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Radial Alignment of the Quadrupole Magnets in the Cornell Electron-Positron Storage Ring

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Abstract

The Cornell Electron-Positron Storage Ring (CESR) has 102 quadrupole magnets to focus the beam around the storage ring. CESR's goal is to deliver high luminosity and its performance is dependent on the alignment of these quadrupole magnets. In this paper the measurement technique of the CESR quadrupole magnets and the analysis of the radial data is presented and discussed.

1. CESR Radial Survey

The goal of a complete CESR survey is to describe the alignment of the CESR quadrupole magnets in space. In reality, the location of a CESR quadrupole magnet is described by the position of the tops of four drill bushings that are mounted on the upper surface of each CESR quadrupole magnet lamination (fig. 1). The bushing plane is defined as the best fit to the tops of the four bushings. The radial position of a quadrupole magnet is given by the radial position of the center of the bushing rectangle. The angular orientation of the quadrupole magnet is the angular orientation of the bushing plane as described by the nautical parameter, which is called the magnets YAW. The YAW is defined as the difference between the average radial position of the right bushings and the left bushings from their theoretical position. Positive YAW means the quadrupole magnet has its right side further to the outside of the CESR ring. For the radial analysis, YAW is expressed in radians, but for output it is expressed as the YAW in mils consistent with the other orientation parameters. The other conventions used are: outside as toward larger CESR radius, inside toward smaller CESR radius, and left and right as standing inside the CESR ring facing out. Up is to a higher elevation. The index of the four fiducial bushing IB=1,4 is shown in fig. 1.

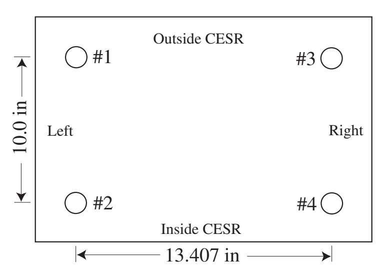

FIG. 1. The top view of a Mark II CESR quadrupole with the four fiducial bushings mounted on the top of the quadrupole. The bushing plane is the rectangle made by the four bushings.

The purpose of the radial survey is to determine the relative radial location of the CESR quadrupole magnets (average radial position and YAW), compare their location with theory and calculate the position error (dR,YAW) so quadrupole magnets that lie outside our radial position tolerances can be re-positioned. Radial data consists of wire measurements that relate each quadrupole magnet to the quadrupole magnets on either side. A radial setup at quadrupole magnet Q=Qset consists of stretching a wire (actually a mono-filament line) from quadrupole magnet Qset-1 (on the left) to quadrupole magnet Qset+1 (on the right) and measuring the distance from two fiducials mounted on Qset to the wire (fig. 2). For a typical radial quadrupole magnet measurement, the wire (mono-filament line) is placed around the dowel that is placed in the drill bushing. The distance between the wire and the center quadrupole magnet's (Qset) drill bushings is measured. The data is entered on data sheets and put into a computer file to be analyzed.

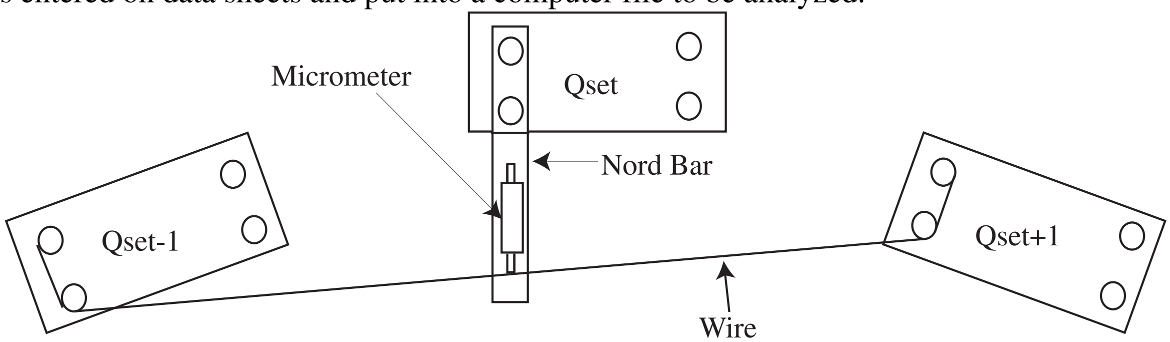

FIG. 2. A typical radial survey set up for the CESR quadrupoles. For this set up dowels are placed in the left inside bushings of quadrupole magnets Qset-1 and Qset+1. The distance between the wire and the quadrupole magnet Qset is measured for both the left and right set of bushings is measured.

The Nord bar, which determined the distance from the fiducial bushing to the wire, is shown in detail in fig. 3.

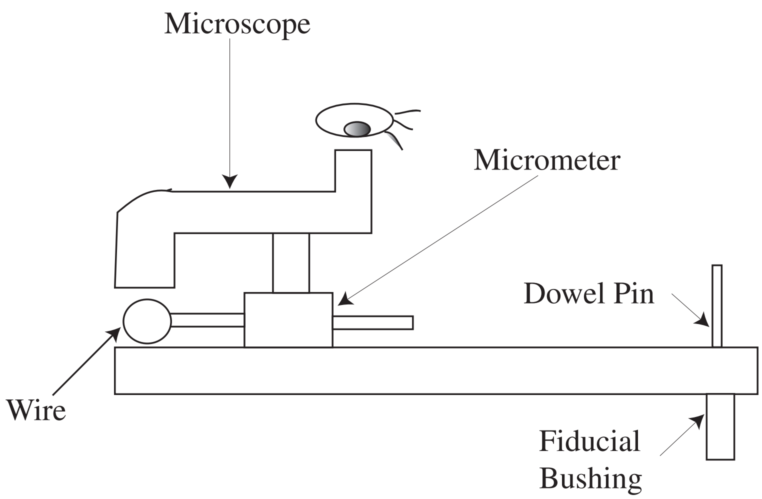

FIG. 3. A detailed picture of the Nord Bar. A dowel pin is place in the quadrupole magnet's bushings to hold the bar steady and the distance of the wire relative to the micrometer is measured by observing when the micrometer head hits the wire through the microscope.

2. Radial Survey Analysis

The theoretical locations of the CESR quadrupole magnets are located in the CESR lattice file[1]. The lattice file gives the desired pointing angle and coordinates of quadrupole and dipole magnets in a X,Y coordinate system that is chosen to describe the set-up geometry used for the wire measurements (fig. 4). For each quadrupole magnet to be measured, Qset, an orthogonal set-up coordinate system (X,Y) can be defined with the origin at the center of quadrupole magnet Qset-1 and the X-axis passing through the center of Qset+1. The set-up parameters consist of the three pointing angles θ_1,θ_2,θ_3 (the angles the left to right quadrupole magnet axis makes relative to the X-axis) of the three quadrupole magnets and the three lengths X_1, Y_1, X_2 shown below. These parameters are derived directly from the CESR lattice and describe the desired quadrupole magnet locations.

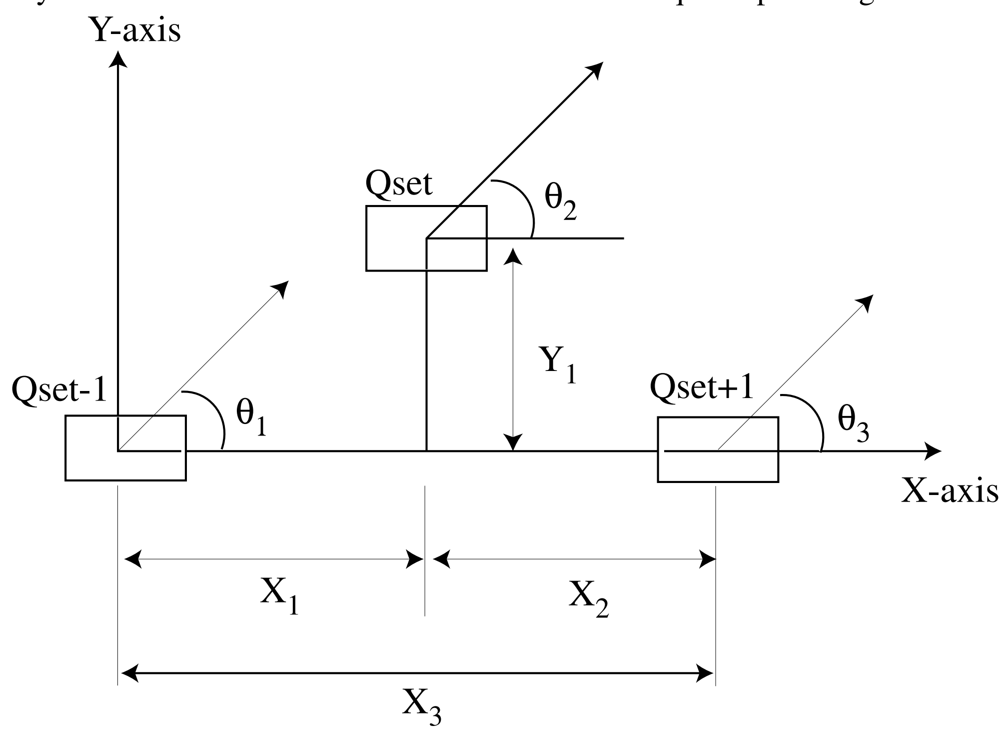

FIG. 4. The X,Y geometry used to describe the theoretical locations of the quadrupole magnets set up Qset for a radial measurement set-up.

The radial analysis programs use a (U,V) coordinate system. This coordinate system removes the dependence of the measurements on the bushings for a stretched wire. The (U,V) coordinate system can be used on the quadrupole and dipole magnets in CESR. This allows the difference from the desired pointing angle (YAW) and radial position (dR) to be calculated (fig. 5). For each set-up

Qset, the three (U,V) coordinate systems can be defined local to each quadrupole magnet and used to locate the quadrupole magnet bushings used by set-up Qset. Each U, V axis is parallel to the setups X, Y axis with the quadrupole magnet center as their origin. Note (U_1,V_1) is identical to the (X,Y) set-up system. We will be considering a wire stretched from bushing o1 to o3 and measurements made from the wire to bushing o2.

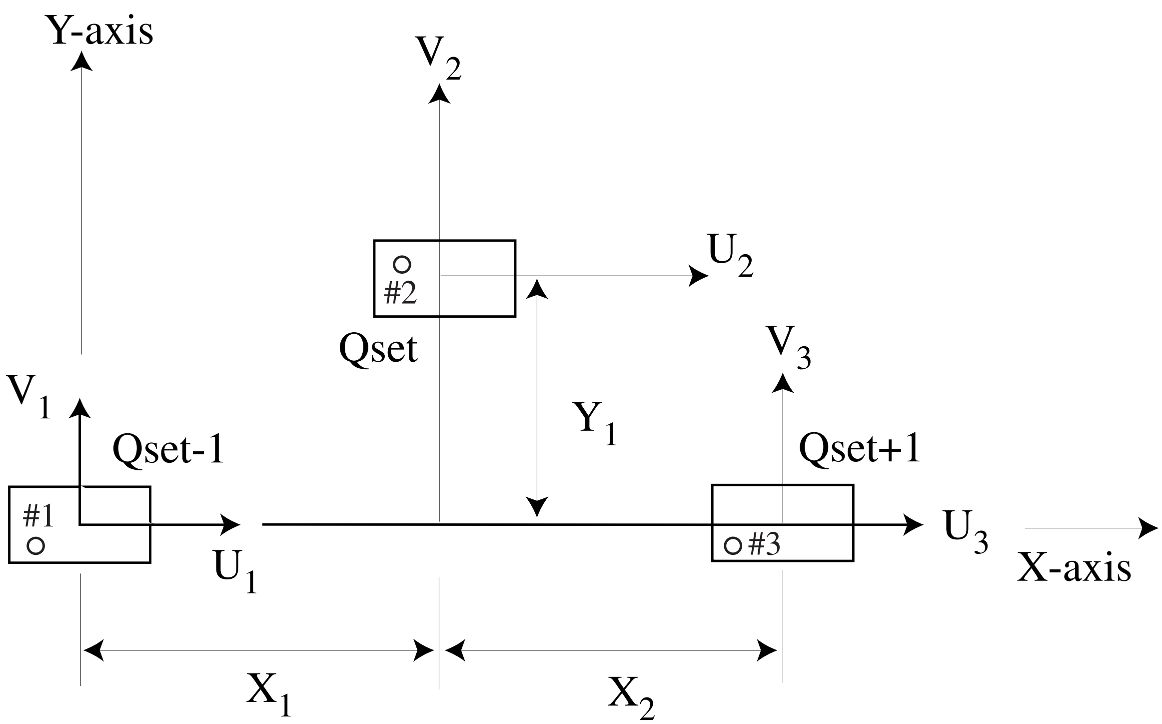

FIG. 5. The U,V geometry used in the radial analysis program.

The relationship between the theoretical location (X,Y) and the measured location (U,V) of the quadrupole magnets can now be made. The relationship of the two coordinate systems has been worked out in detail elsewhere and will not be presented in this paper; rather, a brief description of the radial analysis program will be made[2]. The goal of the radial analysis program is to determine the radial position errors dR(Q) and YAW(Q) for each quadrupole magnet Q.

When examining the problem of determining the alignment of a quadrupole magnet Qset from the measured data two difficulties surface:

1) In determining the YAW(Qset) of each magnet we always take a left and right bushing wire measurement of each quadrupole to calculate the YAW(Qset). YAW(Qset) is dependent on the adjacent quadrupoles radial position errors dR(Qset-1) and dR(Qset+1), but reduced by approximately 1/50 due to the ratio of distances. This weak dependence on the adjacent quadrupoles means that with a fixed input vector dR(Qset) allows us to calculate YAW(Qset). This is done at the start of the analysis program.

2) The data relates the error in radial position dR(Qset) of a quadrupole to the wire. The position of the wire depends on YAW(Qset) and radial position dR of the 'wire quadrupole magnets' dR(Qset-1) and dR(Qset+1), which may not be known. If dR(Qset-1) and dR(Qset+1) are known then the calculated dR(Qset) (called dRcal(Qset)) and YAW(Qset) equations will give the correct alignment of quadrupole magnet Qset. In practice, dR(Qset-1) and dR(Qset+1) are unkown, and this requires an error function to describe how dR(Qset) matches the data. We define an error at quadrupole magnet Q as dYcal(Q)=dRcal(Q)-dRinput(Q) where dRinput(Q) was used as the input alignment of the wire quadrupole magnets and dRcal(Q) is calculated from the measured data. The first order expression for dRcal(Q) in terms of the adjacent dR's is approximately given by (assuming a symmetric ring):

$$\mathrm{dRcal(Q) = dR(Q) + .5 \times dR(Q-1) + .5 \times dR(Q+1)}.$$

The measurements will depend on the position of the adjacent wire quadrupole magnets and it is up to the terms $.5 \times \mathrm{dR(Q-1)}+.5 \times \mathrm{dR(Q+1)}$ to remove this dependence. If an adjacent wire quadrupole magnet is misaligned by dR then the wire at that quadrupole magnet is dR to the outside of the ring. The physical measurement and resulting dRcal(Q) will be reduced by 1/2dR due to the motion of the wire and therefore 1/2dR must be added to dRcal(Q) to get the actual alignment dRcal(Q) of quadrupole magnet Q. Using our definition above for dRcal(Q) also gives a first order expression for our error function dYcal:

$$\begin{aligned}&\mathrm{dYcal(Q) = dRcal(Q) - dRinput(Q)}\\&\mathrm{dYcal(Q) = dR(Q) + .5xdR(Q-1) + .5xdR(Q+1)\text{ - }dRinput(Q)} \quad (1)\end{aligned}$$

where dRinput(Q) are the values that the minimization program uses to minimize dYcal. We will have a solution for the alignment of the CESR ring when dRcal(Q) as calculated equals the alignment vector used as input for the calculation. Thus dYcal as defined above will approach zero as the set dRinput(Q) approaches the actual alignment vector dRcal(Q) for the survey of the CESR ring. The goal of the radial analysis program will be to find a solution vector dRinput(Q) such that dYcal(Q) is minimized. In order to do this we use a minimization program MINOP and hand it a first order expression for dYcal(Q) so that it can include the effect of adjacent quadrupoles in determining the best dRinput(Q).

Below is a brief outline of how the radial program calculates the set dR(Q),YAW(Q) that describes the misalignment of the CESR quadrupole magnets.

1) Local and setup coordinate systems are defined and used to calculate the set-up parameters from the CESR lattice file. The measured data is read into the program.

2) Set dRinput(Q)=0 and calculate YAW(Qset). Iterate to take the effects of YAW(Qset-1) and YAW(Qset+1) on our calculation of YAW(Qset). dRinput(Q) remains at its initial value during this

process. We then fix YAW(Qset) and calculate dRcal(Qset) (from the measured data) which is the starting value for dYcal(Qset) (Since dRinput(Q)=0).

3) Now we input dYcal(Q) and employ MINOP[3] to determine a set of δ(dR(Q)) which minimizes the next calculation of dYcal(Q). We then add δ(dR(Q)) to the last input vector used and obtain $dR_1(Q)$ = dRinput(Q) + δ(dR(Q)) which is the best solution vector that the first iteration of our analysis as yielded. To accomplish this MINOP is supplied with the first order expression for dYcal. MINOP now returns a set of δ(dR(Q)) such that dR_1= dRinput + δ(dR(Q)) will result in a reduced dYcal(Q) when the program is run again. Usually it takes three iterations for the dYcal(Q) values to reduce to acceptable values.

The accuracy of the radial analysis program is determined by creating radial measurement data with the radial and YAW offsets known and letting the radial analysis program find the known misalignments. This is done in the following two examples:

a) Three misaligned quadrupoles in CESR

Let us assume that all the CESR quadrupole magnets are aligned except for three quadrupole magnets which are radially misaligned by +20, -40, and +20 mils with a YAW of 15, -10, 5 mils. The radial test data with these misalignments is fed into the radial alignment program to observe the accuracy of determining the resulting alignment. Figure 6 is the dR and YAW values for the three misaligned quadrupoles after three iterations of the radial analysis program.

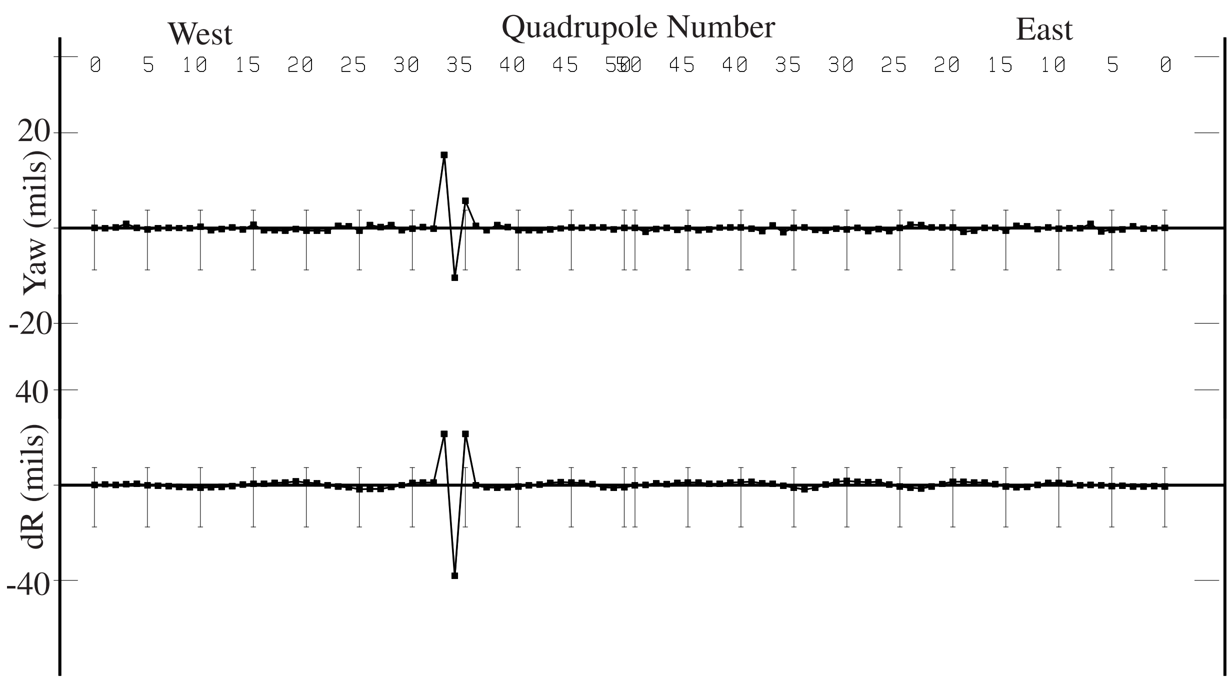

FIG. 6. The CESR quadrupole radial alignment according to the radial analysis program when three quadrupole magnets are misaligned by 20, -40, and 20 mils radially and with a YAW 15,-10, and 5 mils. The misaligned quadrupole magnets are quadrupole magnets 33-35 in the west side of CESR.

Since the offsets of the three quadrupoles are known to be 20, -40, and 20 mils, the difference between the radial analysis program and the known input offsets is plotted in fig. 7 as a function of the radial program's iteration number. Notice that by the third iteration the analysis program has reduced the offset into the noise of the ring. The program's determination of the offset is good to approximately 2-3 mils and the program puts in a 2-3 mil wave in the CESR ring.

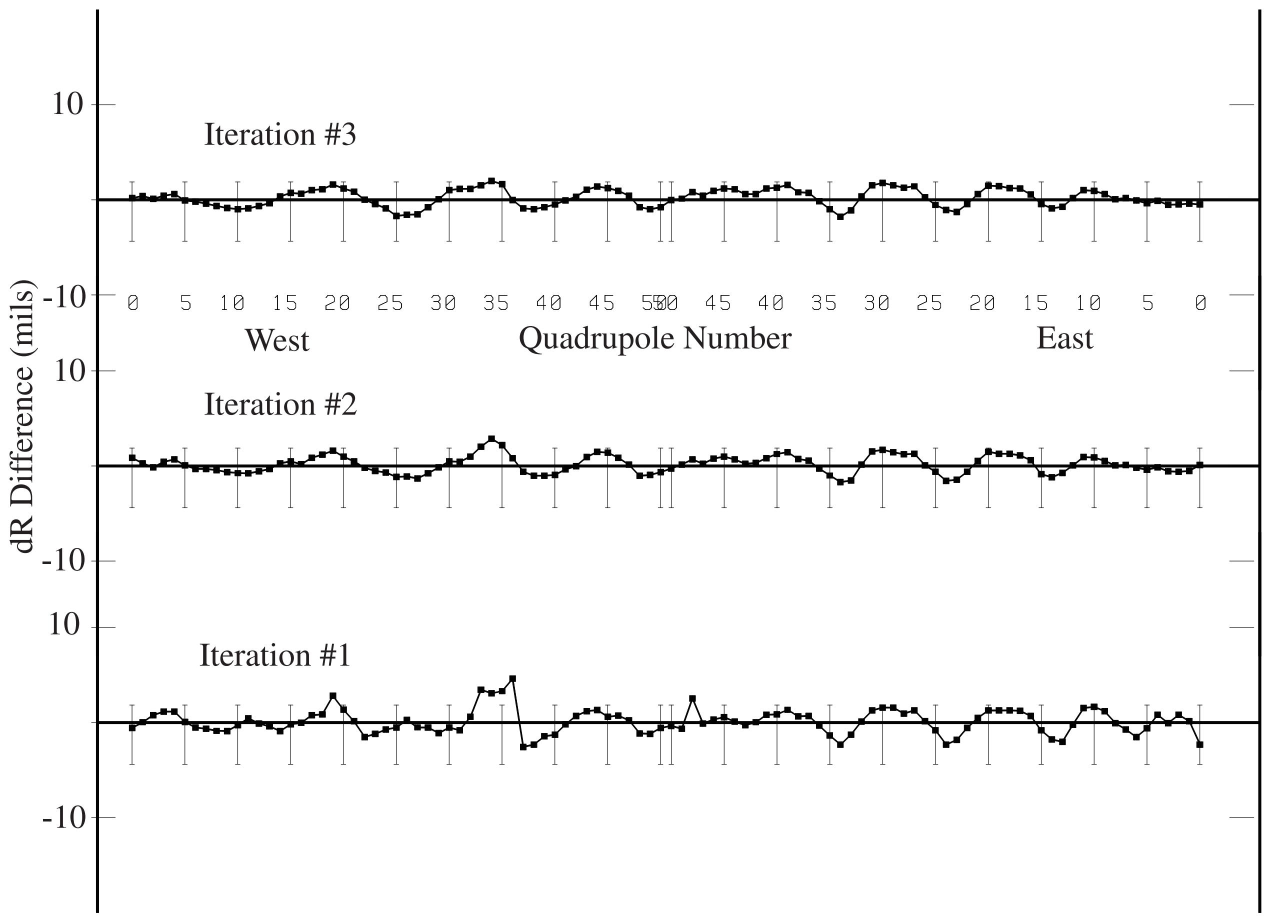

FIG. 7. The difference between the radial analysis programs determination of the radial offset of the quadrupole magnets and the known radial offset of the quadrupole magnet for three different iterations of the program.

The same plot can be made for the YAW of the quadrupole magnets, and as expected, the YAW is determined from the first iteration of the radial analysis program (fig. 8)

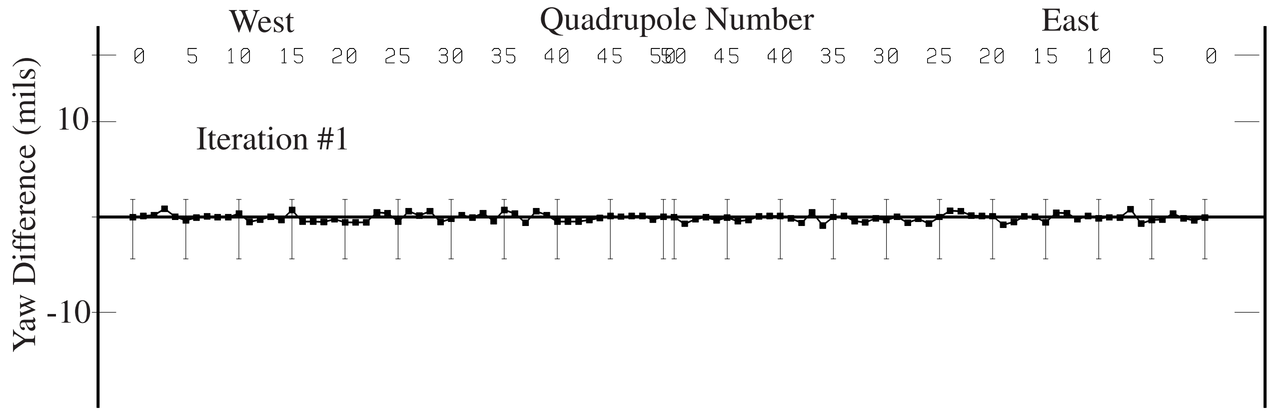

FIG. 8. The difference between the radial analysis programs determination of the YAW of the quadrupole magnets and the known YAW of the quadrupole magnet after one iteration of the program.

b) Misalignment of the CESR

The second example of the performance of the radial analysis program is when every quadrupole magnet has a radial misalignment (dR and YAW). This is accomplished by taking a real CESR radial data set and running it through the radial analysis program to determine the dR and YAW value from that data set. Figure 9 is a histogram of the known dR and YAW values used to make the test data.

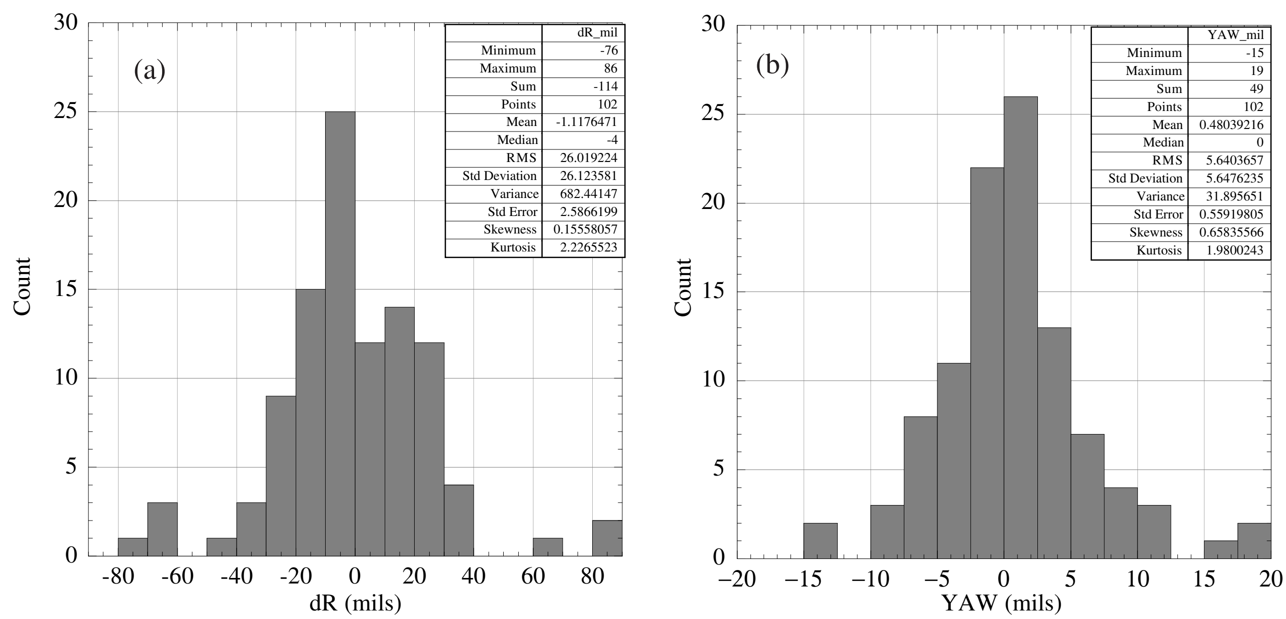

FIG. 9. A histogram of the (a) dR and (b) YAW values of the test data for the misaligned quadrupole magnets. The rms of the data is 26 mils for dR and 5.6 mils for YAW.

The dR and YAW for each quadrupole magnet is used to make test data that is then fed back into the program and analyzed. Figure 10 is the dR and YAW values for the CESR after three iterations of the radial analysis program.

The test data is then read back into the radial analysis program and the difference between the actual and analyzed offsets can be determined. The difference between the radial analysis program and the known input offsets is plotted in fig. 11 as a function of the radial program iteration number. Notice that by the third iteration of the analysis program the difference between the actual offset and the analysis determination of the offset is a wave with a peak amplitude of 4-5 mils. The same plot can be made for the YAW of the quadrupole magnets, and as expected, the YAW is determined from the first iteration of the radial analysis program (fig. 12).

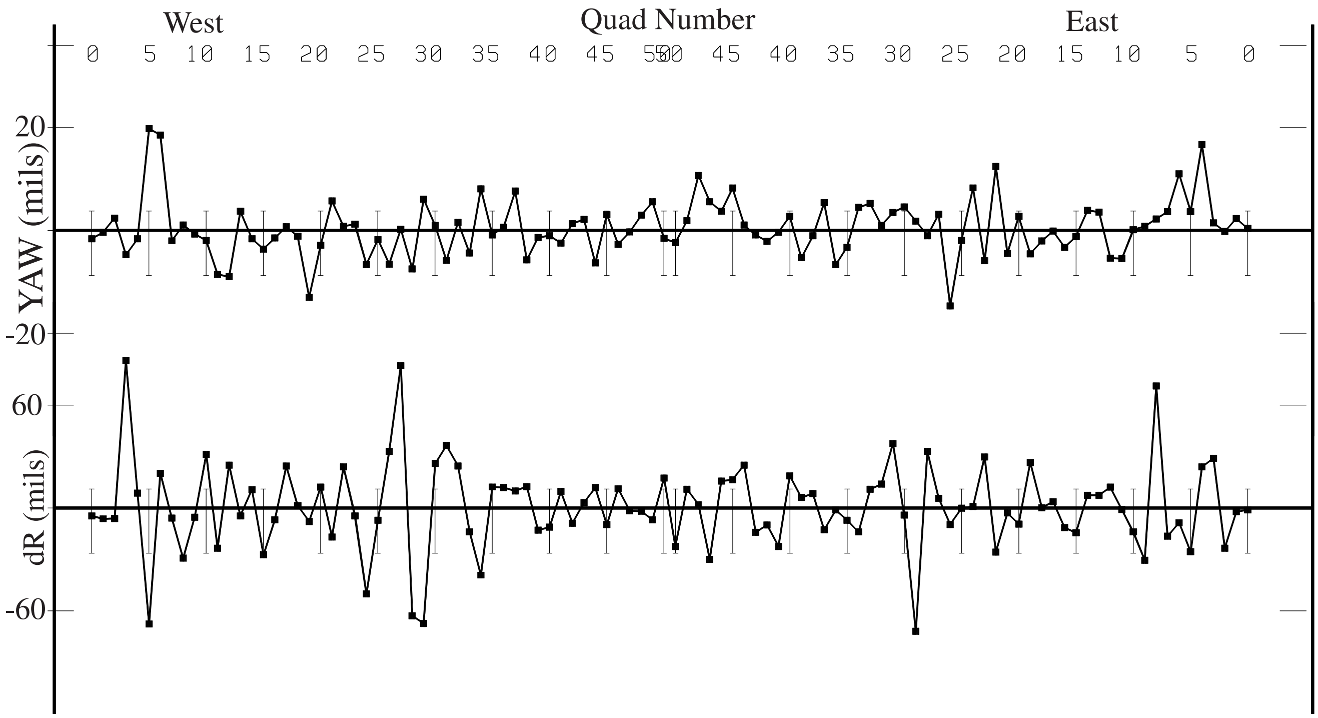

FIG. 10. The CESR quadrupole radial alignment according to the radial analysis program when all the quadrupoles are misaligned.

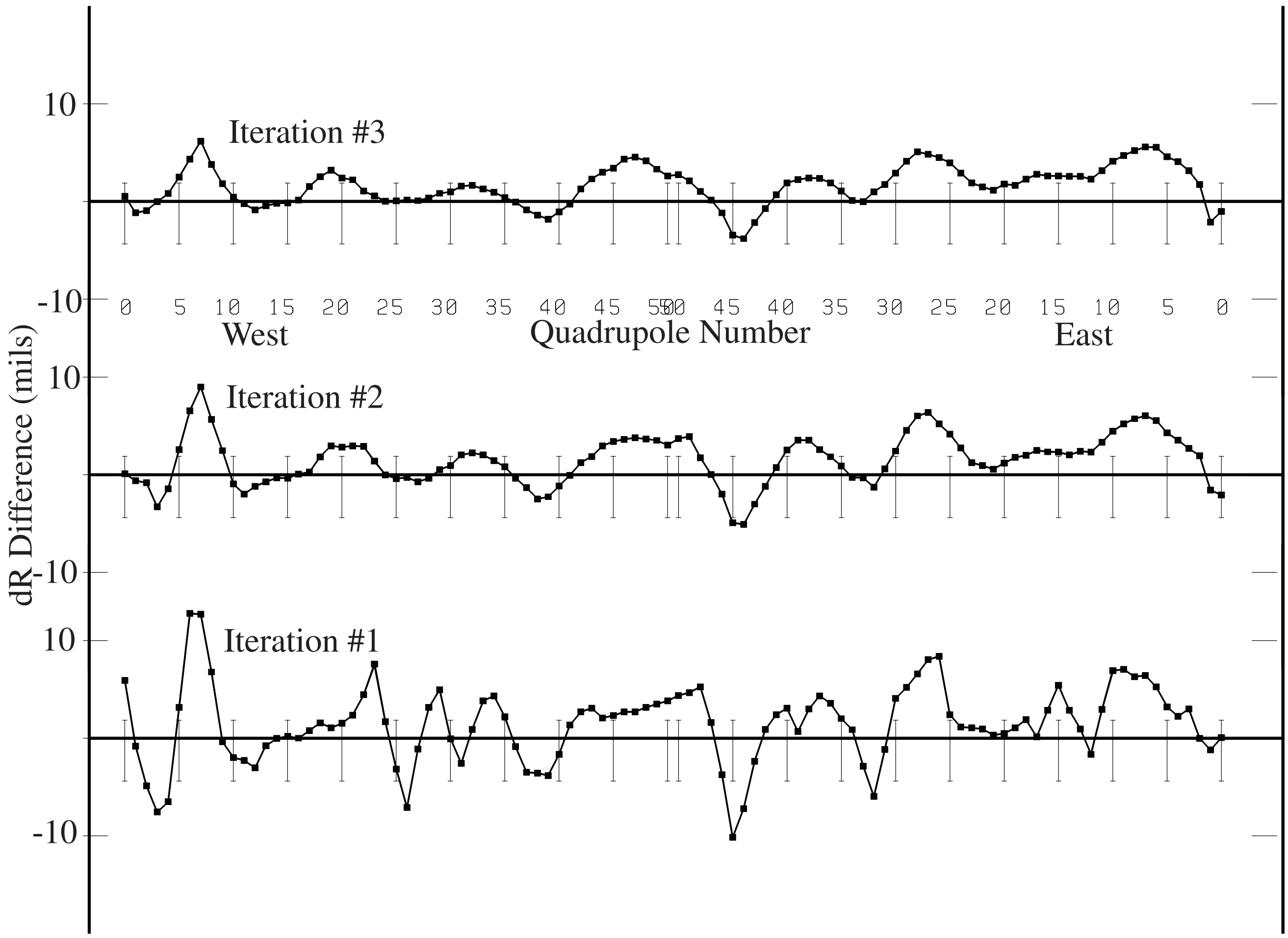

FIG. 11. The difference between the radial analysis program's determination of the radial offset of the quadrupole magnets and the known radial offset of the quadrupole magnet for three different iterations of the program.

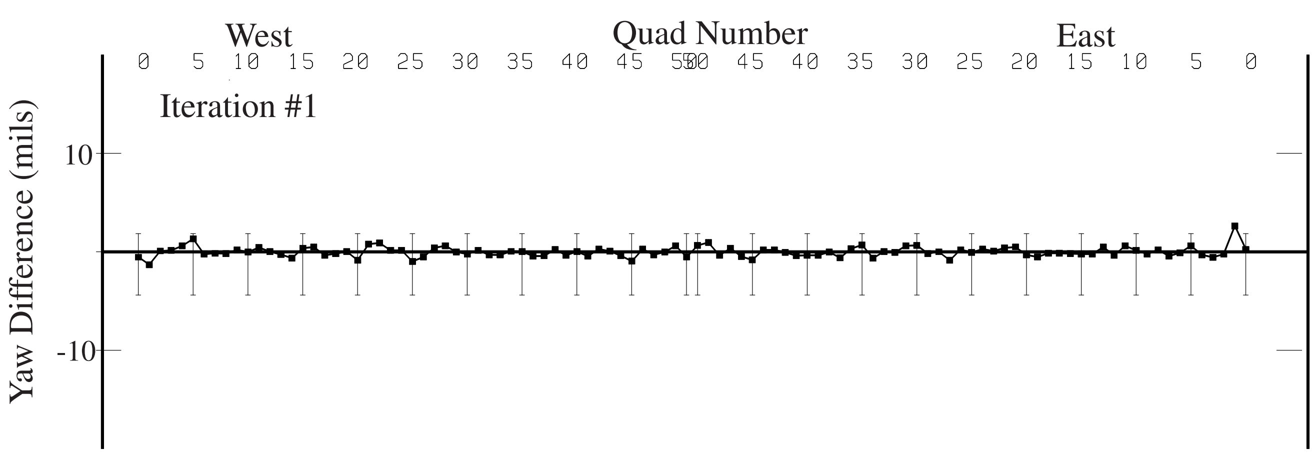

FIG. 12. The difference between the radial analysis program's determination of the YAW of the quadrupole magnets and the known YAW of the quadrupole magnet after one iteration of the program.

3. Alignment of the CESR Quadrupole Magnets

During the shutdown of March 1997 a complete radial survey of CESR was made. It was determined at that time that there was sufficient radial displacement of the quadrupoles that it warranted moving 35 magnets during the next shutdown. The radial position of the CESR quadrupoles before the magnet move is shown on fig. 13. The dR and YAW rms values in these plots are 30.5 mils and 6.8 mils respectively.

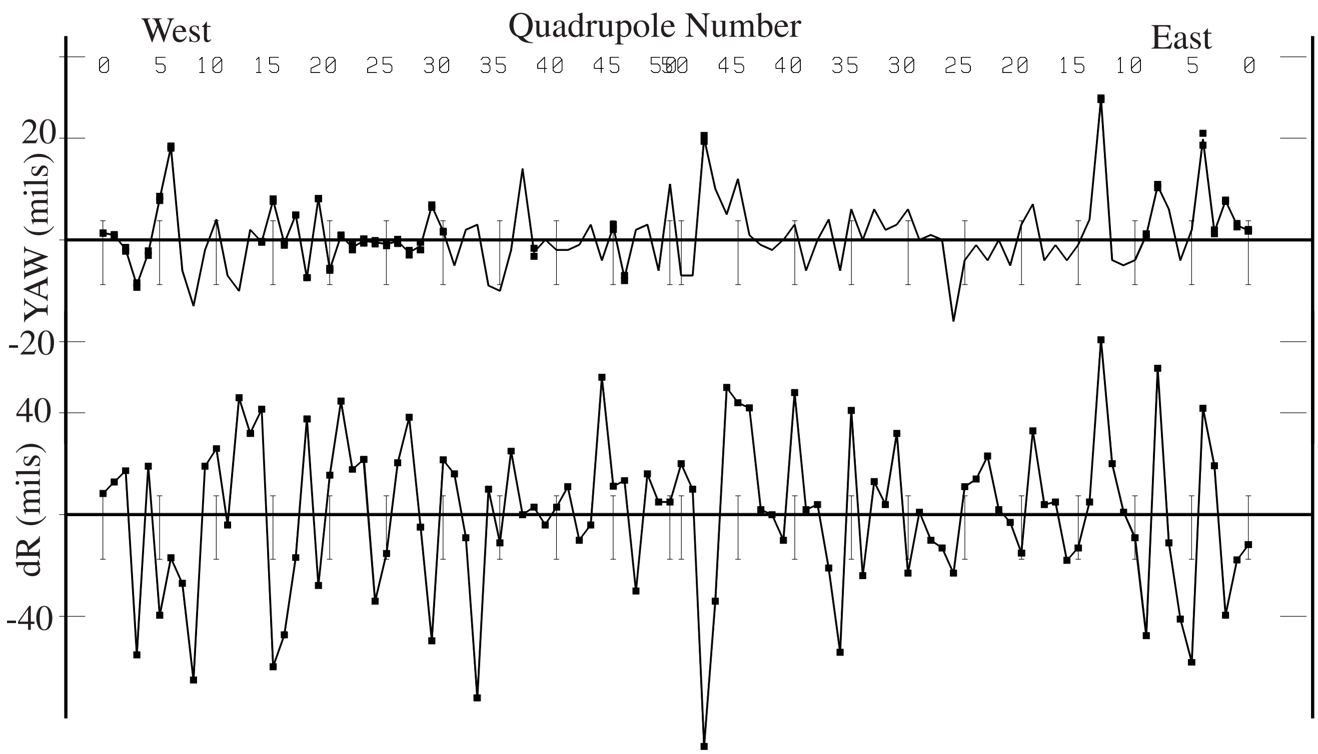

FIG. 13. The measured dR and YAW values for all of the CESR quadrupoles before the radial alignment of the quadrupoles.

After the quadrupoles where moved, another radial survey of CESR was made but this time only the quadrupoles that were moved are measured. It should be noted that the quadruples around 10 East could not be moved during this down-period due to the new superconducting RF station installation and quadrupole magnet 7 West was left with a large YAW due to the vacuum chamber constraint found while moving the magnet. This large YAW should not effect the performance of CESR because quadrupole 7 West does not have a sextupole magnet attached to its base. A picture of the radial position of the CESR quadrupole magnets after the magnets move was made is shown in fig. 14. The dR and YAW rms values in these plots are 18.2 mils and 5.9 mils respectively.

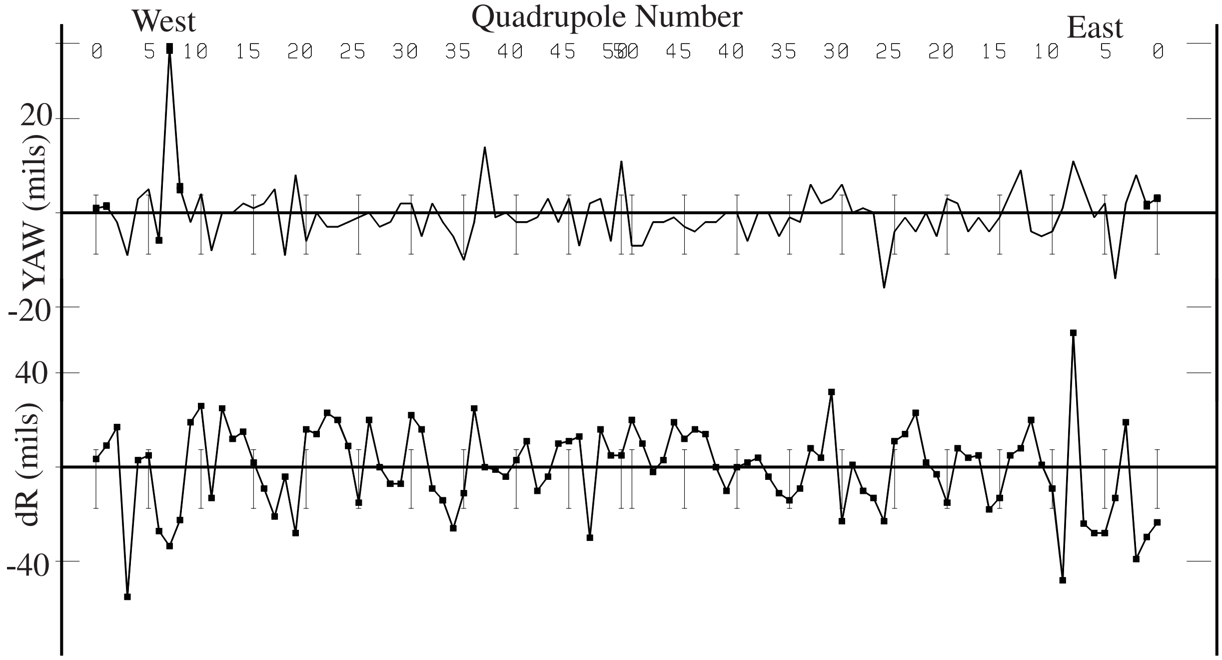

FIG. 13. The measured dR and YAW values for all of the CESR quadrupoles after the radial alignment of the quadrupoles.

4. Correlation between Quadrupole Magnet Radial and Level Data

While analyzing the radial data from March 1997 an interesting observation was made. Correlating the change in the radial location for all the CESR quadrupole magnets with their change in roll gives information into which magnets have moved (fig. 14).

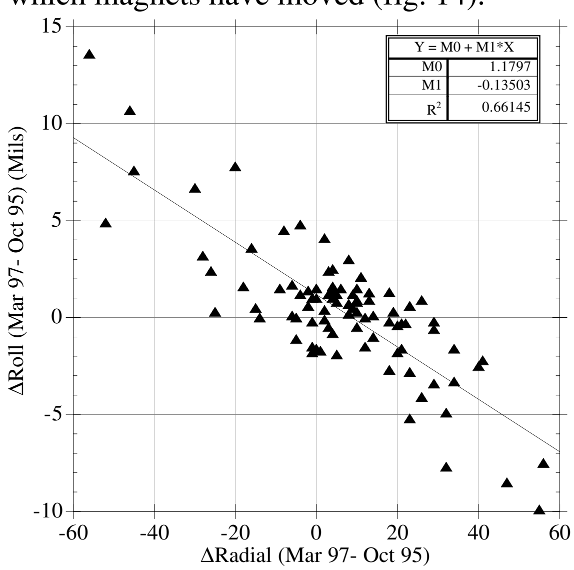

FIG. 14. A correlation plot between the change in roll with the change in radial position for all the CESR quadrupole magnets that where not moved between October 1995 and March 1997. The data is fit to a straight line.

A 10 mil roll produces an angular rotation of

$$\Delta\varphi = \frac{10 \text{ mils}}{10 \text{ in}} = 1 \text{ mrad}$$

and according to the fit to the data a 10 mil roll corresponds to a 65 mil radial offset. According to the dimensions of the quadrupole stand (fig. 15), a change in the radial position due to a 1 mrad roll around the base of the stand is

$$\Delta R = 1 \text{ mrad x } 65.5 \text{ in} = 65.5 \text{ mils}$$

which agrees with the fitted data. This suggests that the radial motion of the quadrupole magnets occur at the base of the stand. The actual motion can be attributed to several phenomena: 1) The vacuum chamber that runs through the center of the quadrupole magnets is attached to the magnet and therefore any forces on the vacuum chamber, due to heating from synchrotron radiation or vacuum chamber misalignment, is a force on the quadrupole magnet. 2) At the base of the quadrupole stand there is a significant amount of rust and decay of the concrete base. 3) Slow ground motion over time can shift the quadrupole magnet locations.

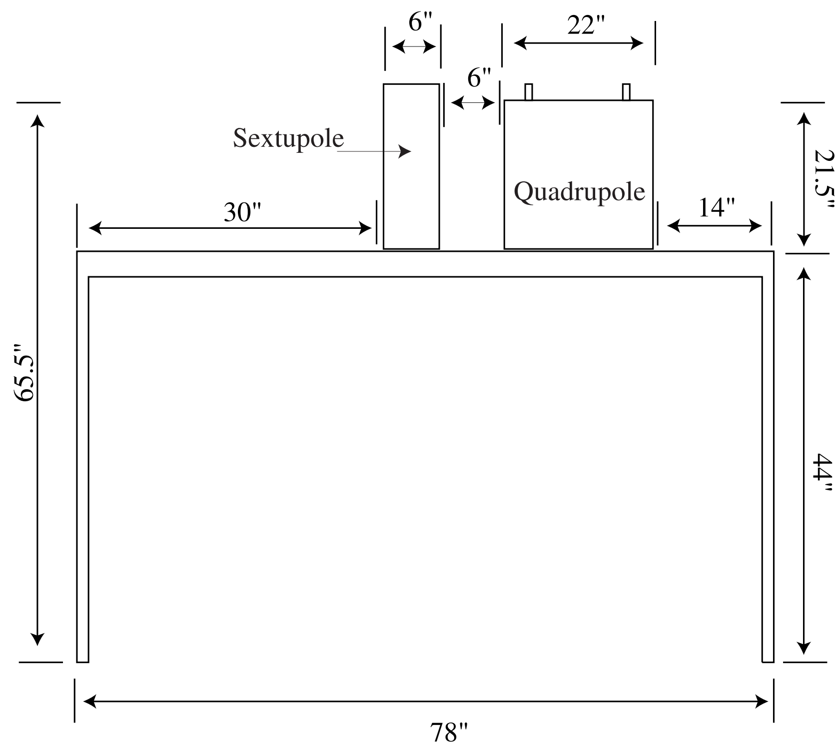

FIG. 15. A typical quadrupole and sextupole magnet stand in CESR. The dimensions are measured with a tape measure and are good to about an inch. The dimensions of the magnets are the iron dimensions not the steel dimensions.

5. Conclusions

The radial alignment of the CESR quadrupole magnets with the method presented in this paper is highly successful in determining the offsets of the magnets. With the present radial analysis program the magnet offsets has the potential to be determined to within 5 mils, which, by the way, is most likely better than the accuracy of moving the magnets to their proper location. Even with the present system there are several areas of improvement and understanding that needs to be explored: 1) Measurement taking is time consuming and laborious. 2) Data entry for the program needs to be automated. 3) The radial analysis program needs to be reorganized/modified so that when CESR upgrades are made the program can be easily modified. 4) The quadrupole magnets that are attached to the CESR vacuum chamber need to be disconnected in order to make moving the magnets easier and provide less stress on the magnets to move. 5) Determining the radial location of the quadrupole magnets with the wire measurement depends on the longitudinal position of the magnets. The program has been modified to correct this error and the relative location of the quadrupoles will correct this uncertainty. These future improvements will make the radial alignment procedure less of a strain on the limited resources at the laboratory.

6. Acknowledgments

The authors would like to thank Gerry Rouse for formulating the geometry for the radial analysis program. Gerry, you are sorely missed!

c) References

[1] The CESR magnet lattice file is provided by Stuart Peck.

[2] Rouse, G.,"Radial Analysis Geometry-RAD4.DOC", unpublished, 1997

[3] Dennis J.E. and Mei, H.H.W.,"An Unconstrained Optimization Algorithm Which Uses Function and Gradient Values", TR 75-246, June 1975.