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THE TEVATRON ORBIT PROGRAM*

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THE TEVATRON ORBIT PROGRAM

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Abstract: We describe the structure and algorithms of the program system used to control the beam position in the Fermilab superconducting accelerator, the Tevatron. The program is capable of establishing a first turn in the machine by iteratively adjusting correction element dipoles , closing the first turn using a least squares algorithm, and establishing the desired closed orbits during the acceleration cycle, as well as finding the full tune of the machine at any energy.

1. Introduction

Beam position control in the Tevatron is especially important since beam loss during any part of the accelerator cycle can cause one or more superconducting magnets to quench, resulting in downtimes of an hour or so. During the early days of commissioning , when a closed orbit is not yet established in the machine and one is still trying to steer the beam through the first turn, delays of an hour or so at each stage of the tuning process can present a serious obstacle to progress. Considerations of this type pointed to the necessity to

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automate the process of beam manipulation, and the Tevatron Orbit Program (henceforth referred to as ORBIT) was the result. In what follows, we will describe the algorithms used in the program, the structure of the program and the results obtained.

ORBIT is capable of the following functions.

1. Given reasonable injection parameters, it can establish a first turn in the machine by iteratively changing the current in the trim dipole elements. The beam position information is provided to it by the beam position monitors (BPM) [1] which are installed in close proximity to the trim dipoles. There is a one to one correspondence between the BPMs and the trim dipoles. Considerable effort went into the BPM's to provide high sensitivity and multiple data collection modes and into the accelerators to enable them to accelerate short batches of low intensity (~40 bunches x10 ^{9}protons/bunch.) The position of the orbit can be varied at will at any location to a desired value.

2. By iteratively adjusting the injection kicker at location E17 (known hence forth as the E17 kicker) , and the E17 trim dipole and a number of trim dipoles upstream of the injection point, ORBIT can match the second turn to the first turn and thereby establish a closed orbit. See Figure 1 for a schematic of the accelerator stations.

3. During acceleration, the current in the trim dipoles scales with the current in the main dipoles. However, there are energy dependences in the harmonic content of the machine and what is a good closed orbit at injection will deteriorate during acceleration. ORBIT is capable of

correcting the orbit at discrete energies. (The correction energies are known locally as slots and we will refer to them in what follows as such.). The microprocessor based trim dipole function generators (DFGs) [2] then linearly interpolate between the slots and output current settings accordingly.

4. By changing a single trim dipole at a slot, it is possible to induce a distortion in the closed orbit. ORBIT is capable of determining the full tune of the machine (as opposed to the fractional tune) by fitting the difference between the two closed orbits to a theoretical curve. The tune can be extracted as a function of energy. This points out wrong detector polarities in the process, a crucial capability in the initial stages of the commissioning.

5. A Tevatron simulator program (TEVLAT) [3] that contains the measured multipoles of the Energy Saver magnets can be invoked from ORBIT. It is possible to debug any new algorithms using the simulator while the machine is being used for high energy physics.

2. Algorithms

The basic problem in beam tuning can be cast into a least squares algorithm, namely: given n positions to be altered and m currents that can be changed (with m less than or equal to n), find the m currents that minimize the sum of the squares of the deviations from the desired values of the n positions.

We will describe the algorithm for the horizontal co-ordinate. The vertical co-ordinates are handled separately and similarly. We neglect any effects due to coupling.

Let X^d_j be the desired position at BPM j and
X^m_j be the measured position at BPM j.
and $X_j = X^d_j - X^m_j$
X_j (j=1,n) constitutes a vector of position changes one would like to accomplish. One now assumes an ideal accelerator with no non-linearities. Then if you make a set of current changes at trim dipoles given by C_k (k=1,m), then the theoretical position changes will be given by

$$X^T_j = \sum_k (\delta X^T_j/\delta C_k) C_k = \sum_k F_{jk} C_k$$

Then the problem is to minimize

$$S^2 = \sum_j (X_j - X^T_j)^2$$

$$(\delta S^2/\delta C_k) = \sum_j 2(X_j - X^T_j)(\delta X^T_j/\delta C_k) = 0$$

at minimum

$$\sum_j (\delta X^T_j/\delta C_k) X^T_j = \sum_j (\delta X^T_j/\delta C_k) X_j$$

substituting for $X^T{}_j$

$$\sum_{jm} F_{jk} F_{jm} C_m = \sum_{j} F_{jk} X_j$$

or $F^T FC = F^T X$ in matrix notation (F^T implies F transposed)

$F^T F$ is a square matrix of dimensions mxm. Solving for C,

$$C = (F^T F)^{-1} FX$$

The matrix F is given by

$$F_{jk} = \lambda\sqrt{(\beta_j \beta_k)} \quad \sin(\phi_{jk}) \text{ for an ideal accelerator.}$$

if the position j is downstream of the current k. F_{jk} is zero otherwise. β_j, β_k are the beta functions at j and k. ϕ_{jk} is the phase advance from j to k. λ is a proportionality constant.

In the special case when m=n, the number of currents to change = number of positions. Then the equation $F^T FC = FX$ simplifies to $FC = X$ since F^T is square and can be inverted. i.e.

$$C = F^{-1}\,X$$

F is now a triangular matrix since F_{jk} is zero if j is not downstream of k. Triangular matrices are inverted trivially.

3. Three Bumps

One can also think of the problem of adjusting n positions using trim dipoles placed in a one to one correspondence with the position detectors in terms of familiar "Three Bumps". This is the special case where m=n in the least squares algorithm. Consider a position detector at position j, where you want to alter the position by X_j (see Figure 2)

This is done by changing the current at j-1. But after the position change is made at j, one wants to insure that the orbit remains unchanged at and after position j+1. This is done by adjusting the currents at j and j+1 so that the position and angle at j+1 remain the same. The solution is

$$C_{j-1} = X_j/(\lambda\sqrt{}(\beta_j\beta_{j-1})\sin\phi_{j-1,j})$$

$$C_j \;= -C_{j-1}\sqrt{}(\beta_{j-1}/\beta_j)(\sin\phi_{j-1,j+1}/\sin\phi_{j,j+1})$$

$$C_{j+1} = C_{j-1}\sqrt{(\beta_{j-1}/\beta_{j+1})}(\sin\phi_{j-1,j}/\sin\phi_{j,j+1})$$

This set of three currents that alter the position at BPM j by X_j and ensure that the orbit at and after BPM j+1 remains unaltered is known as a three-bump. One can now show that the least squares special case solution where m=n and $C=F^{-1}X$ is expressible in terms of a series of three bumps. This can be shown by direct substitution. There is one important proviso, however. In the three bump algorithm, in order to change n positions, one needs to alter n+2 currents. The last two currents ensure that the orbit remains undisturbed after the nth position. In the least squares case, the number of currents to change is exactly n. When establishing the first turn in the machine, the beam exits the machine after ,say, n positions. To correct the n positions to nominal orbit, only the first n currents should be changed. i.e. the least squares solution should be applied as is and the last two current changes in the three bump chain should not be made. This is so since making the last two current changes would cause the beam position and angle at the n+1 position to remain unchanged. i.e the beam would still exit the machine! When a closed orbit is established and one wants to change n positions, then the full n+2 changes have to be applied to ensure that the closed orbit remains unaltered after the nth position.

To summarize, the Tevatron is designed so that there exists a one-to-one correspondence between the BPMs and trim dipoles. To change n positions, the least squares algorithm becomes equivalent to a sum of n three bumps but with an important difference. The number of currents to change with the least squares algorithm is exactly n. This should be used when establishing the first turn. After the closed orbit is established, the full three bump chain with n+2 current changes should be used.

In practice, very often a set of BPMs or trim dipoles will be inoperable at any given time. If a BPM is not working, the three bump associated with it is not performed. If a trim dipole is not working, it and its associated BPM is removed from the chain of three bumps.

Also a wrong polarity in a dipole or detector can be taken into account in software by setting an appropriate status bit.

4. The Closure Algorithm

After the first turn is established, it is necessary to ensure that the second turn closes on to the first turn. This has to be done without disturbing the first turn. The E17 kicker (see Figure 3) fires at injection. Its effect is felt by the first turn, but not by the second. A string of BPMs downstream of the E17 kicker are instrumented so that they can report data on the first and the second turn. Figure 3 shows the 1st and the 2nd turns in the horizontal view. The closure algorithm is as follows. A string of trim dipoles starting at D49, D48 etc can be adjusted along with the E17 dipole to minimize the difference between the 1st and the 2nd turns downstream of E17. The algorithm to do this is just the least squares algorithm described above, since the number of currents to change is strictly less than the number of positions over which minimization is to have effect. The kicker voltage is then adjusted to keep the net E17 strength the same during the 1st turn.

The algorithm is iterative and changes are made from pulse to pulse until closure within desired limits is obtained. In the vertical view, a similar algorithm is used. Magnets in sector D are adjusted to minimize the differences between the first and the second turns vertically.

The philosophy of closure adopted here obviates the necessity of retuning the injection line after the first turn is established. This results in a rapid establishment of a closed orbit. During the course of operation, it was found that the strength of the E17 kicker was not adequate to establish closure for some orbits which were required to be off center horizontally at D49 and E11. It was then found that closure could be still established by removing the E17 dipole from the closure algorithm completely and keeping the kicker voltage constant at a value well below the allowed maximum. ORBIT now contains an option either to adjust or hold constant the E17 kicker voltage while establishing closure.

All the beam tuning algorithms are applied iteratively until the orbit obtained at the BPMs is satisfactory. At each step of the iteration, the user has the ability to apply only a fraction of the calculated corrections if he feels that the full correction will lead to divergences. In practice, this step cut factor was left at a value close to unity without ill effects.

The closure algorithm was instrumental in reducing losses at injection and allowing intensities of ~10^{13} protons to be accelerated in the Tevatron without magnet quenches at injection.

5. SLOTS

As the acceleration proceeds, the currents determined at injection are automatically scaled according to momentum by the DFGs. However, due to the current dependence of some of the multipole moments, the closed orbit needs further correction as a function of momentum. This is done at discrete values of momenta which are settable from a master program. The selected values of momenta are known as Energy Slots. They are usually spaced apart in energy by 100GEV. ORBIT can select the working energy slot and correct the orbit for that slot to a series of desired positions.

The DFGs have a table of these slot bend angles and interpolate between the appropriate slots as the acceleration proceeds.

In addition, there are time slots which are correction points defined by their time of occurrence in the acceleration cycle. For instance, immediately after injection, the closed orbit has an intentional distortion at E11 , E13 and E15. This distortion is necessary during injection and is formed by currents in the injection time slots which decay to zero roughly 3 seconds after injection, removing the distortion.
Similarly during extraction, the beam has to be made to approach the extraction septa. These corrections are also done using time slots at extraction.

This division of the corrections into energy slots and time slots provides the user with rough ramp independence. For instance, the ramp shape as well as the extraction times can be varied, without having to retune the orbits. The momentum dependent corrections will remain as they are. The redefinition of the extraction timings is communicated to the DFGs by ORBIT.

The slot settings can be backed up on to a VAX keyed access file from which the settings from a previously saved file can be restored. This is very useful during corrections when the user has made some error and wants to return quickly to settings he knows will work.

6. Desired positions and momentum offsets

ORBIT enables the user to specify the desired position at each BPM. At present there are four sets of desired positions used; one for the injection slot, the second for all the acceleration slots and the third and fourth for the beginning and ending extraction slots. Thus the beam can be set to different positions at the extraction septa at the beginning and end of extraction if need be. It was not found necessary to alter the desired positions during acceleration. When slot currents are saved and restored, the desired positions accompany the appropriate slots.

ORBIT also enables the user to alter the desired horizontal positions, so that all the desired positions are offset according to a specified momentum offset $\Delta p/p$.

$$X'^{D}_{j} = X^{D}_{j} + (\Delta p/p)\eta_j$$

where ($\eta_j = \delta X_j / \delta \log_e p$) is computed by TEVLAT.

It also enables the user to selectively apply this change so that some desired positions are absolute no matter what the specified momentum offset.

During acceleration, there can be slight mismatches between the momentum of a slot as established by the guide fields and the desired positions and that given by the radio frequency cavities. If one tries to correct the orbit to the desired absolute positions, it is possible to enter into a conflict with the r.f cavities. At each iteration, the trim dipoles will try to correct the orbit to the desired absolute positions and the r.f feedback loop will try to put it at a slightly displaced orbit with the net result that the trim dipoles may be driven out of range of their operating limits. To avoid this, the following prescription is used to change the desired positions slightly in order to accomodate the r.f.

Firstly the $(\Delta p/p)_{rf}$ is estimated as follows

$$(\Delta p/p)_{rf} = \sum_{j}(X^{j} - X^{j}_{N})/(\Sigma\eta_{j})$$

where X^{j}_{N} is the nominal horizontal position at j, and X^{j} is the observed position.

This estimated $\Delta p/p$ is used to correct the desired position for the next iteration.

$$X^{j}_{D} = X^{j}_{N} + \eta_{j}\,(\Delta p/p)_{rf}$$

After convergence, the r.f can be adjusted to remove the observed $\Delta p/p$.

7. Finding the Tune

When a single trim dipole is changed, the closed orbit in the machine gets distorted. The difference between the distorted and undistorted closed orbit can be fitted to the functional form

$$X(s) = a\sqrt{\beta(s)}\,\cos(\nu\phi(s)+\varepsilon)$$

where x is the displacement at azimuth s
a is the amplitude of the oscillation
β is the beta function
ν is the full tune
ϕ is the normalized phase advance at azimuth s. i.e it increases by 2π around the circumference.

ε is the phase offset.

The tune finding algorithm consists of the following. During a pulse the closed orbit positions at the momentum of interest are read and stored away.

During the next cycle, a trim dipole is ramped above its normal settings. The excitation in the trim dipole as well as its position can be chosen at will before the tune finding algorithm is put into effect. The difference in the two closed orbits is fitted to the above formula. The beta functions and normalized phase advances are available for an ideal machine. It is assumed that for small changes in tune, these do not depart drastically from ideal values. The orbit distortion formula is then fitted to the data with a,ν, and ε as free parameters using the program MINUIT. [4] This yields the full tune to a precision of 0.005 units when the fit is performed over the full ring.

During the establishment of the first turn, a similar procedure can be followed and a fit performed. The fit is only performed to positions downstream of the excited dipole since a closed orbit does not as yet exist. The functional form of the fit is nevertheless the same. This fit, while verifying the tune, can be used for an even more crucial function, namely verifying that the BPMs are all connected with the correct polarity. Any wrong polarity BPM will stand out in the residuals to the fit provided it is not located near a zero of the oscillation. By choosing various trim dipoles to excite, all the BPM polarities can be verified. Wrong polarities can be taken into account by the software, allowing the algorithms to converge gracefully. This feature of ORBIT was crucial during the initial stages of the Tevatron in detecting a handful of wrong BPM polarities.

8. Structure of ORBIT

The Tevatron is controlled by several Operator consoles working in parallel. Each Operator console is driven by a PDP-11/34. Each is equipped with a color television terminal with keyboard, a movable cursor and interrupt, a touch panel, a Lexidata color display and a Tektronix display scope with hard copy. The PDP-11/34s are networked to the Tevatron controls. The networking is controlled by programs that reside on each of the PDP-11/34s as well as on a central VAX 11/780 which acts as the network supervisor. Normally all application programs reside on the PDP-11/34. For large programs such as ORBIT, this results in the need to overlay extensively due to memory limitations on the PDP-11/34. It was therefore decided to split ORBIT into two sections. The major section containing the algorithms as well as data acquisition and DFG control would reside on the VAX. The operator interface and control as well as Graphics would reside on the PDP-11/34. This reduced the size of the PDP-11/34 program to managable proportions, though still with numerous overlays. The VAX also would be the home for MINUIT and TEVLAT as well as for ORBHLP, a task which uses the VAX help facility to display menu oriented help statements on the PDP-11/34. (see Figure 4). TEVLAT is used for debugging purposes to test algorithms while the machine is being used for other purposes.

All communication to the Tevatron is done from the VAX program. The PDP-11/34 program merely displays the data acquired by the VAX as well as the latest current settings computed by it.

Program control on the PDP-11/34 is achieved as follows. Statements indicating program options are displayed on the Color TV terminal. Such a display constitutes a page. Interrupting under one of the options can cause other pages to be displayed giving the operator further options in a tree structure of commands. The appropriate interrupt causes the PDP-11/34 program to send a message to the VAX which causes it to take the desired action. Any time the operator is in doubt, he interrupts for help which causes the task ORBHLP to be invoked. ORBHLP has at its command a menu-oriented VAX help file much in the same style as the conventional VAX help feature. This enables the operator to reach the help topic of interest very quickly without having to read through the full help manual.

Further control is available through the touch panel switches, which can be used as additional menu-oriented input.

9. Results

Figure 5(a) shows the first attempt at steering beam through the Tevatron. The E and F sector trim dipole currents were set to the values determined by the program during the E and F sector tests of April 1983. The beam exited the machine after traversing ~2/3 of the circumference. Figure 5(b) shows the result after one correction by ORBIT. The beam traversed the whole ring. The oscillations were significantly reduced for the first half of the ring, enabling the beam to complete the full turn. The tune finding part of the program was then used to determine bad BPM polarities. After these were found and entered into ORBIT, it was possible rapidly to smooth the orbit to nominal values and to proceed towards attempting closure. During April of 1983, it was possible to obtain the E and F sector currents in two iterations. Thus in effect, three iterations were necessary for the program to circulate beam around the ring. During simulation using TEVLAT, it is possible for the program to go from zero current settings to converged smooth orbit in 4 to 5 iterations. There has been no occasion to try this in practice.

Figure 6(a) shows a smoothed first turn orbit with the injection bump and the second turn. After 4 iterations of the closure algorithm, the second turn closes on to the first turn and the positions are matched downstream of the E17 kicker as shown in Figure 6(b). During these iterations, the E17 kicker was floated and two magnets in sector D in each view as well as the E17 dipole were changed by the closure algorithm.

Figure 7 shows a typical closed orbit at 300 GEV. The upper curve displays the trim dipole currents. The lower curve is the closed orbit in the vertical plane. The 1.5mm bump at B49 and C11 stations is deliberate.

In Figure 8(a), the bottom curve is an orbit distortion induced by changing the dipole at E15 and the top curve is the MINUIT fit to the oscillation. Figure 8(b) is the superimposition of the two. It can be seen that the ideal accelerator parameters give an excellent description of the Tevatron in practice. The tune was determined to be 19.483 ± 0.005, for this data set.

Figure 9 shows a typical display of closed orbits at various slots. The program can be left in this mode and will refresh this display on a pulse by pulse basis. If there is a sudden loss of beam during acceleration, it becomes immediately obvious from this display where and when it occurred.

To summarize, the Tevatron Orbit Program enables the orbit to be established and manipulated with ease and a minimum of user intervention. As such it has been an invaluable tool in commissioning and operating the world's first superconducting accelerator.

The authors wish to thank Kevin Cahill, Rod Gerig and Therese Watts for writing code for communicating between the VAX and PDP-11/34, the BPM system and the DFGs respectively. We wish to thank Dixon Bogert and Dave Beechy for support, the accelerator Operators for their enthusiasm and are indebted to Don and Helen Edwards for numerous illuminating discussions.

10. Figure Captions

Figure 1.

Schematic of accelerator stations.

Figure 2.

Three bump at position j

Figure 3.

The first and second turn near the point of injection Horizontal view.

Figure 4.

The structure of the program

Figure 5.

(a) The first attempt at injecting the beam into the Tevatron.Horizontal radial position vs. azimuth.

(b) After the first correction, the beam traverses the whole ring.

Figure 6.

(a) Smoothed first turn and the second turn with oscillations. Horizontal view.

(b) after application of the closure algorithm. Horizontal position after 4 iterations.

Figure 7.

Smoothed closed orbit at 300 GeV in the vertical plane. The Bump at B49/C11 is deliberate. The trim dipole currents to produce this orbit are plotted in the upper curve.

Figure 8.

(a) Bottom curve shows orbit distortion induced by changing dipole at E15. Top curve is the MINUIT fit to the oscillation.

(b) The fit superimposed on the data.

Figure 9.

A typical display of closed orbits at various slots from injection to extraction.

References

[1] R.E.Shafer, R.E.Gerig, A.E.Baumbaugh, C.R.Wegner, Proc. 12th Int. Conf. On high Energy Accelerators, Batavia Ill. 1983, p609-615.

[2] D.Beechy, D.Bogert, S.Segler, T.Watts, IEEE Trans. Nucl. Sci. NS-28(3) 2311-2313 (1981)

[3] TEVLAT is a program written by A.D. Russell.

[4] MINUIT is a CERN general purpose fitting program written by F.James.

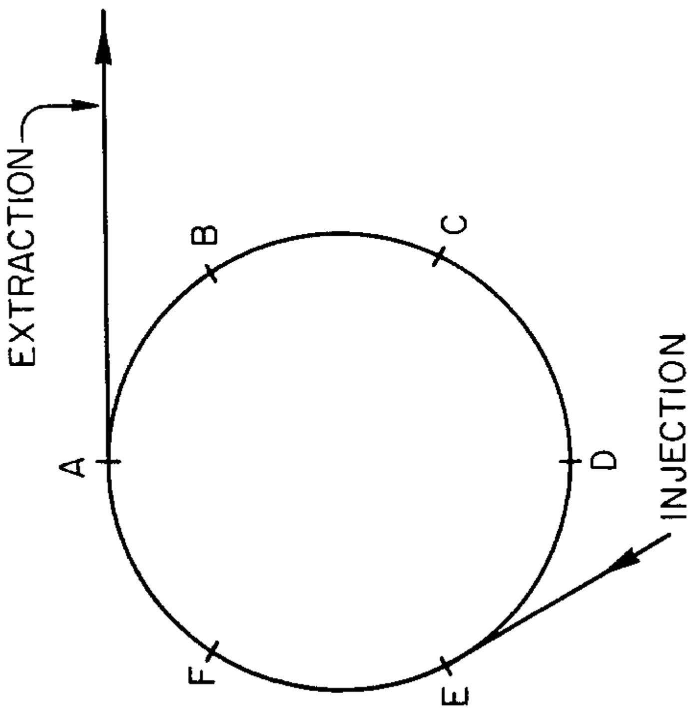
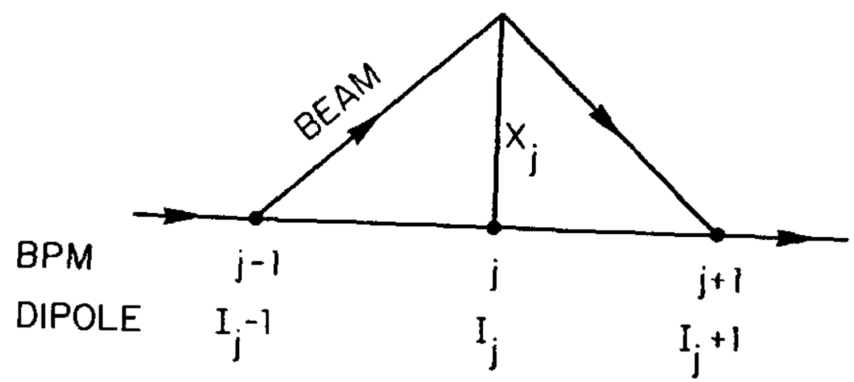


Figure 1



THREE BUMP

Figure 2

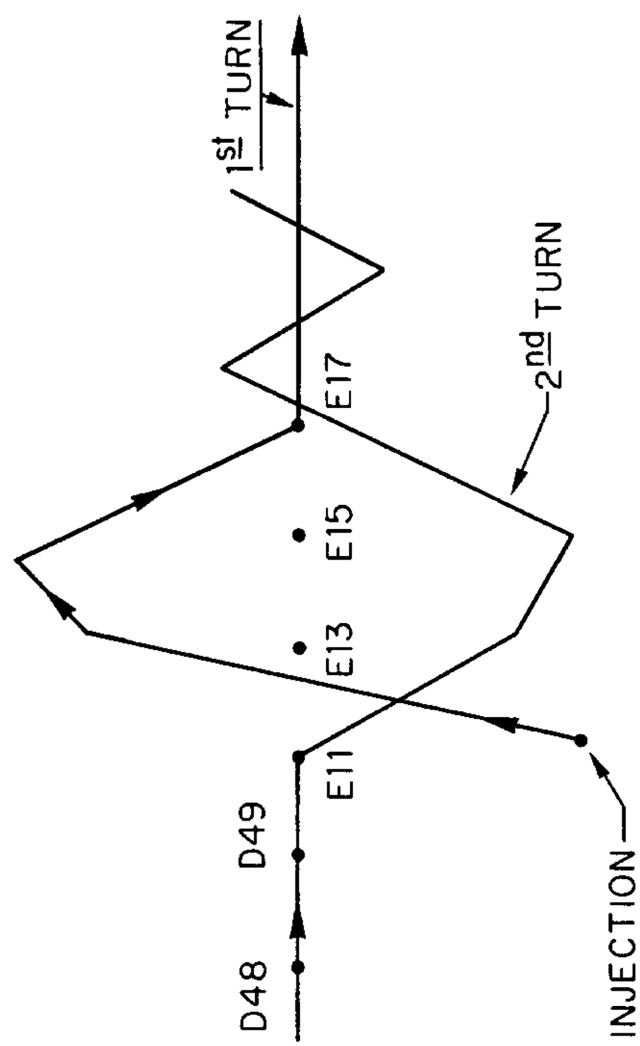


Figure 3

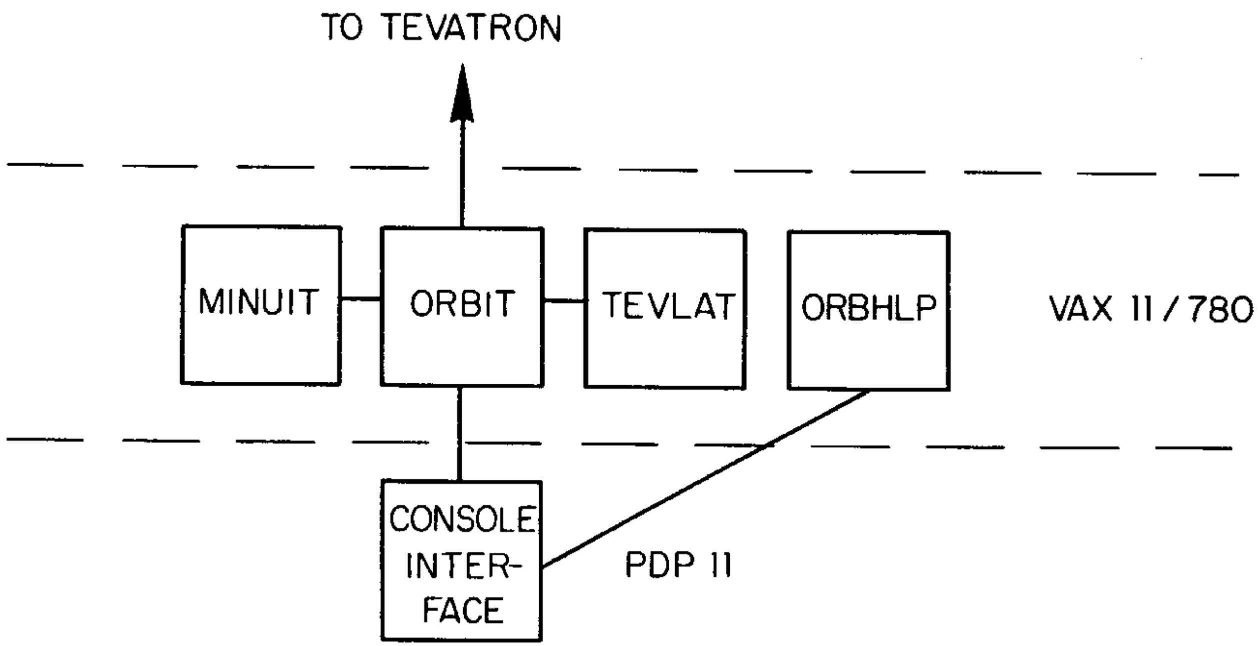

TO TEVATRON
MINUIT
ORBIT
TEVLAT
ORBHLP
VAX 11/780
CONSOLE INTER-FACE
PDP 11

Figure 4

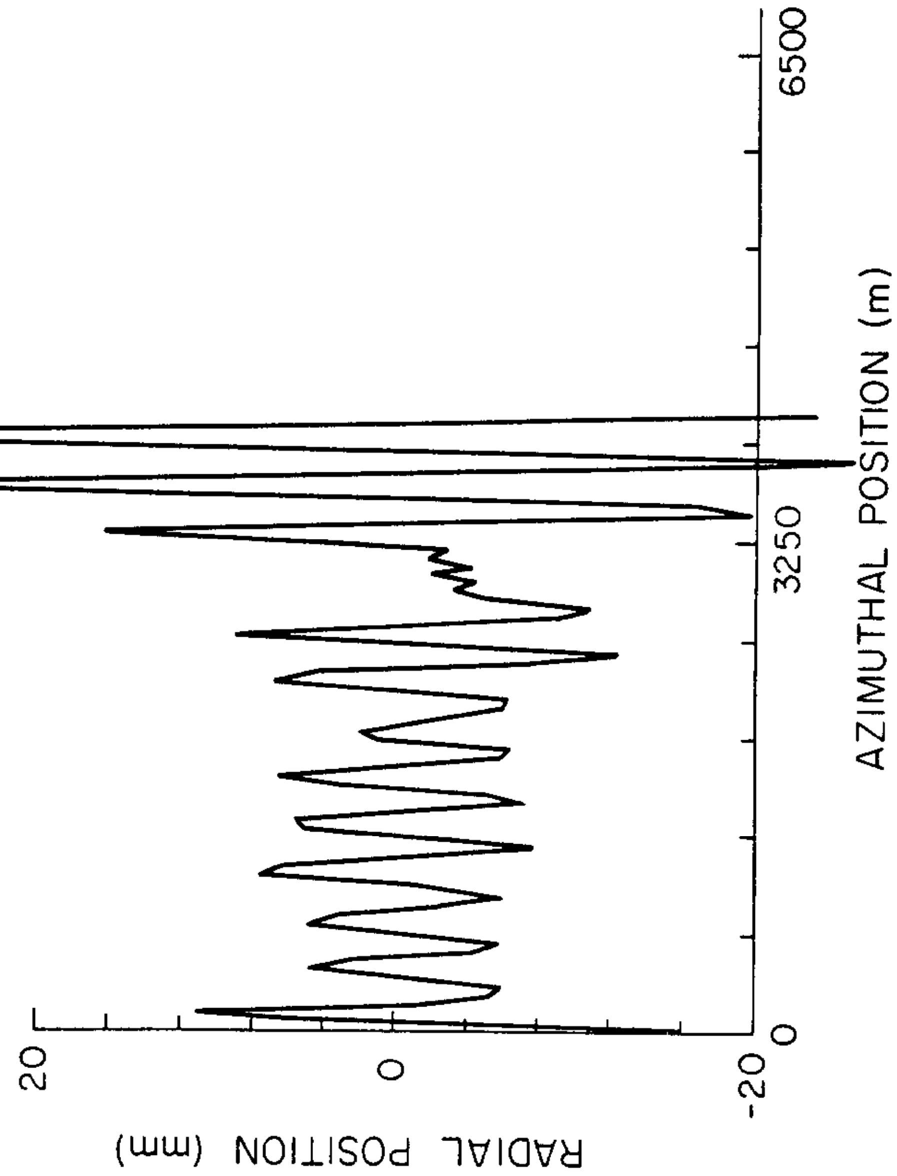


Figure 5(a)

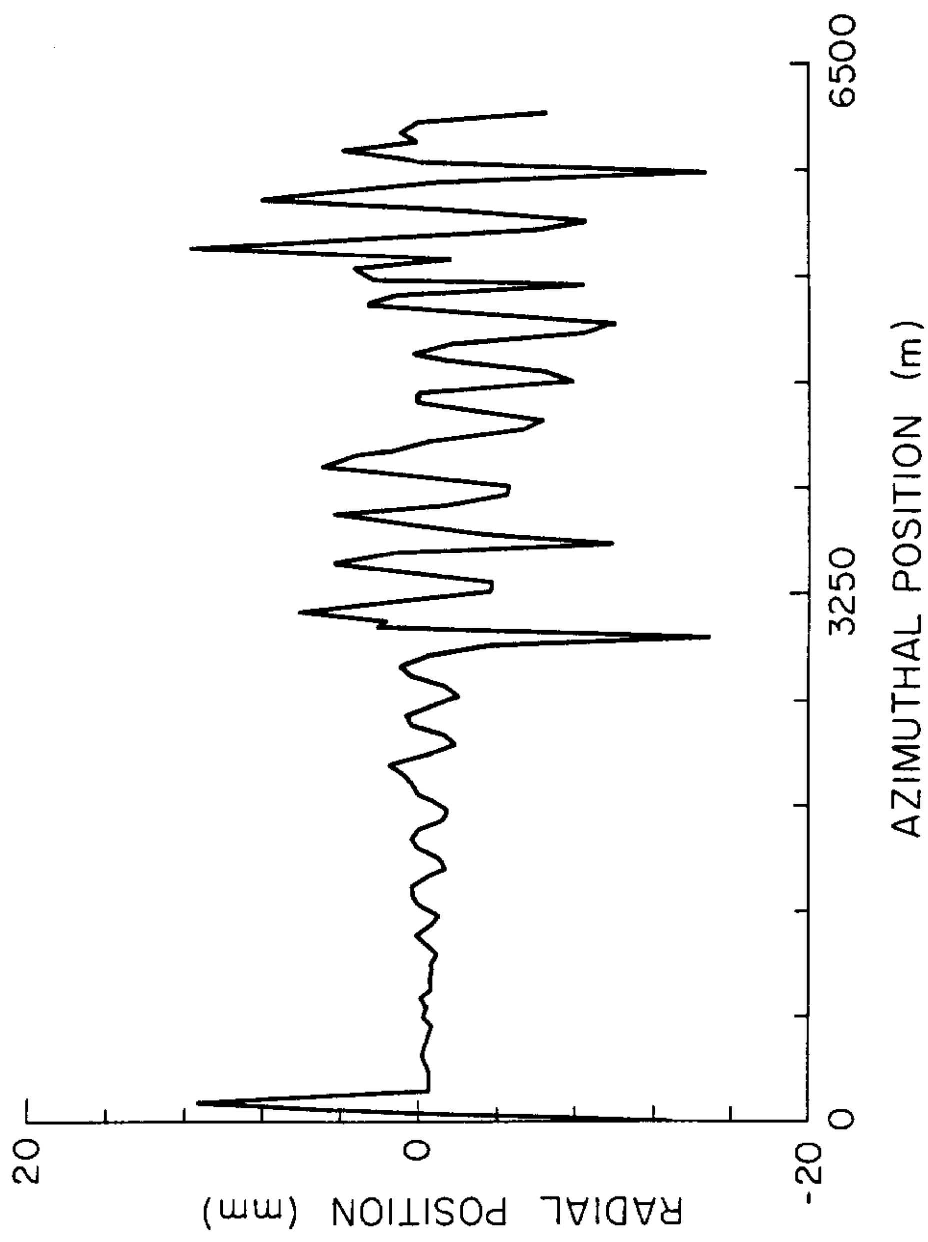
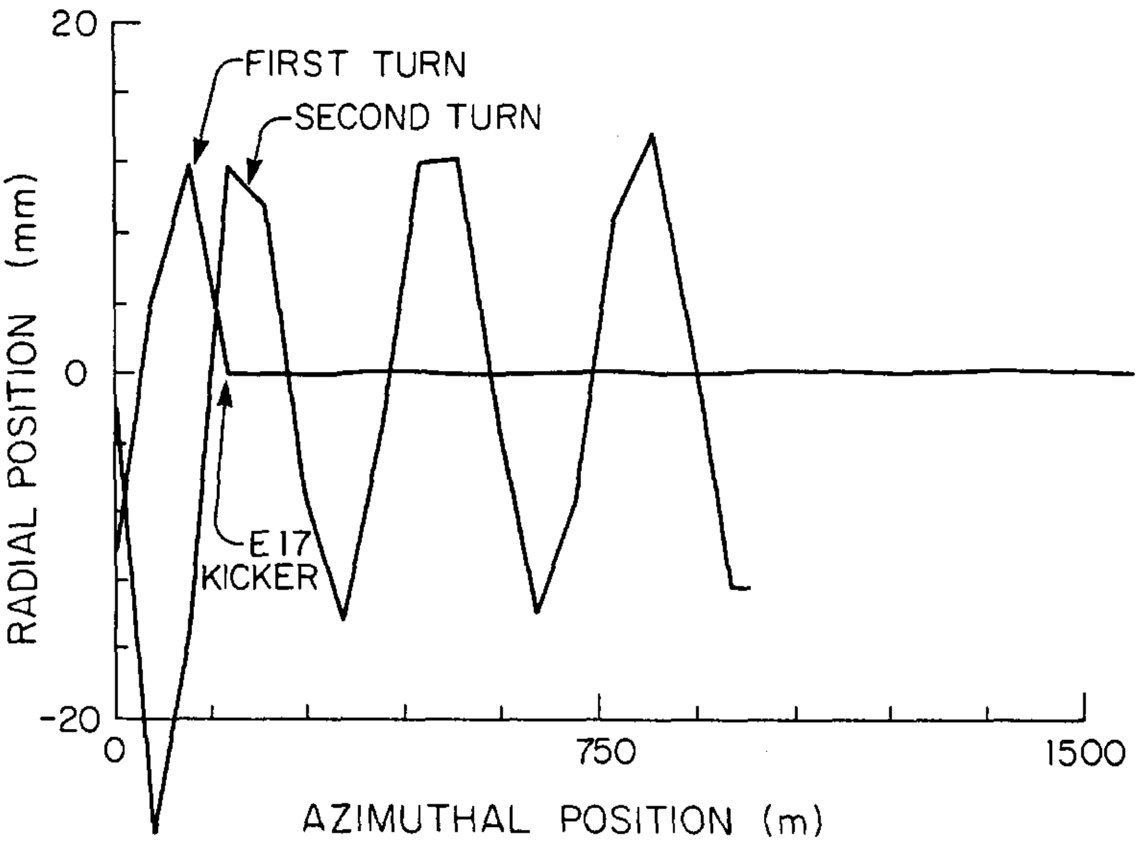


Figure 5(b)



20
0
-20
0
750
1500
FIRST TURN
SECOND TURN
E 17
KICKER
RADIAL POSITION (mm)
AZIMUTHAL POSITION (m)

Figure 6(a)

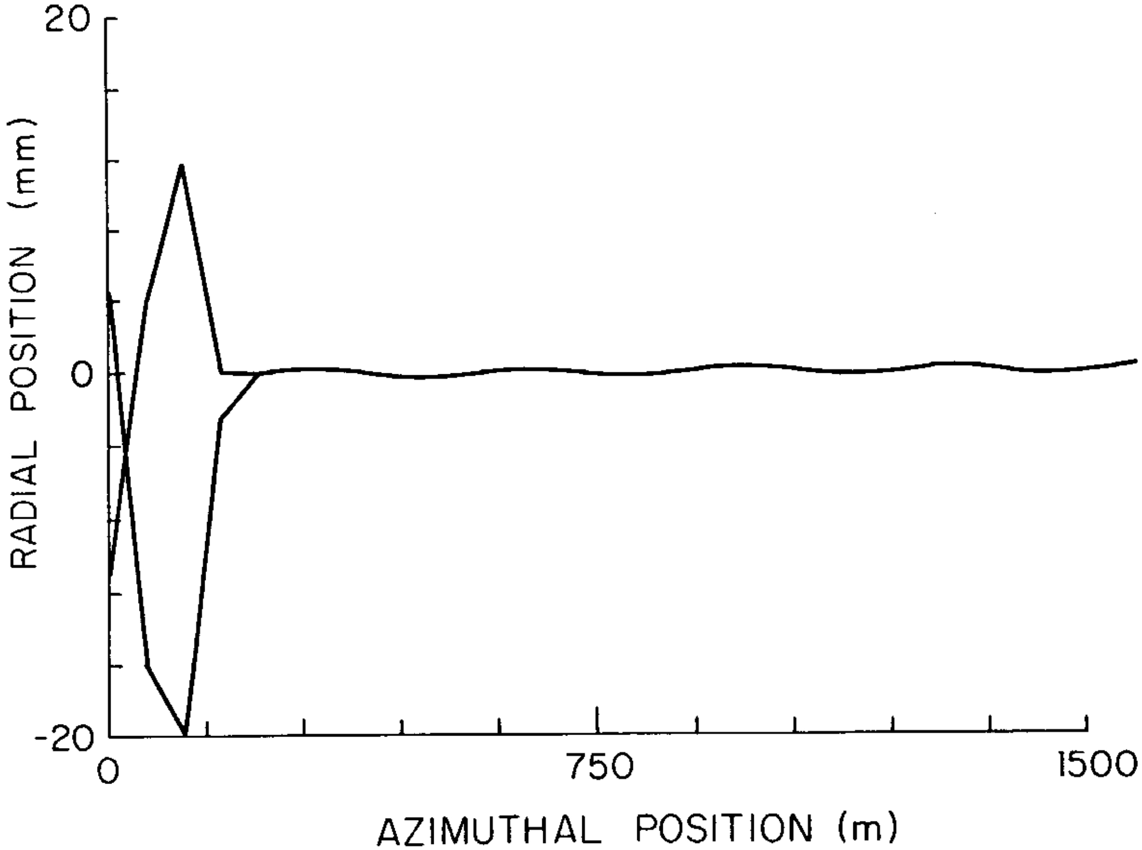


Figure 6(b)

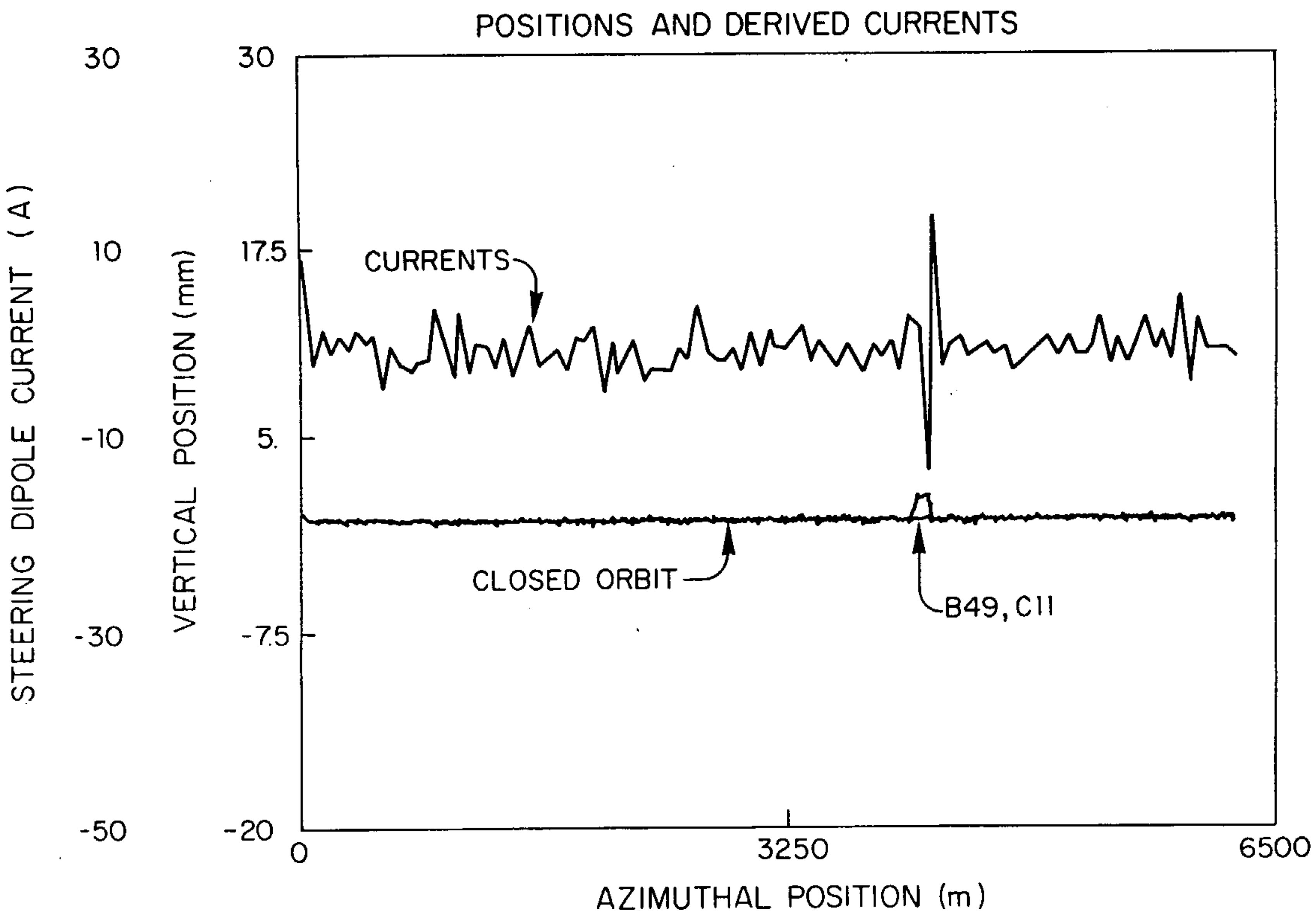

POSITIONS AND DERIVED CURRENTS
STEERING DIPOLE CURRENT (A)
30
10
-10
-30
-50
VERTICAL POSITION (mm)
30
17.5
5.
-7.5
-20
CURRENTS
CLOSED ORBIT
B49, C11
0
3250
6500
AZIMUTHAL POSITION (m)

Figure 7

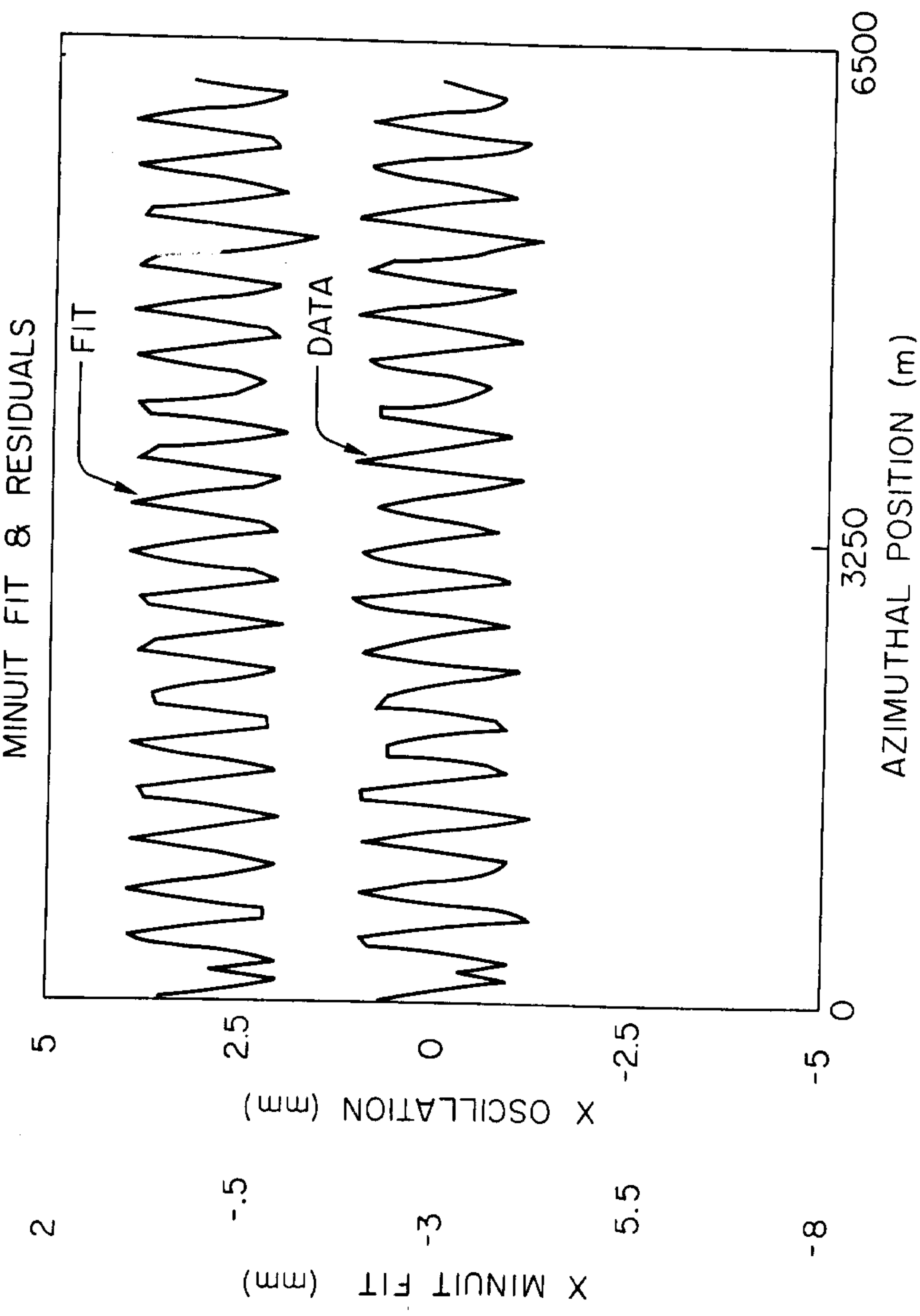

MINUIT FIT & RESIDUALS
FIT
DATA
AZIMUTHAL POSITION (m)
0
3250
6500
X OSCILLATION (mm)
5
2.5
0
-2.5
-5
X MINUIT FIT (mm)
2
-.5
-3
5.5
-8

Figure 8(a)

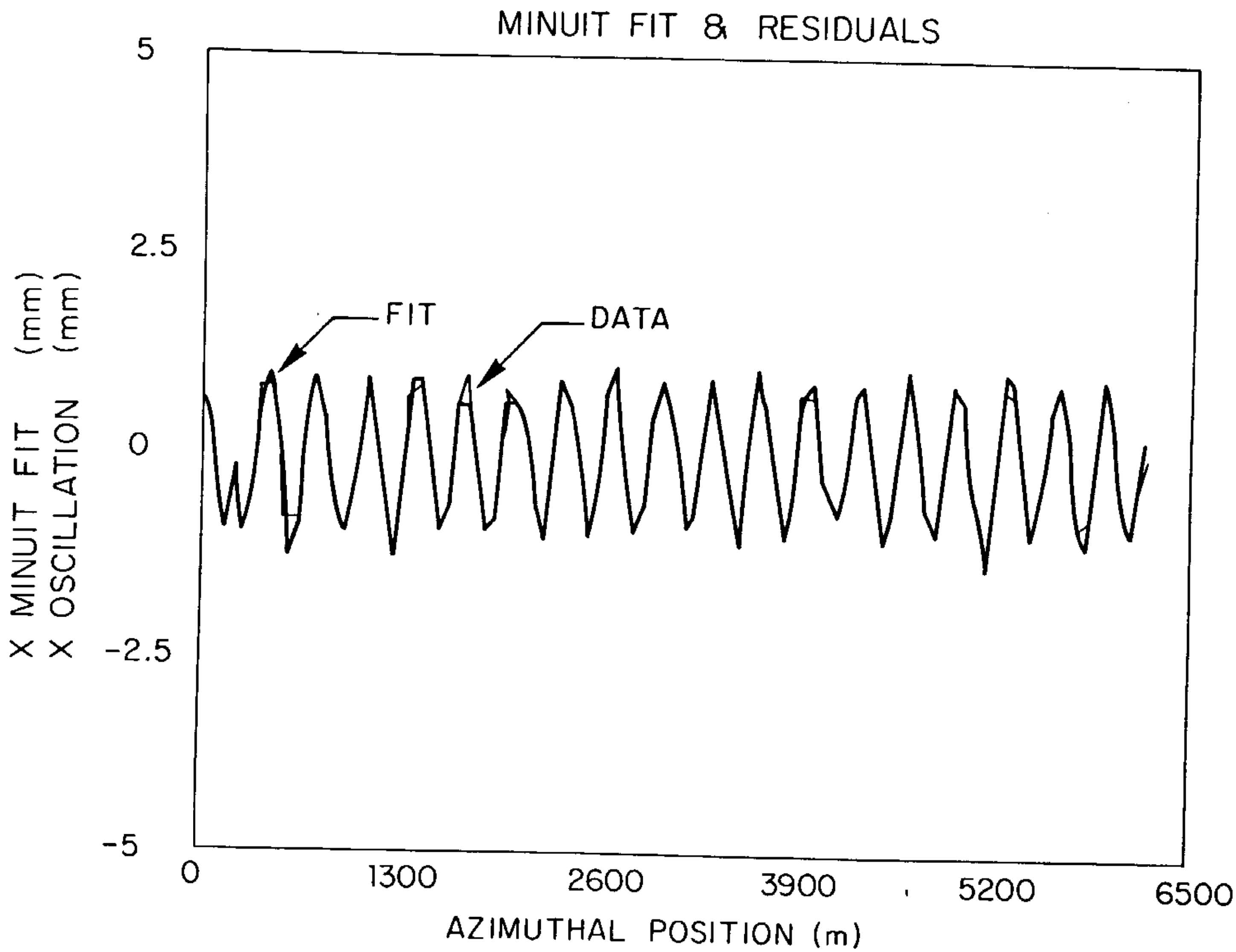

MINUIT FIT & RESIDUALS
X MINUIT FIT (mm)
X OSCILLATION (mm)
5
2.5
0
-2.5
-5
FIT
DATA
0
1300
2600
3900
5200
6500
AZIMUTHAL POSITION (m)

Figure 8(b)

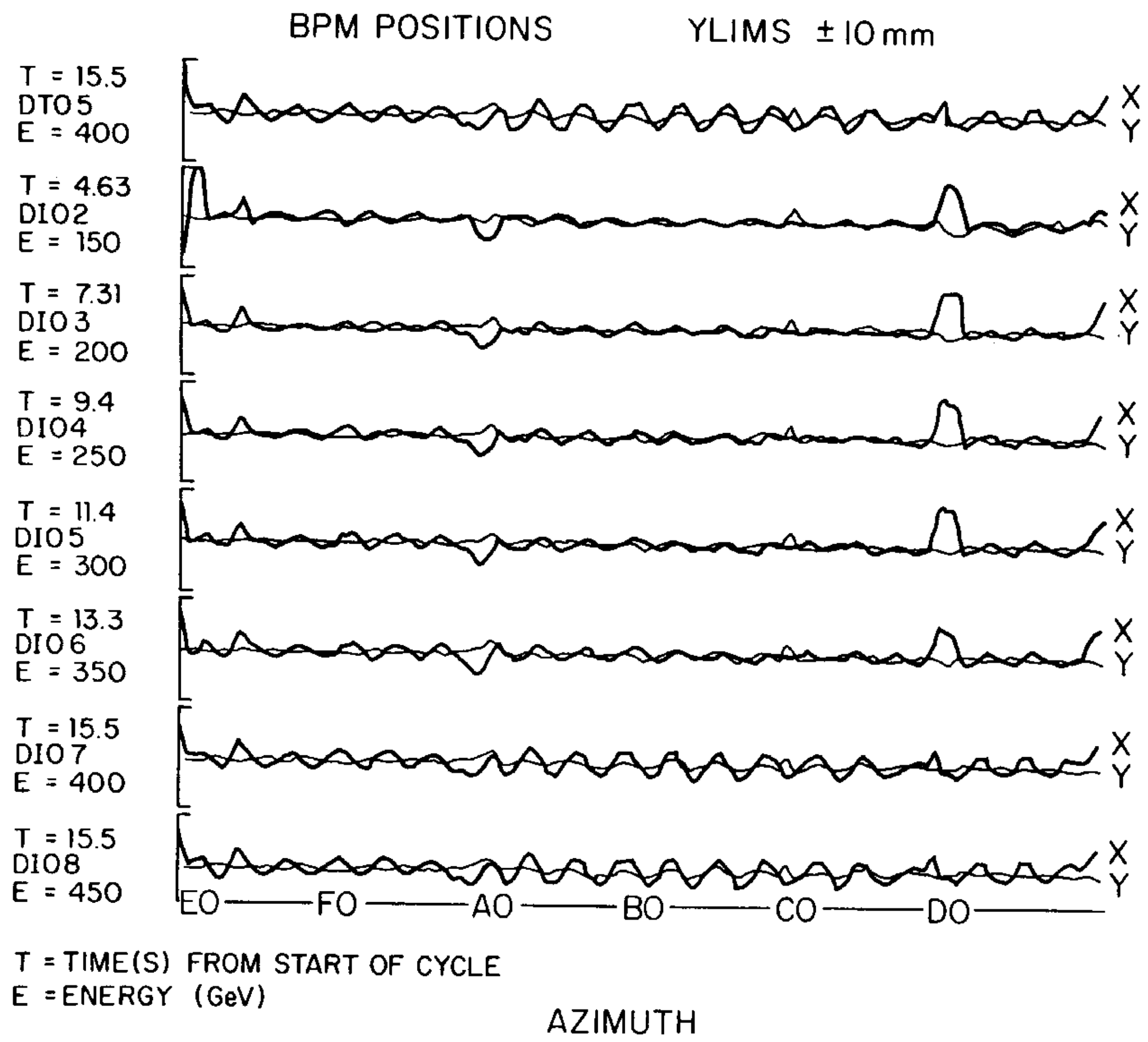

BPM POSITIONS
YLIMS ±10mm
T = 15.5
DTO5
E = 400
T = 4.63
DIO2
E = 150
T = 7.31
DIO3
E = 200
T = 9.4
DIO4
E = 250
T = 11.4
DIO5
E = 300
T = 13.3
DIO6
E = 350
T = 15.5
DIO7
E = 400
T = 15.5
DIO8
E = 450
X
Y
EO
FO
AO
BO
CO
DO
T = TIME(S) FROM START OF CYCLE
E = ENERGY (GeV)
AZIMUTH

Figure 9