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Introduction

To successfully provide beam to experiments from the Tevatron requires that we be able to perform many distinct operations on the internal accelerator beam. These include injecting beam, correcting the orbit, accelerating and then squeezing or extracting the beam. To perform many of these operations we depend on a knowledge of the lattice functions at various points in the lattice.

The values of the lattice functions used in calculating the value for a bump or for the setting of a corrector come from a computer model of the Tevatron. If the model does not give the correct values of the lattice functions then the desired operation may not be performed correctly. It is therefore important that we be able to experimentally verify our model of the Tevatron. With the installation of the new low-β magnets at B0, and the modifications of the lattice at D0, it is necessary that we measure the β functions at different locations in the lattice and compare them with the values calculated from our model.

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Method of Measurement

We measured the value of the β function at seven locations in the lattice using a method described by Courant and Synder in their paper *Theory of the Alternate Gradient Synchrotron.*[1]

When the gradient, B', of a quadrupole is changed by an small amount $\Delta B'$ (with resulting change in $k^2, \Delta k^2 = \Delta B'/[B\rho]$) the tune will change by an amount $\Delta\nu = \frac{1}{4\pi}\beta(\Delta k^2 \cdot l)$ where l is the length of the quadrupole. Solving for β;

$$\beta = \frac{4\pi\Delta\nu}{(\Delta k^2)\cdot l}$$

in the limit where $\Delta k^2 \rightarrow 0$.

In the new Tevatron lattice it is possible to independently vary the current in the strong correction quadrupoles located in the spool pieces at A43, A44, A46, A47, B14, B16, and B17 and we therefore measured the β functions at those locations for the following lattices:

- Injection lattice, separators off, 150GeV.
- Flat top orbit, "1 helix", 900GeV.
- Low-β, "3 helix", 900Gev. [2]
- Low-β, separators off, 900GeV.

For all the lattices the experimental procedure was the same; individually vary the current in the quadrupoles and measure the resulting tune shift in both planes. [3]

[1] Ann Phy 3,1(1958)

[2] The difference between the "1 helix and the "3 helix" is in the number of separators turned on and the separator voltages. With both p and $\bar{p}$ in the Tevatron,the "1 helix" would have no collision points, while the "3 helix" would have $\bar{p}p$ collisions at the B0 and D0 interaction points. The β measurements were made with only protons and the only difference, due to the different separator settings, is in closed orbits.

[3] The data were taken by N. Gelfand, D. Herrup, S. Saritepe, and D. Siergiej

Analysis of the Data

The measurements consist of the current in the quadrupoles and the associated tune shifts. In order to measure β we need to know the gradient in the quadrupoles as a function of the current, *i.e.* the transfer constant for the magnet. An attempt has been made, at MTF, to measure the transfer constant of the short quadrupoles, which were varied in the β measurements, and which are located in spool pieces. They also measured the transfer constants of the new low-β quadrupoles located in the lattice, and the long quadrupoles in the new low-β triplet. For the short quadrupoles, which were varied to measure β, the MTF measurements are several (2-5)% lower than the nominal values.

Unfortunately problems have been identified with these MTF measurements of the transfer constants. At least some of these problems are thought to be associated with the length of the magnet, and there is some hope that the measured transfer constants for the short quadrupoles in the spool pieces might be reliable. That has not yet, unfortunately, been demonstrated. Because of the uncertainty about the reliability of the measured transfer constants, the nominal values found in the "Pink Book" [4] have been used in computing β from the current in the short quadrupoles and the measured tune shifts. If reliable measured values for the transfer constants become available, then the measured values for β reported here can be easily corrected using the new values for the transfer constants.

The uncertainty in the value of the transfer constant of these quadrupoles is a fundamental limit in our ability to determine β.

For each of the short quadrupoles, the measured values of $\Delta\nu$ in each plane were fit to a quadratic polynomial in k^2. The value of the slope found in the fitting is used to compute the values of β at that location. For each measurement a statistical uncertainty in the determination of β can be estimated from the quality of the fit.

The results of the measurements, along with an estimate of the statistical error, are given in Table I.

[4] "Tevatron Low-Beta Quadrupoles, Requirements and Specifications"

Table I.
Measured Values of β

Lattice	Injection	Flat Top	Low-β	Low-β
Energy	150GeV	900GeV	900GeV	900GeV
Separators	Off	"1 helix"	"3 helix"	Off
Location				
A43, $\beta_x(m)$	26.2±0.3	30.4±0.4	31.7±8.6	33.1±2.1
A44, $\beta_x(m)$	83.7±0.8	89.3±1.0	56.1±2.5	56.0±4.1
A46, $\beta_x(m)$	145.0±1.3	154.4±1.0	163.3±1.9	175.7±4.8
A47, $\beta_x(m)$	0.00±2.9	8.1±1.1	7.52±2.1	3.5±7.5
B14, $\beta_x(m)$	21.0±1.5	21.7±1.6	19.3±2.0	14.1±4.6
B16, $\beta_x(m)$	31.3±0.9	33.1±1.3	40.0±13.2	41.8±5.6
B17, $\beta_x(m)$	90.2±0.6	90.6±1.4	77.7±23.0	87.2±4.5
A43, $\beta_y(m)$	56.6±0.4	75.6±0.6	70.9±1.0	68.3±3.5
A44, $\beta_y(m)$	27.9±1.5	30.6±0.7	24.3±1.6	26.7±1.6
A46, $\beta_y(m)$	22.1±1.5	23.0±1.6	16.1±1.3	21.8±2.0
A47, $\beta_y(m)$	103.2±4.3	105.4±1.3	103.9±4.1	109.1±2.9
B14, $\beta_y(m)$	248.4±1.1	211.3±1.4	214.8±2.3	217.5±1.1
B16, $\beta_y(m)$	119.2±1.0	107.8±0.7	91.8±2.3	91.6±1.5
B17, $\beta_y(m)$	25.0±1.2	27.8±1.6	22.2±2.9	28.4±4.1

The stated errors are an estimate of the statistical uncertainty coming from the tune measurements; the systematic uncertainty, due to the uncertainty in the transfer constant, should should be added to them. It is obvious that some of the measurements, particularly those made at low-β, are not very good and should be repeated. [5]

The difference in the value of β measured with and without the separators is generally small.

[5]The accuracy of the measurements at low-β suffered from the short time allotted to the measurements. This resulted in the tune shift being measured for fewer values of the current than is desirable.

Comparison With a Computer Model of the Tevatron

The number of points at which we have measured the value of β is far smaller then the number of points at which we need to know β in order to adjust the correction elements or even the lattice itself. The needed values of β are computed from a model of the Tevatron; our measured values constitute both a check of the model and may also indicate how the model might be modified to more closely approximate the Tevatron. The model is used as input to the tracking and lattice program Tevlat[6].

The model of the Tevatron used here incorporates the following features:

- The lattice description contained in the Synch input file ATC1.IN developed by Karl Koepke;
- The locations of the different lattice elements in the tunnel as given by Glen Goderre;
- The high order multipoles for the magnets as measured at the MTF;
- The currents in the low-β quadrupoles as defined by the C49 control program. The magnet current, using the "Pink Book" value of the transfer constant, determines the gradients in the low-β quadrupoles, viz. the long quadrupoles in the triplet [7], the 54" quadrupoles and the short quadrupoles in the spool pieces (the same quadrupoles used to measure β) ;
- The deviation of the strength of the individual quadrupoles from the measured average strength for that type of quadrupole in the lattice using the data from the MTF measurements; [8]

[6] Tevlat was written by A. Russell. It has since been extensively rewritten. Information about the program, along with a manual containing information about the program is available from N. Gelfand

[7] The four 132" quadrupoles are connected in series to one power supply and the two 232" quadrupoles are connected in series to another power supply

[8] It is assumed here that while the MTF measurements of the strength of a quadrupole may be wrong, by a factor which may depend on the length of the quadrupole, the measured variation in the strength of the quadrupoles of the same type and length is correct.

- The information that the current in the tuning quad at E25 was reversed, and that the tuning quads at A45, B15 and E17 were not connected.

The calculations are done using TEVLAT. [9]

Figure 1 shows the results of the calculation and the measurements for the injection lattice at 150GeV. The calculated values include a correction for the energy dependence of the strength of the 66" lattice quads as determined from MTF measurements. The agreement is only reasonable,the rms difference (Δ) between the measured and the calculated points is 13.1m. The agreement between the measured and calculated values can be improved with modest changes (less than or equal to $\approx 0.2\%$) to the strengths of the quadrupoles in the low- β triplet. The value of Δ can be reduced to ≈ 10. I cannot regard this as a significant improvement. In addition this should not be considered as a method of measuring the transfer constants. There are many combinations of changes possible which all give essentially the same value of Δ.

Table II compares the measured values of β with the values calculated using the nominal values for the transfer constants for the low-β quadrupoles.

Table II
Comparison of the Measured and Calculated Values of β at Injection.

	$\beta_x(m)$			$\beta_y(m)$		
Location	Calculated	Measured	Δ	Calculated	Measured	Δ
A43	32.5	26.2±0.3	6.3	74.5	56.6±0.4	17.9
A44	96.6	83.7±0.8	12.9	31.9	27.9±1.5	4.0
A46	153.9	145.0±1.3	8.9	30.3	22.1±1.5	8.3
A47	7.1	0.0±2.9	7.1	115.7	103.2±4.3	12.5
B14	26.2	21.0±1.5	5.2	210.6	248.4±1.1	-37.8
B16	31.1	31.3±0.9	-0.3	125.3	120.3±1.0	1.1
B17	91.8	90.2±0.6	1.5	32.6	25.0±1.2	7.5

Following the measurements made at 150GeV a "1 helix" was established, and the beam was accelerated to 900GeV. The lattice at flat top (900GeV)

[9] A preliminary version of the analysis can be found in the Conference Record of the 1991 IEEE Particle Accelerator Conference Vol 1, pg 81. The major difference between this analysis and the earlier one, is that we now have better representation of the lattice.

should be the same as the lattice at injection. It is known, from the MTF measurements, that the gradients of the quadrupoles exhibit a current dependence. In addition the tune at flat top was different from the tune at 150GeV which means that the β function at flat top, even without the change in the strength of quadrupoles, would also be different. The measurements of β were repeated. The Tevlat calculations were done without the "1 helix" for simplicity. With the nominal quadrupole gradients the rms deviation between the measured and calculated values (figure 2) of β is Δ =4.5m, which is much better than the results for the injection lattice.

The β function was then "squeezed" at the B0 interaction point and the β measurements were repeated with both the "3 Helix" and with the separators turned off. These measurements have larger errors than those done with the injection lattice which is probably due to the time constraints under which they were made. The values of β measured with the "3 Helix" are in good agreement with those measured with the separators off.

The measured values of β are in poor agreement (Δ= 16.5m) with the values of β calculated using the nominal values of the transfer constants (figure 3). The agreement can be improved (Δ =10.1) by using different values for the transfer constants for the quadrupoles in the triplet.

The comparison between the measured and calculated values of β, using the nominal transfer constants for the low-β quadrupoles in the triplet, is summarized in Table III for the data taken at flat top and in Table IV for the low-β data.

Table III
Comparison of the Measured and Calculated Values of β at 900GeV.

	$\beta_x(m)$			$\beta_y(m)$		
Location	Calculated	Measured	Δ	Calculated	Measured	Δ
A43	32.6	30.4±0.4	2.2	78.9	75.6±0.6	3.3
A44	98.4	89.3±1.0	9.1	32.8	30.6±0.7	2.2
A46	155.4	154.4±1.0	1.0	28.3	23.0±1.6	5.4
A47	7.0	8.1±1.1	-1.1	112.3	105.4±1.3	7.0
B14	26.6	21.7±1.6	4.9	207.3	211.3±1.4	-3.9
B16	30.7	33.1±1.3	-2.4	113.1	107.8±0.7	5.3
B17	89.7	90.6±1.4	-0.9	31.6	27.8±1.6	3.7

Table IV
Comparison of the Measured and Calculated Values of β at low-β.

	$\beta_x(m)$			$\beta_y(m)$		
Location	Calculated	Measured	Δ	Calculated	Measured	Δ
A43	31.1	33.1±2.1	-2.0	84.4	68.3±3.5	16.2
A44	104.1	56.0±4.1	48.1	28.8	26.7±1.6	2.2
A46	177.0	175.7±4.8	1.3	29.0	21.8±2.0	7.1
A47	8.2	3.5±7.5	4.7	124.5	109.1±2.9	15.3
B14	28.5	14.1±4.6	14.4	218.8	217.5±1.1	1.3
B16	27.0	41.8±5.6	-14.7	110.6	91.6±1.5	18.4
B17	97.4	87.2±4.6	10.2	29.1	28.4±4.1	0.6

Conclusions and Suggestions.

The agreement between the measurements and our model is not as good as we would like. The only good agreement is with the injection lattice at 900GeV flattop. I choose to regard this as not fortuitous and therefore believe that the computer model used for calculating the lattice functions in the Tevatron in basically correct. We then have to understand the relatively poor agreement at 150GeV and at low-β.

The lattices at injection (150GeV) and at flat top (900GeV) should be identical. Any difference in the lattice functions is due to the current dependence of the quadrupole transfer constants and, due to changes in the closed orbit, the high order multipoles in the dipoles . The change measured at MTF of the transfer constants is as large as 1% for the 232" quadrupoles and is less for the shorter ones. It is not likely that the 1% variation is correct but, in any case, searching for better values of the transfer constants does not result in a significant improvement in the quality of the fit. A possible explanation of the difference *could* be that the beam at 150GeV is different from the beam at 900GeV; both the size of the beam and dp/p are smaller at 900GeV. Furthermore the chromaticity of the beam could be different at the two energies. [10] I, for one, do not yet understand how the changes in beam size or chromaticity would effect the measurements of tune. I think that it is important to understand if there is any effect, and if so, to do a better controlled experiment in the future.

In going from flat top to low-β, only the 54" magnets outside of the interaction change significantly. The improvement in the agreement at low-β resulting from the modified transfer constants suggests that the nominal transfer constants are not the correct values. The fact that the agreement is not better demonstrates that there are still some problems with our model.

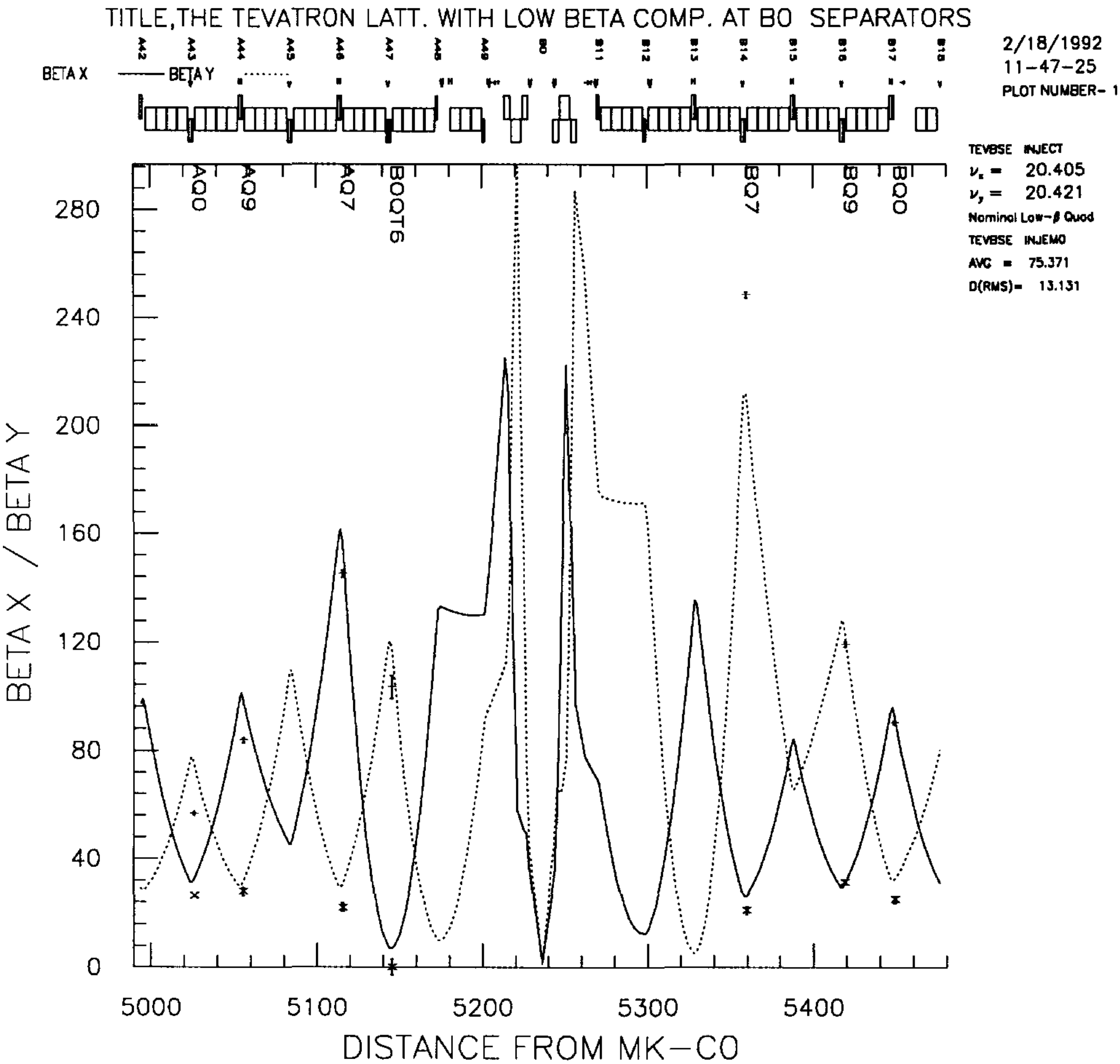
In order to further investigate our model (or any other model) of the Tevatron we will need to measure β at additional locations. The strong quadrupoles in the spool pieces around D0 could be used and it also would be very helpful to measure β using the independently powered quadrupoles at F27,F28,F33 and F34, that were used previously to measure β [11]

At each interaction region the 132" quadrupoles are connected in series while the 232" quadrupoles are in series on a separate circuit. It could also be useful to vary the currents in the four circuits powering the triplet quads and measure the resulting tune shifts. The calculations can be compared directly with the Tevatron model.

These measurements, if they are to be done well, will require several shifts of machine time.

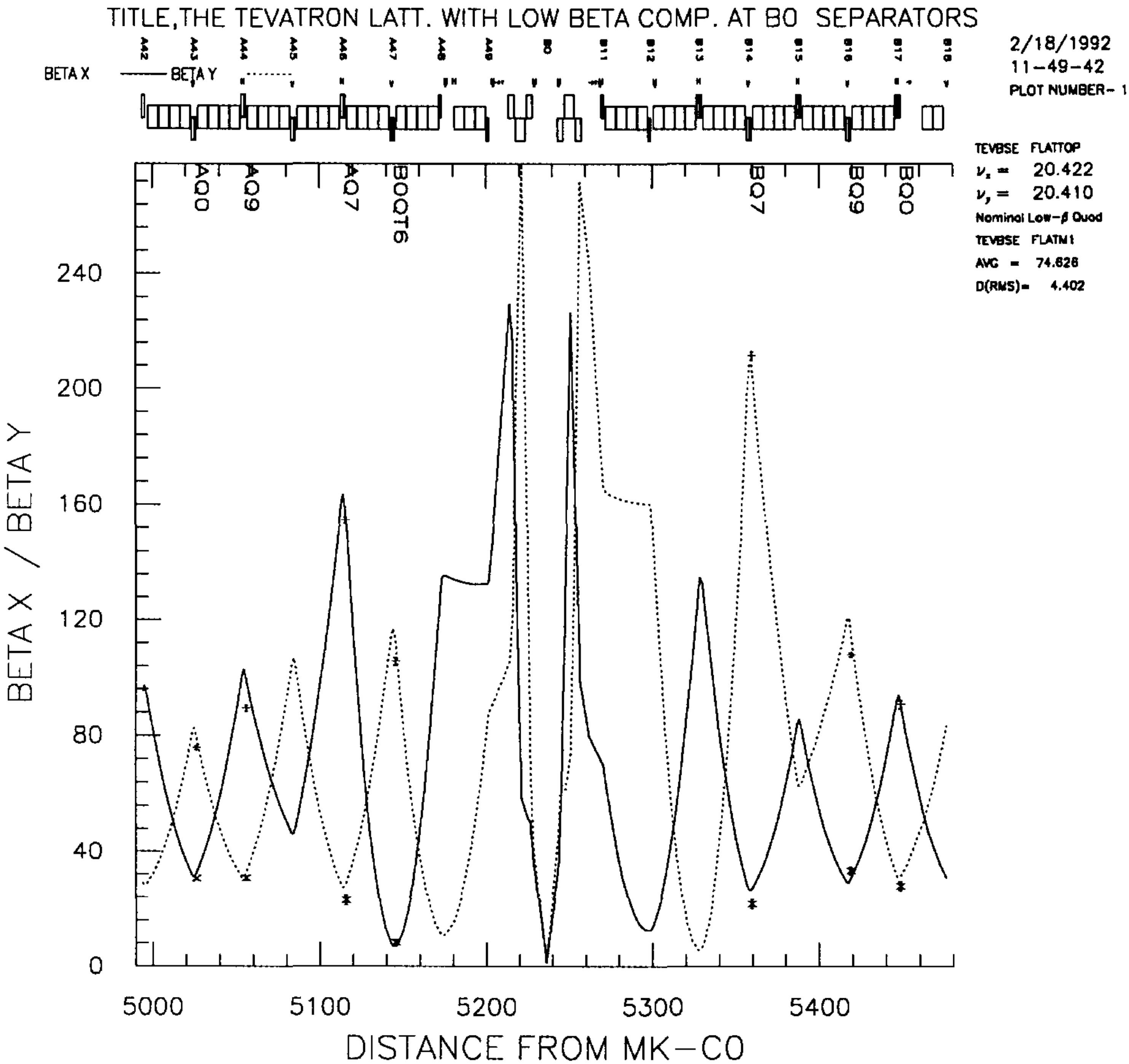
[10] There is a current dependence in the Tevatron dipoles, which if not corrected, would result in a change in the chromaticity as we accelerate the beam.

[11] *Measurements of β in the TEVATRON and Comparisons with Calculations*, N. M. Gelfand, R. P. Johnson, P. Zhang, Proceedings of the 1989 IEEE Particle Accelerator Conference pg. 1427



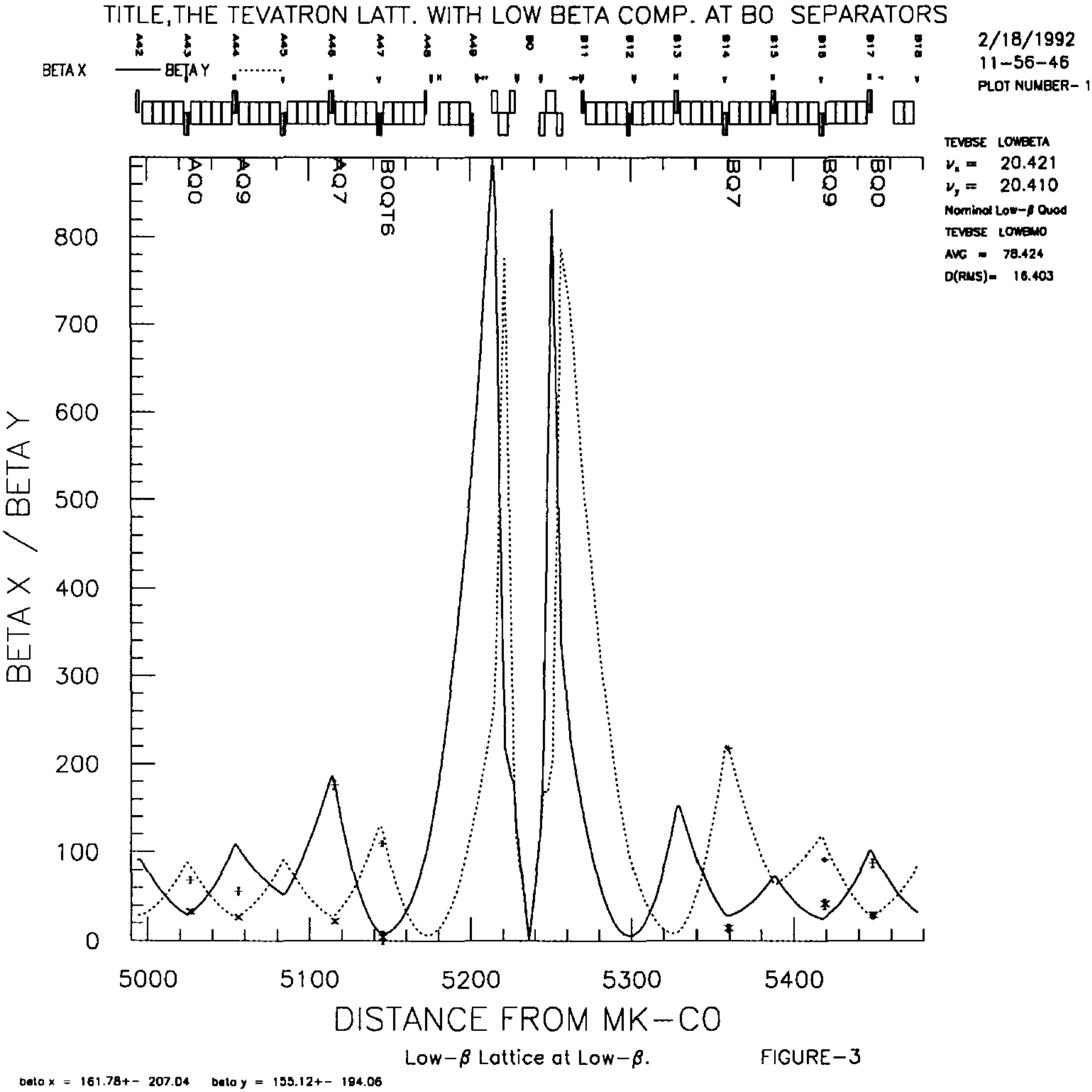
Low-β Lattice at Injection. FIGURE-1

beta x = 82.50+- 56.11 beta y = 97.04+- 75.48



Low-β Lattice at 900GeV FT. FIGURE-2

beta x = 83.17+- 56.90 beta y = 93.41+- 71.57



Low-β Lattice at Low-β. FIGURE-3