The Effect of Misalignment in the Tevatron.

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Introduction

This note discusses the measurements of the locations (survey) of the magnets in the Tevatron. In addition it will contain the results of calculations of the corrector currents needed to compensate for the misalignments.

Misalignment of Tevatron magnets can affect the performance of the Tevatron. Rolled[1] quadrupoles produce coupling. Horizontal and vertical displacements in the quadrupoles and rolls in the dipoles will change the closed orbit. The effect of these misalignments is easily discerned in the Tevatron.

We can compensate for the coupling with the skew quadrupole correctors. The closed orbit can be set to the desired position with the horizontal and vertical dipole correctors. The required corrector currents can be quite large if the misalignments are big, and can result in difficulties in Tevatron operation.

This note discusses the measurements of the locations (survey) of the magnets in the Tevatron. In addition it will contain the results of calculations of the corrector currents needed to compensate for the misalignments.

The report will be divided into two parts; first a brief discussion of the situation as it existed in early 2003 and second, a comparison with the recent measurements.

Situation in Early 2003

The performance of the Tevatron during the early part of Run II was less than stellar. There were many difficulties and the solutions for the problems

[1] The roll is a rotation about the beam direction in the magnet

were elusive, despite the many explanations that were advanced.

Among the problems were the large currents in the skew quadrupole circuits. These could have been caused by quadrupole rolls[2].The rolls in the dipoles will cause a change in the closed orbit; primarily in the vertical. In addition the high order multipoles (HOM) in the dipoles could "feed down" and generate coupling [3]. It was therefore decided to measure the rolls of the Tevatron magnets[4]. The results are shown in Figure 1.[5] Two features are clearly obvious:

- There were many sections of the ring where the roll was $> 1.0mr$;
- The magnets rolled mainly towards the inside of the ring.

Effect of Rolled Dipoles on the Closed Orbit

The effect of dipole rolls can be determined with a little algebra.

The magnetic field initially is in the vertical direction;

$$\vec{B} = B_y \hat{\jmath}$$

If the magnet is rolled by an angle θ, the magnetic field seen by the beam is:

$$\vec{B} = B_y \sin(\theta)\hat{\imath} + B_y \cos(\theta)\hat{\jmath}$$

The change in the field is

$$\Delta(\vec{B}) = B_y \sin(\theta)\hat{\imath} + B_y(1 - \cos(\theta))\hat{\jmath}$$

which for small θ is;

$$\Delta(\vec{B}) = B_y\theta\hat{\imath} + B_y(\theta^2/2)\hat{\jmath}$$

In tracking codes such as TEVLAT[6] or MAD, we treat $\Delta\vec{B}$ as producing a kick that modifies the nominal closed orbit produced by the field $\vec{B}$.

[2]We now know that the skew quadrupole currents were due to the movement of the coils within the yoke of the dipole magnets. The movement was caused by the deformation of the G11 in the coil suspension.

[3]The HOM were used in the calculations.

[4]For a discussion of the measurements please see R. Stefanski, "Status Report of the Tevatron Alignment Task Force.",Beams-doc 1003-v3 (Feb18,2004).

[5]The text at the upright of each figure identifies the data and has the average of the x and y variables as well as their standard deviations.

[6]A. Russell. Private communication

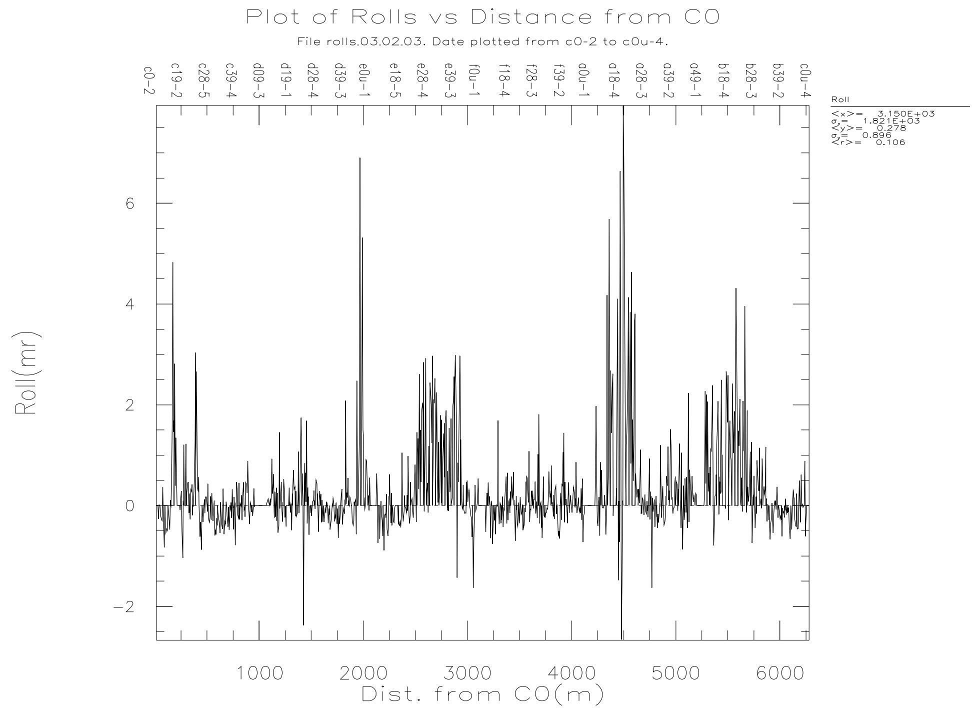

Figure 1: Measured Tevatron Rolls on 3/2/2003.

The kicks corresponding to a change of $\Delta\vec{B}$ is

$$\Delta x' = (-\Delta B_y/B)(B \cdot l)/([B\rho])$$

$$\Delta y' = (+\Delta B_x/B)(B \cdot l)/([B\rho])$$

where $[B\rho]$ is a measure of the momentum of the particle.

$$[B\rho](Tm) = 3.3356 \cdot P(GeV/c)$$

Then $(B \cdot l)/[B\rho]$ is the bend angle in the dipoles which for the Tevatron is $8.12mr$.

Thus

$$\Delta x' \approx -4.06 \cdot 10^{-3} \cdot \theta^2$$

and

$$\Delta y' \approx +8.12 \cdot 10^{-3} \cdot \theta$$

.

Because the roll angle θ is small, $< 10mr$, the value of $\Delta x'$ is small, $< 10^{-6}mr$, and I will not consider it further.

The change in the vertical closed orbit, due to a kick of strength $\Delta y'$ is well known to be[7]:

$$\Delta y(s) = \Delta y' \sqrt{\beta(s)_y \beta_{y0}} \cos(\psi - \pi\nu)/(2\sin(\pi\nu))$$

Where

- $y(s)$ is the closed orbit distortion at a point a distance s from the position point of the kick;
- $\beta(s)_y$ is the value of the β_y function at s;
- β_{y0} is the value of the β_y function at the position of the kick;
- ν is the tune;
- ψ is the phase advance from the point of the kick to the point s.

In the Tevatron lattice the maximum value of β in the arcs is $\approx 100m$ and the current operating tune is $\nu \approx 0.58$. Thus a $1mr$ roll can produce an orbit distortion as large as $\approx 0.3mm$. The effect of the systematic rolls of the dipoles, produces a large distortion in the vertical closed orbit. The measured rolls alone, that is without the HOM, generate a closed orbit distortion with excursions $> 20mm$, and in regions with large β, larger than the physical aperture [8].

The effect of the rolls is corrected with the vertical dipole correctors (VDFG). The currents in the VDFG to correct these rolls were excessively large creating problems in Tevatron operations.

Calculation of the Corrector Strengths Using Tevlat.

The model of the Tevatron used with Tevlat includes the VDFG. In order to calculate the strengths in the correctors I assumed that the desired vertical

[7]This formula appears in many references, for example,"An Introductions to Circular Accelerators", D.A. Edwards, AIP Conference Proceedings No. 127

[8]With the HOM and the measured rolls no closed orbit is possible without using the correctors.

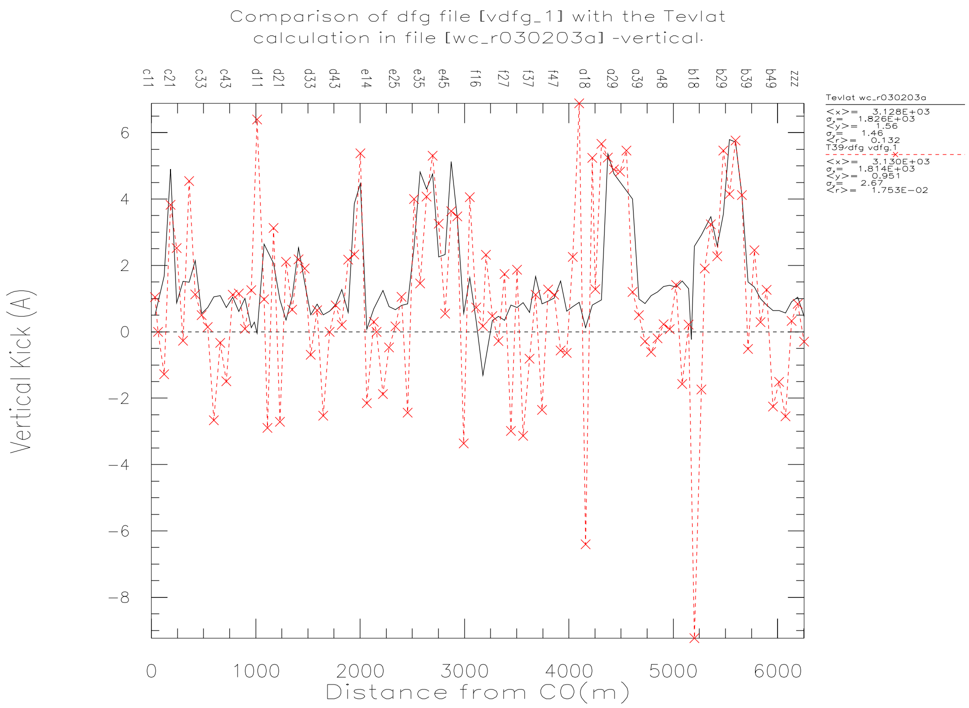

Figure 2: Comparison of Computed Setting of the VDFG with the Console Values. Rolls as of 3/2/03. (The dotted line shows the measured corrector strengths, the solid line shows the results of the calculation.)

closed orbit goes through the centers of the magnets. The corrector values needed to set the closed orbit, including the effect of the rolls, were computed. A comparison with the values set in console program C50 is found in Figure 2. The agreement is good, particularly in the regions of large rolls, even though the calculation does not include vertical misalignments.

Conclusion

The currents in the VDFG were understood, in most cases, in terms of the measured rolls of the dipoles.

Analysis of Recent Alignment Measurements

The AMG has begun the analysis of the survey of the magnets in the Tevatron and released the preliminary results in a series of files available for study only. What follows describes an attempt to use the AMG data to identify misaligned magnets and compute their effect on the corrector settings.

Rolls

The recent roll measurements (Figure 3) show the effect of the movement of the magnets, since 2003, to correct their rolls. The maximum roll is now $< 4mr$ rather than the $> 6mr$ seen earlier. Further the number of magnets with rolls $> 1mr$ has been substantially reduced. I can use these rolls to estimate the corrector currents and compare them to the actual currents used in the Tevatron (Figure 4).[9] Just as the situation in March, 2003 the agreement between the calculated and measured currents is best where the measured rolls are large. I conclude that when the rolls are large they are the dominant effect in the settings of the vertical correctors. When they are small, which Figure 3 suggests is $< 1mr$, then other factors determine the size of the corrector currents.

Vertical Misalignments

An obvious factor in the vertical dipole corrector currents is the vertical misalignments of the lattice quadrupoles. Unlike the rolls, which are determined by local measurements of a magnet, the vertical displacements of the quadrupoles depends on a survey of the entire ring. The measurements were made in the Fall, 2003 using a "Laser Tracker". The data are being reduced by the AMG and early, preliminary, results are available.

To determine the vertical misalignment I assume that the elements in the Tevatron lie in a plane. The misalignment is distance the element is from the plane of the Tevatron.

I can fit the survey data in either the **fscsH** or the **fscsZ** coordinate systems[10] I minimize the sum of deviations of the magnet from a plane,

[9] There are two correctors near D0 and B0 where the actually currents are much larger than the calculated values. They are adjacent to the low$-\beta$ insertions at B0 and D0, and almost certainly reflect the special conditions there.

[10] Descriptions of the coordinate systems can be found in Beams-doc 1148 by Babatunde

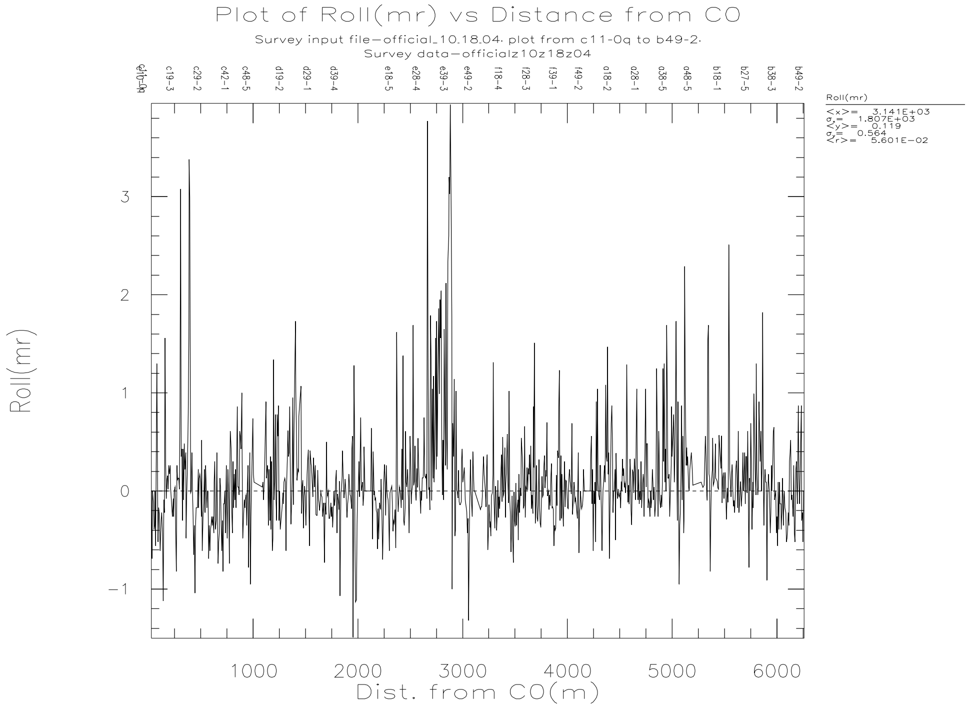

Figure 3: Measured Rolls for Dipoles and Quadrupoles -fscsH

which I define to be the plane of the Tevatron. The deviations are plotted in Figure 5.

The offset of the dipoles, except through the HOM, do not contribute to the currents in the dipole correctors. Figure 6 shows the deviation of the quadrupoles from the plane of the Tevatron. The majority of the quadrupole elements are within $2mm$ of the fitted plane. As shown below these small offsets can easily be corrected with the dipole correctors in the Tevatron.

A digression.

I have calculated the closed orbit distortion for a $1mm$ vertical offset at f15-1 and f16-1. The offset at f15-1 (the quadrupole

"O'Sheg" Oshinowo. Additional information can be obtained at http://ppd.fnal.gov/align/amg_doc.html.
This URL contains a link to the Beams-doc 1148 as well as additional information.

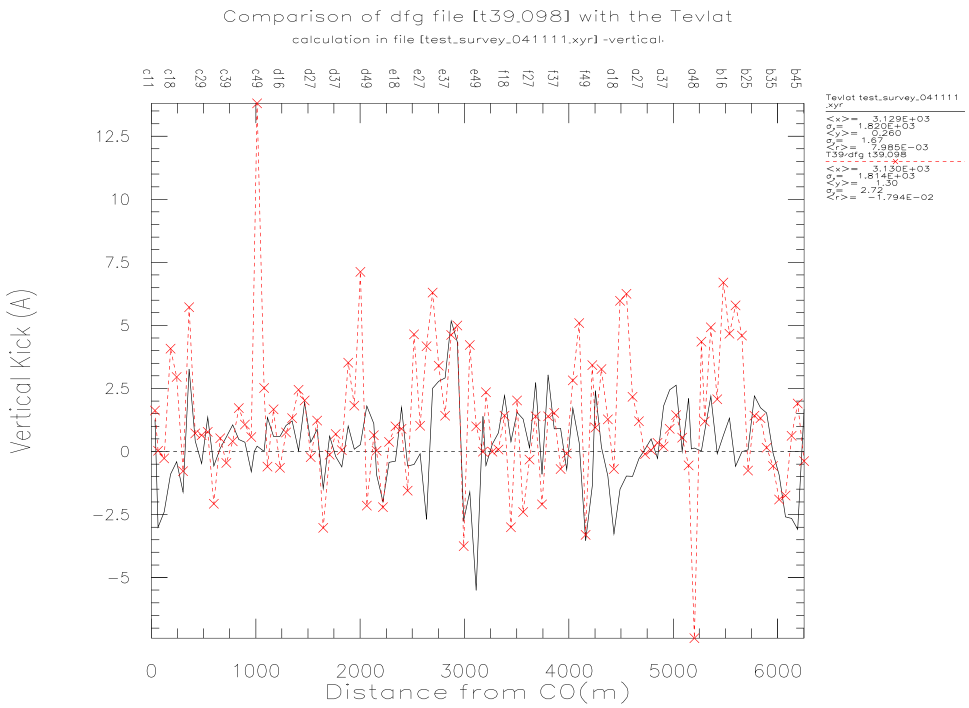

Figure 4: Comparison of Computed Setting of the VDFG with the Currents in the Tevatron Correctors.(Roll Data of 7/20/2004) (The dotted line shows the measured corrector strengths, the solid line shows the results of the calculation.)

here is a QF66) generates a closed orbit with a $\sigma \approx 0.7mm$ shift at the BPM locations. This can be corrected with the vertical dipole correctors at f14 and f16. The required currents in each are $\approx 0.7A$ at E=150GeV.

The offset at f16-1 (the quadrupole here is a QD66) produces a closed orbit with a $\sigma \approx 1.9mm$ shift at the BPM locations. A current of $\approx -2.3A$ at 150GeV will correct the closed orbit.

Figure 7 shows the vertical offset of the quadrupoles plotted with the measured and computed corrector currents. There does not seem to be a strong correlation between the vertical offsets and the observed corrector

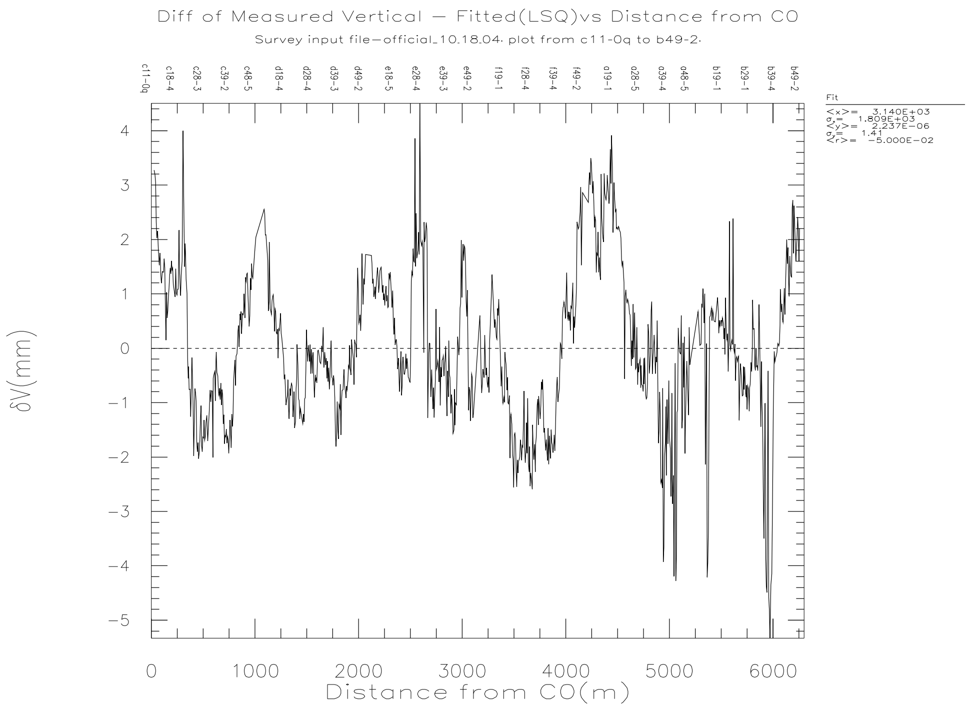

Figure 5: Vertical Deviation From the Plane of the Tevatron -fscsH

currents. The currents in the VDFG calculted from the offsets also does not agree with the observed currents.

Horizontal Misalignments

The Tevatron is not a circle and to determine the horizontal misalignment of the Tevatron I need to know where in the plane of the Tevatron I expect to find the magnets. This requires that we have a model, that is a computer description of the actual lattice. After more than twenty years, thanks to the efforts of many people[11], we are now approaching, what I believe to be is, an accurate model for the Tevatron. The model has the correct length for the Tevatron, $2\pi\ km$, the correct total bend, $2\pi\ rad$, and the lattice

[11] I mention only those who efforts I am personally aware: Glen Goodere, Peter Bagley, Mike Martens and Leo Michelotti

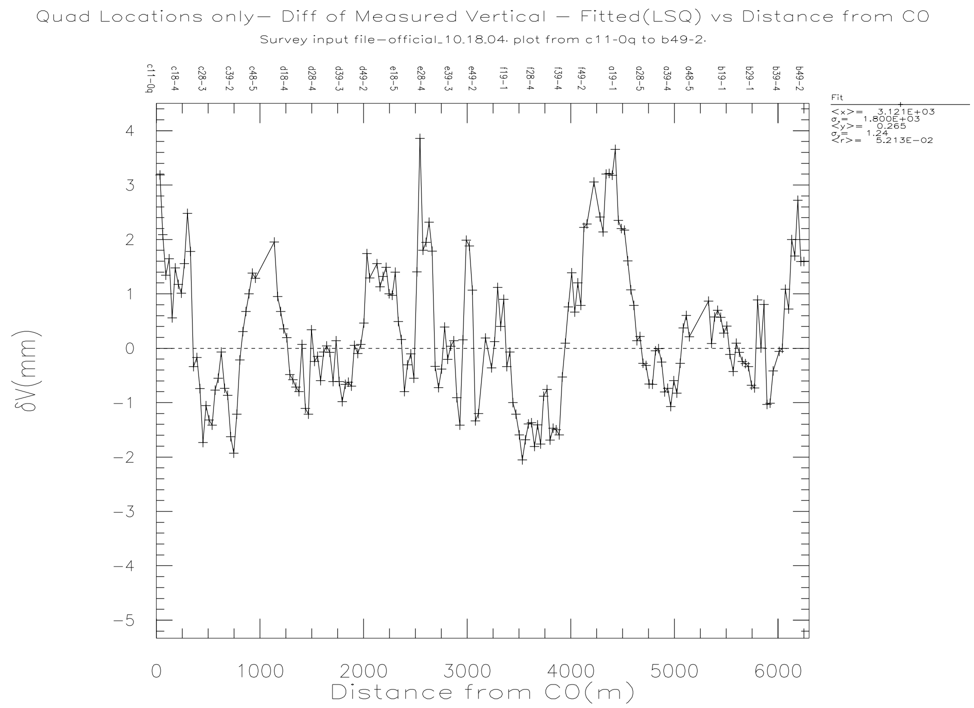

Figure 6: Vertical Deviation of Quadrupoles From the Plane of the Tevatron -fscsH. Data of 7/20/04.

is closed. Though these are obvious requirements for the model, it is a significant advance to have constructed the model.

I have compared my calculations for the locations of the magnets with those of Leo Michelotti and found no significant differences. In the discussion below I have compared my calculation with the measured survey data to look for misalignments.

The calculated values for the coordinates of the magnets and the measured values are not in the same coordinate systems. The coordinate systems were aligned by translating and rotating the coordinates of the magnets in the model, the calculated coordinates, so as to minimize the difference from the measured, to the survey coordinates. Having aligned the coordinate systems I can compute the distance the survey position of the magnet differs from the desired positions of the magnet as given by the model.

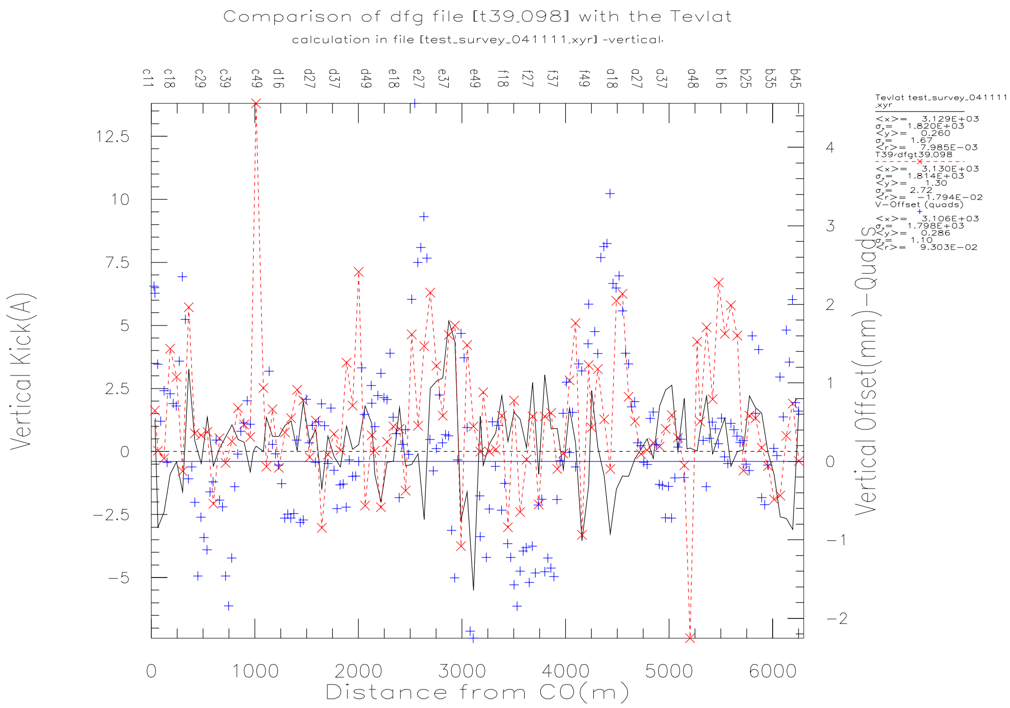

Figure 7: Comparison of the Vertical Offset of the Quadrupoles (fscsH) with the Currents in the VDFG. (The dotted line with "X" are the measured corrector strengths, the solid line are the results of the Tevlat calculation. The + are the vertical offsets calculated from the survey data.)

I have calculated the radial distance from center of the coordinate system for each of the magnets using both the survey coordinates and the model coordinates. The difference is displayed in Figure 8 for the quadrupoles. [12]

The survey data and the model agree fairly well; the σ of the difference is $\approx 4mm$. There are regions where there are large ($> 7mm$ differences between the survey data and the model calculations. It is therefore useful to compute the currents in the horizontal correctors from these horizontal offsets and compare the results with the measured corrector currents. (Figure 9)

Once again we can see that there are regions in the lattice where the

[12] Points where the difference is more than $50mm$ are not plotted. They are clearly poorly measured points.

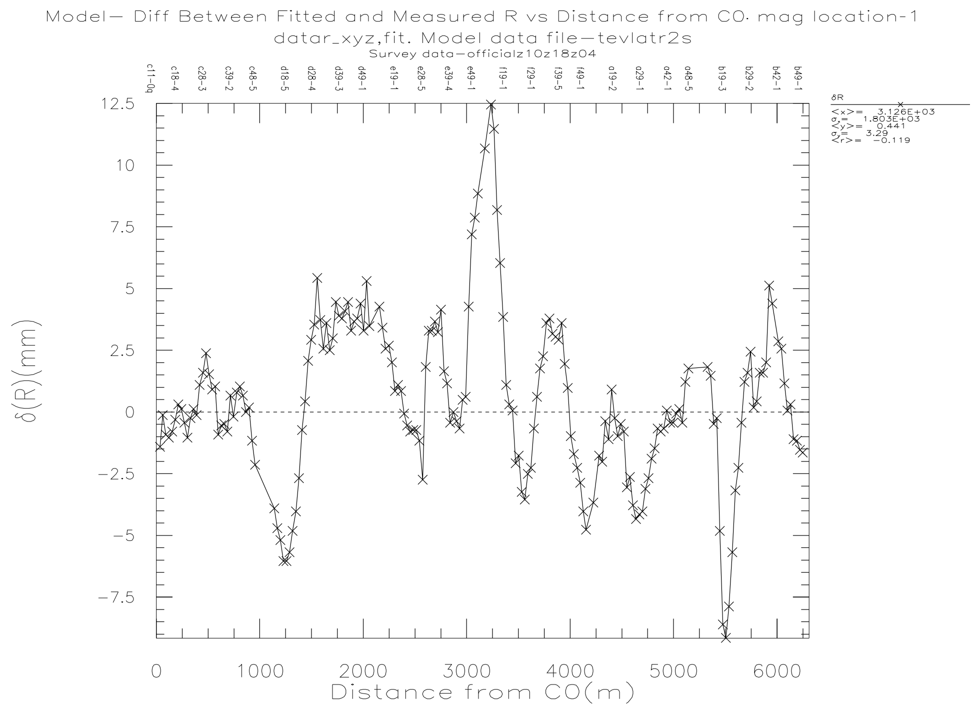

Figure 8: δR Deviation of Quadrupoles -fscsH. δR of 7/20/04.Rol

values of the horizontal corrector currents calculated from the horizontal offsets derived from the survey data agree with the current collected in the console program T39 currents. On the other hand there are obviously parts of the lattice where the T39 data are in disagreements with the calculations. The regions of agreement suggests that the basic model is correct. The regions where there is not agreement indicates, to me, that in those regions we are missing essential information. It could be that the survey data are in error, or that incorrect transfer constants are used for the DFG, or that the algorithms used to set the DFG recorded in T39 were different from those used in the Tevlat calculations. This is most likely true at the "0" locations where bumps are introduced into the closed orbit. More data and future analysis may be able to explain the discrepancies.

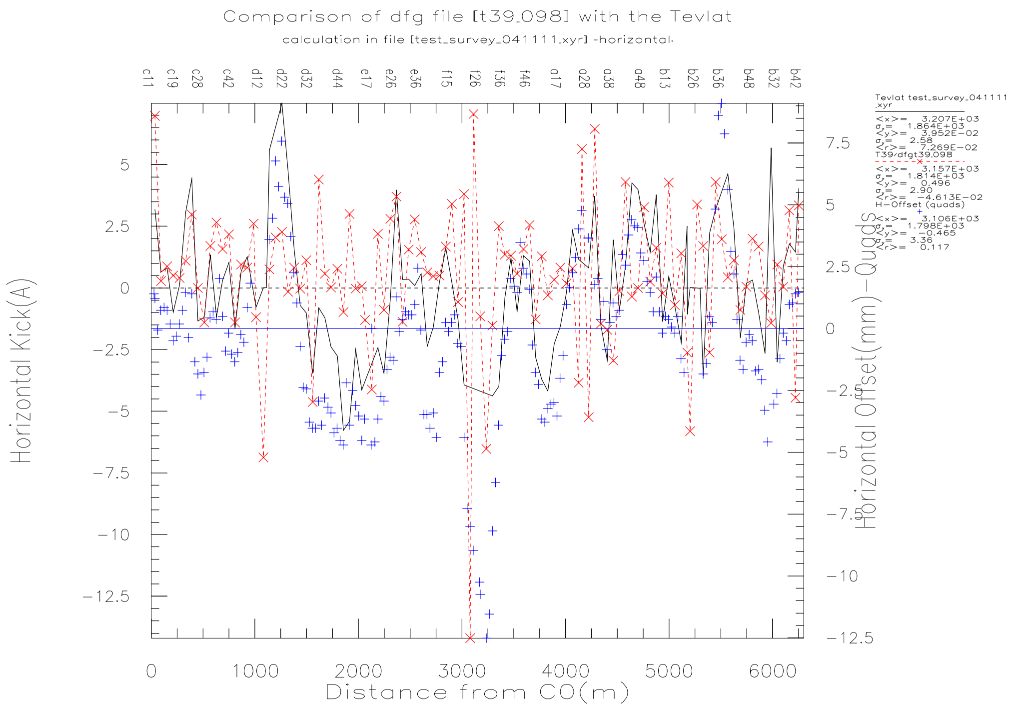

Figure 9: Comparison of Computed Setting of the HDFG with the Console Values. δR of 7/20/2004.(The dotted line with "X" are the measured corrector strengths, the solid line are the results of the calculation. The "+" are the horizontal offsets calculated from the survey data.)

Conclusions.

The introduction of the rolls of the dipole magnets into the lattice models enabled us to better understand the currents in the VDFG. The ability to see good correlation between the currents calculated for the VDFG when the rolls are included in the model and the actual currents used for operating the Tevatron meant that we knew how to reduce the currents. When the rolls of the dipoles were reduced in certain sections of the ring there was a calculable reduction in the VDFG currents. This can result in greater flexibility in operations.

A model of the Tevatron has been constructed which is in good agreement with the survey data, both horizontally and vertically. It is not possible at this time to say that we can predict the currents in the DFG from the survey data. I suspect that this is partially due to the preliminary nature of the results from the alignment group as well as a lack of experience working with the data. In the near future I look forward to being able to use the survey data together with the corrector currents, to identify misaligned magnets. When the misalignments are corrected I suspect that operating the Tevatron will be simpler.

Acknowledgements

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