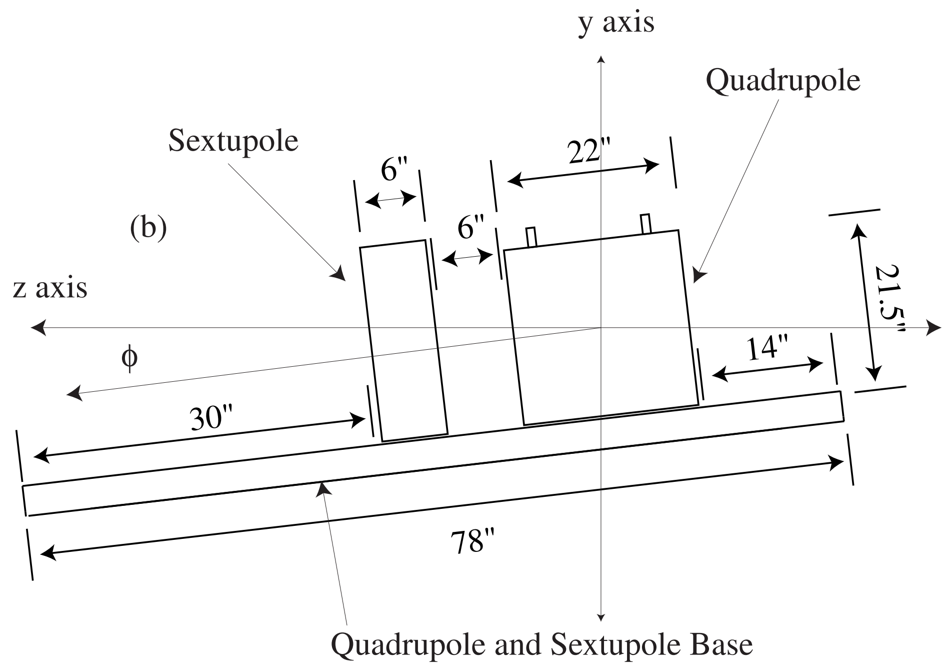

FIG. 2. The geometry of a CESR quadrupole magnet rotated about the x-axis (into the paper) by an angle ϕ. This rotation is referred to as the pitch of the quadrupole. In most locations in the CESR ring a sextupole is placed on the same table and the affect of a pitch on the sextupole is a vertical displacement.

2. CESR Level Survey

All CESR quadrupole magnet surveys reference four drill bushings that are mounted on top of each magnet. The drill bushings are placed at the corners of a rectangle centered at the top of the quadrupole. We define a bushing index (IB=1,4) in terms of our reference directions (fig. 3)

$$\#1 = LO = \text{Left Outside} = Y(1) \quad \#3 = RO = \text{Right Outside} = Y(3)$$
$$\#2 = LI = \text{Left Inside} = Y(2) \quad \#4 = RI = \text{Right Inside} = Y(4)$$

We use nautical names to define the deviation in angular position of a quad relative to its theoretical location. We define these deviations in terms of rotations about three perpendicular axis. A roll is a rotation about the longitudinal axis (the beam direction or z-axis), a pitch is a rotation about a CESR radius (or x-axis) and a YAW is a rotation about a vertical axis (or y-axis). The YAW is determined from the radial measurements of the quadrupoles[1]. From the four drill bushings placed on each quadrupole magnet, the difference in height between drill bushings determines the rotation and pitch of each magnet according to the following prescription:

$$\text{Roll left} = Y(1) - Y(2) = \text{Ydif}(1)$$
$$\text{Roll right} = Y(3) - Y(4) = \text{Ydif}(2)$$
$$\text{Pitch outside} = Y(3) - Y(1) = \text{Ydif}(3)$$
$$\text{Pitch inside} = Y(4) - Y(2) = \text{Ydif}(4)$$

Now we define the average roll, pitch as:

$$\begin{aligned} \text{Roll} &= (\text{Ydif}(2) + \text{Ydif}(1)) / 2 \\ \text{Pitch} &= (\text{Ydif}(3) + \text{Ydif}(4)) / 2 \end{aligned} \tag{1}$$

and the sign convention implied by our definitions is:

Positive roll means the outside of the quadrupole is high.
Positive pitch means the right side of the quadrupole is high.

The above analysis describes the roll and pitch of a quadrupole in terms of bushing elevation differences that are measured in units of mils.

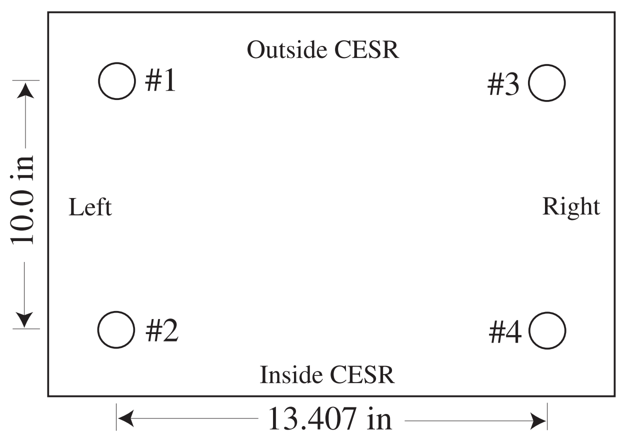

FIG. 3. The top view of a typical CESR quadrupole with the four fiducial bushings mounted on the top of a “typical” CESR quadrupole. The bushing plane is the rectangle made by the four bushings. The interaction region quadrupoles have a longitudinal spacing of 15.504 in instead of 13.407 inches.

The instrument used to measure the heights of the bushings is called an “L-level”. The L-level consists of two bars mounted on an L capable of laying in three of the four drill bushings. Each bar is hinged at one end with a bubble level mounted on the top bar (fig. 3). The height of the drill bushings is measured with a bubble level and digital dial gauges mounted on the L-Level. The L-level is placed across three of the left or right drill bushings. The top bar is adjusted to be level by a vertical screw, once level, the opening distance of the two bars is measured with two electronic digital dial gauge mounted 10" and 13.402” from the pivot. Two setups per quad allow both the pitch and roll of the quad to be measured independent of the calibration of the L-level. Data is taken first with L-level on bushings 1,2,3 and roll left and pitch out are measured by the left radial and the outside longitudinal bar levels. In this position the radial bar level dial gauge is towards the inside and the longitudinal bar level dial gauge is to the left so both bar levels are in positive use (positive roll gives a positive dial gauge reading).

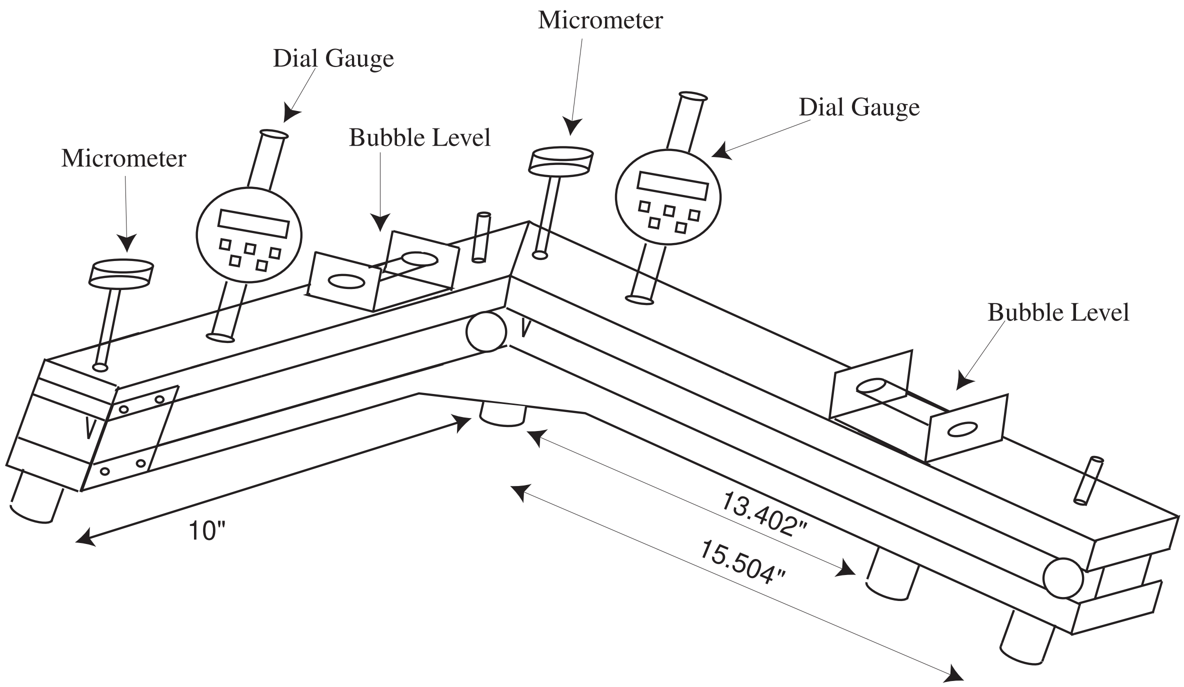

FIG. 4. A detailed picture of the L-level used to measure the roll and pitch of the CESR quadrupole magnets. The L-level sits on top of three drill bushings and measures the roll and pitch of the magnet. There are two cups that fit on the drill bushings on the right level. The cup that is 13.402” from the pivot is used to measure the normal quadrupoles and the cup that is 15.504” from the pivot is used to measure the interaction region quadrupoles.

The second setup uses bushings 2,4,3 and roll right and pitch in are measured by the right radial and the inside longitudinal bar levels. In this position the radial bar level dial gauge is towards the outside and the longitudinal bar level dial gauge is to the right so both bar levels are in negative use. Once measured with the L-level, the roll and pitch of the quadrupoles can be calculated from equation 1.

3. Alignment of the CESR Quadrupoles

During every down period the quadrupole levels (roll and pitch) are measured. It takes between two to three eight hour shifts to measure all of the quadrupole levels in CESR. During the down period of September 1997 the quadrupoles where surveyed and 36 of the quadrupoles where leveled. Figure 5 is the measured roll and pitch of the CESR quadrupoles before they where leveled and fig. 6 is the measured pitch and roll of the quadrupoles after they were leveled.

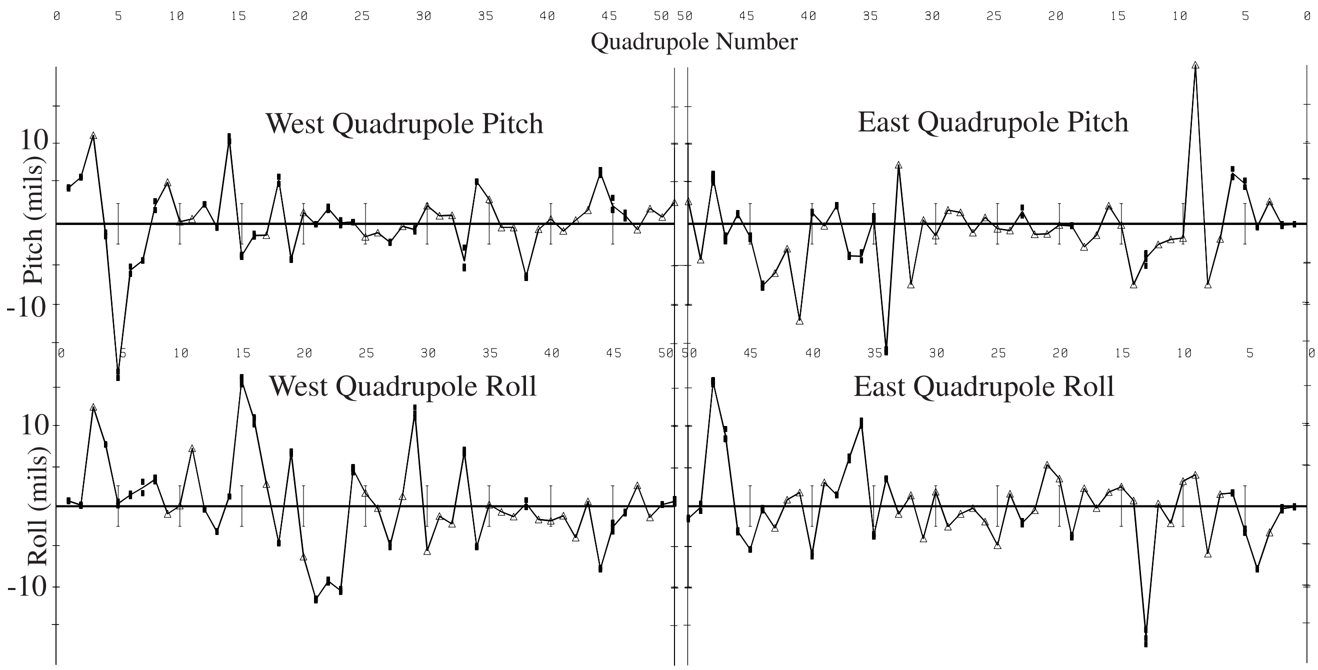

FIG. 5. The measured roll and pitch of the CESR quadrupoles before they were leveled. The mean and rms roll is 0.11 and 5.10 mils and the mean and rms pitch are -0.25 and 4.84 mils. Several quadrupoles were measured more than once and both measurements are plotted. The line goes through the mean of the multiple measurements. The interaction region is located at quadrupole zero on the plot.

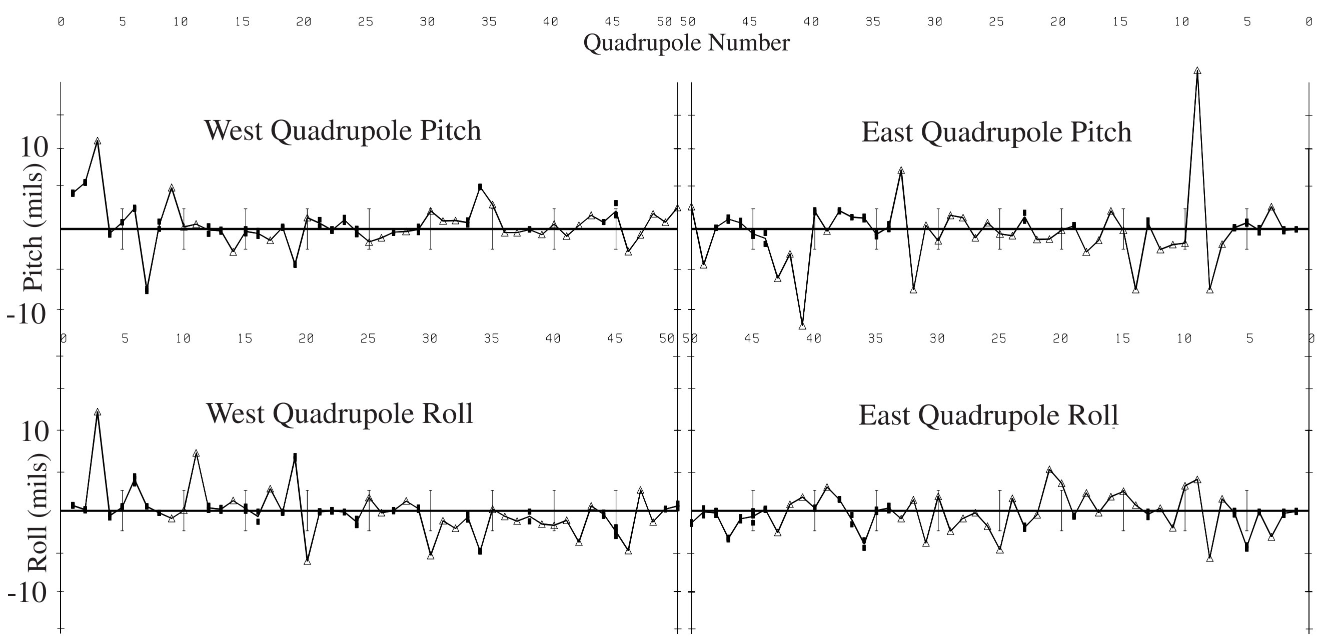

FIG. 6. The measured roll and pitch of the CESR quadrupoles after they were leveled. The mean and rms roll is -0.17 and 2.69 mils and the mean and rms pitch are 0.13 and 3.59 mils. Quadrupole 3 west was not moved due to vacuum chamber constraints. Quadrupole 9 east was not moved because the new superconducting RF cavity was being installed in that region during the down period.

Three comments can be made about the results of leveling the quadrupole magnets: 1) There was an rms. decrease in the roll by almost a factor of two and a decrease in the rms. pitch of 35% from moving the magnets. 2) Several of the quadrupole magnets around the interaction region were not moved due to the installation of the new superconductiong RF cavity or from obstructions near the magnets. 3) The quadrupole magnets in the west regions typically have larger misalignments than the quadrupole magnets in the east region.

The levels of each quadrupole have been archived over the past 10 years in data files. The history files allow us to track the movement each magnet over a long period of time because not all magnets move at the same speed. Figures 7 (a) and (b) are history plots of two magnets in the CESR ring over the past 7 years. Notice that quadrupole 18 west during this time span has been leveled two different time whereas quadrupole 39 west has not been leveled at all during this time span.

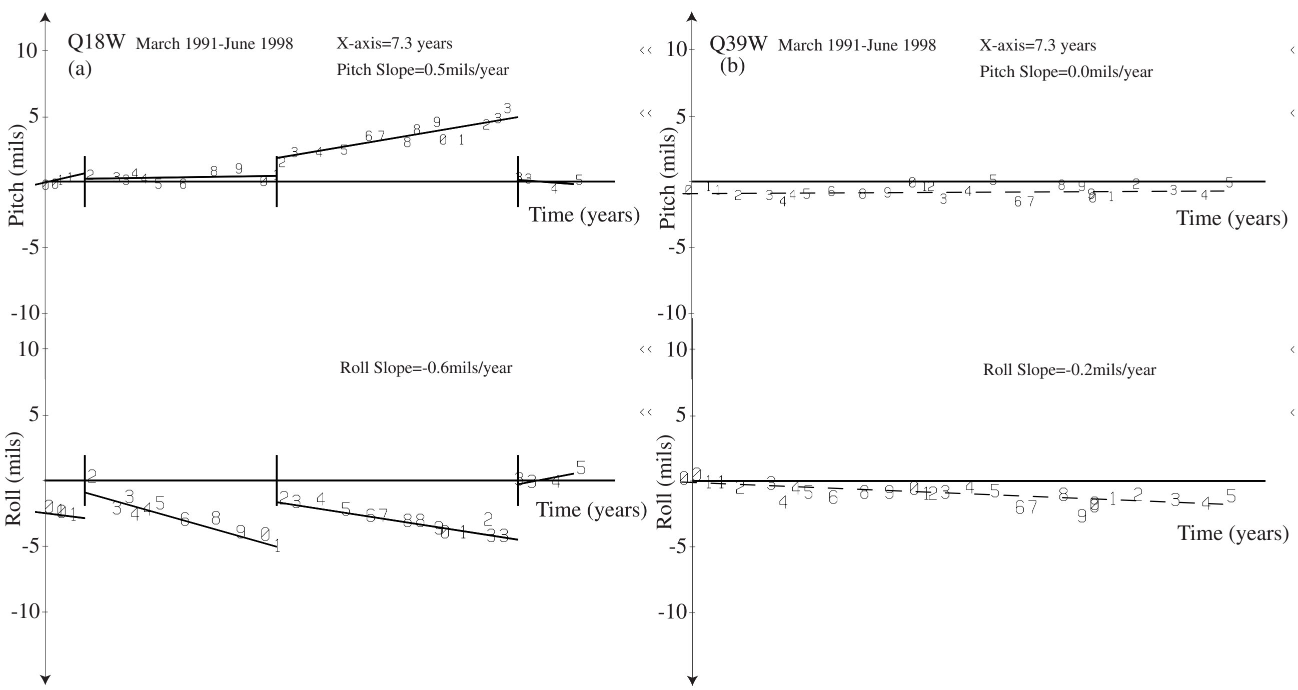

FIG. 7. The roll and pitch between March 1991 and June 1998 for quadrupole (a) 18 west and (b) 39 west. The lines on the horizontal axis signify the times when the quadrupole was moved. The slope of the pitch and roll during this period is denoted on each plot. Each number plotted represents a single measurement of the quadrupole for a specific down period. When the same number appears twice next to each other on the horizontal axis it signifies that the quadrupole was measured twice during that down period.

The slope of the roll and pitch between March 1991 and June 1998 for all the quadrupole magnets in CESR is plotted in fig. 8.

Several comments can be made about the coupling results. 1) As mentioned earlier, the magnets move more rapidly in the west region than in the east region of CESR. This is only true for the slope of the roll and not the pitch of the quadrupoles. An explanation of this phenomena exists in the west and not in the east and for the roll and not the pitch. The vacuum chamber that runs through the center of the quadrupole magnets is attached to the quadrupoles. Any forces on the vacuum chamber, due to heating from synchrotron radiation or vacuum chamber misalignment, is a force on the quadrupole magnet. This force is applied in different directions depending on the vacuum chamber constraints it will tend to make the magnet roll around its base [1]. This only affects the roll and not the pitch of the magnet. The CESR tunnel is more stable in the east region than in the west and that is why the quadrupole bases move more rapidly in the west region. 2) Four of the quadrupole magnets in CESR have a roll slope that is greater than five mils/year. These four quadrupoles will be unpinned from the vacuum chamber in the near future to reduce the need to move these quadrupole so frequently.

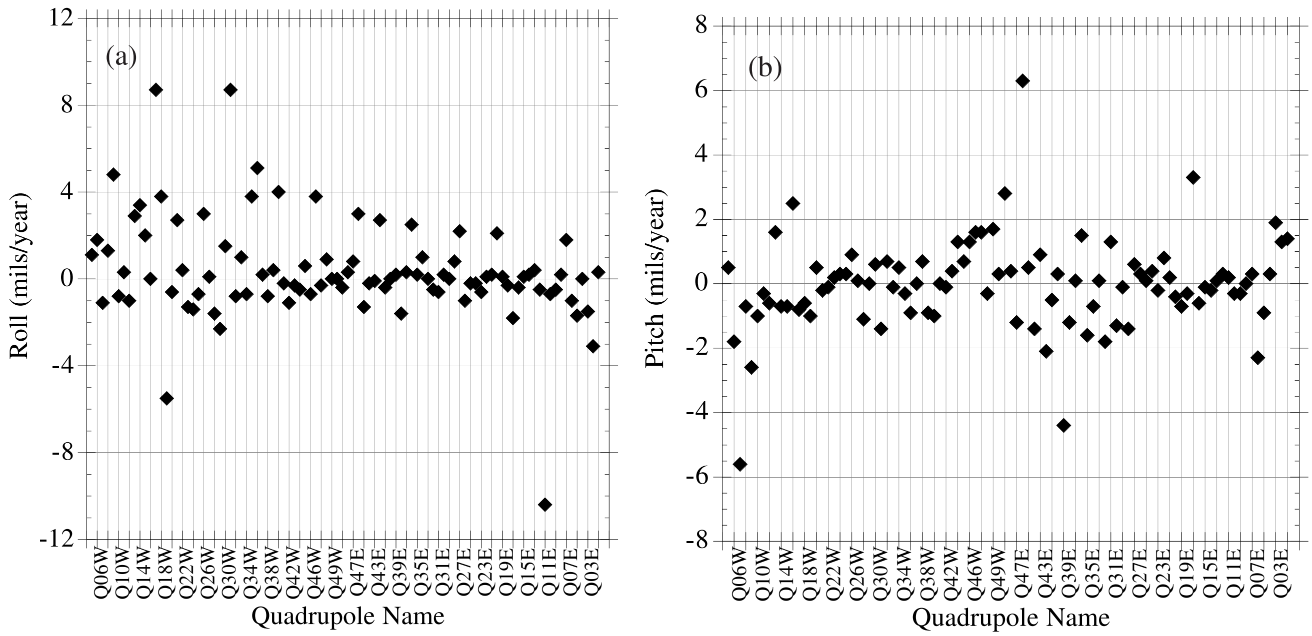

FIG. 8. The slope of the (a) roll and (b) pitch for each quadrupole magnet in the CESR ring. The slope for each magnet is calculated between March 1991 and June 1998.

4. Effects on CESR Performance

In high-energy accelerators one of the sources of linear coupling arises from alignment errors due to rotated quadrupole fields. Rotated quadrupoles introduce coupling between the horizontal and vertical planes. Since CESR collides flat beams (small vertical beam size) the coupling of planes results in an increase in the vertical beam size and reduces the luminosity. The coupling of the vertical and horizontal motion requires skew quadrupoles for correction. A performance benefit that can be attributed to leveling the quadrupoles in CESR is the reduction of transverse coupling. In the presence of coupling the vertical beam size maybe enlarged. To measure coupling in CESR a normal mode of the beam is coherently excited by a shaker and the relative phase and amplitude of the two normal transverse (vertical and horizontal) modes is measured[3]. From this measurement the coupling transfer matrix $\overline{C}$ can be determined. The $\overline{C}_{12}$ term of the 2x2 coupling matrix was measured before and after the quads where leveled and the results are shown in figures 10 and 11.

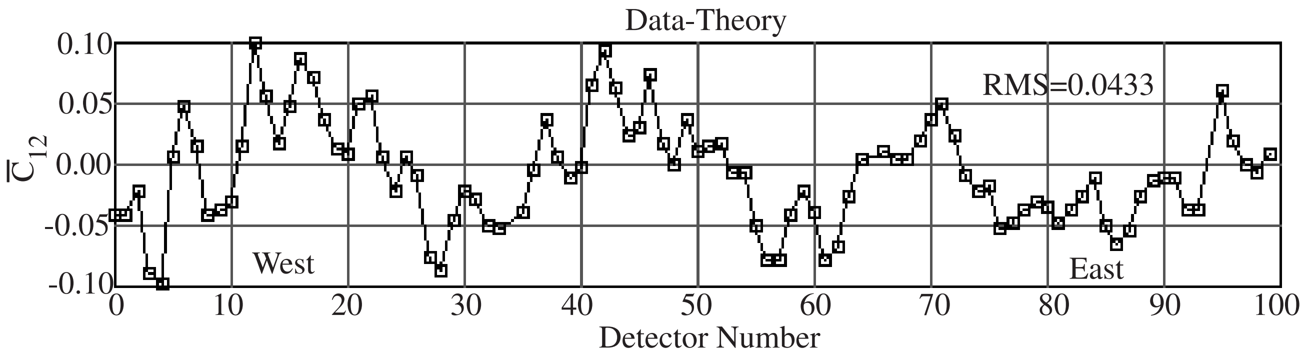

FIG. 10. $\overline{C}_{12}$ at each detector around the ring measured before the quadrupoles were leveled. The rms. value is 4.3%[4].

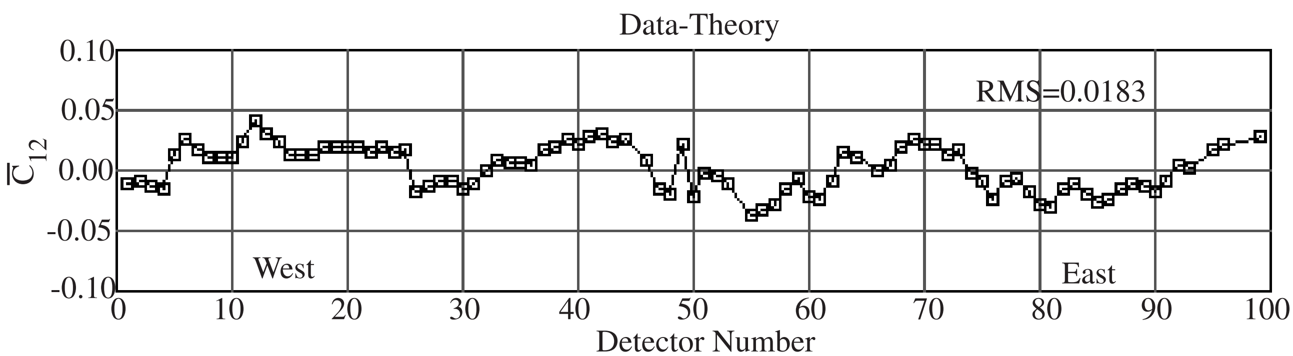

FIG. 11. $\overline{C}_{12}$ at each detector around the ring measured after the quadrupoles were leveled. The rms. value is 1.8%[4].

Several comments can be made about the coupling results. 1) The coupling measurements shown were made with the skew quadrupoles turned off so the two measurements are on equal footing as far as coupling goes. 2) During the down period the back-leg windings of some of the dipole steering were moved away from the beampipe and that might have reduced the coupling in addition to leveling the quadrupoles. 3) Both measurements have significant global coupling (long wavelength) but the localized coupling (short wavelength) is greatly reduced after the quadrupole magnets were leveled.

5. Conclusions

Keeping the quadrupoles level in CESR with the method described has been highly successful over the last ten years and it has enhanced the performance of CESR. The measurement technique described in this paper can accurately measure the quadrupoles rotation to 0.1 mrad. With this accuracy, and our ability to level magnets when they are out of tolerance, allows us to keep transverse coupling to a minimum and reduces our dependence on skew quadrupoles.

6. Acknowledgments

The authors would like to thank David Sagan for taking the coupling measurements. Gerry Rouse, who has lead the survey group for the past ten years, will be greatly missed.

7. References

[1] R. Holtzapple, R. Eshelman, D. Rice, G. Rouse, and A. Tamakuwala, “Radial Alignment of the Quadrupole Magnets in the Cornell Electron-Positron Storage Ring”, Cornell CBN 99-24, Sept. 1999.

[2] Sands, M., "The Physics of Electron Storage Rings: An Introduction", SLAC-0121, Nov 1970. 172pp.

[3] Bagley, P. and Rubin, D.,”Correction of Transverse Coupling in a Storage Ring”, Proc. 1989 Part. Acc. Conf. (San Francisco) p. 874, 1989.

[4] The CESR coupling measurements are provided by David Sagan.