Fermi National Accelerator Laboratory

FERMILAB-Pub-85/59
2040.000
(Submitted to Particle Accelerators)

TESTS OF ORBITAL DYNAMICS USING THE TEVATRON*

D. A. Edwards and R. P. Johnson
Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA

and

F. Willeke
DESY, Hamburg, West Germany

April 1985

*Presented at the Workshop on Orbital Dynamics and Applications to Accelerators, Berkeley, California, March 7-12, 1985.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

TESTS OF ORBITAL DYNAMICS USING THE TEVATRON

D. A. EDWARDS, R.P. JOHNSON AND F. WILLEKE
Fermilab and DESY

Abstract Measurements of Tevatron beam behavior relevant to questions of orbital dynamics are described. General techniques and some preliminary results from phase space distortion experiments are presented.

INTRODUCTION

The number of accelerator experiments on the Tevatron which involve comparisons with calculations is small. There are two separate reasons that this situation should improve in the near future. The first is the need to understand the Tevatron itself well enough to use it effectively as a proton-antiproton collider. The second reason is to help resolve design issues of the SSC. There is considerable interest in testing the machine models and mathematical techniques used to predict the behavior of beams in the SSC. The Tevatron is a natural choice for many of these tests.

Interesting questions of orbital dynamics in a synchrotron often involve the long-term behavior of circulating protons when additional, nonlinear fields are considered. Our first controlled experiments involve the study of effects of magnetic sextupole fields, where the restoring force depends on the square of the transverse displacement from the central orbit.

In this paper we will give a general overview of the Tevatron with enough of the general features described to allow a non-specialist to follow a description of an experiment. We will then describe an experiment to measure the effects of some additional sextupole magnets on the beam behavior. Since this is the first such measurement at Fermilab, we will describe in some detail the experimental techniques used so far and the practical complications which have been discovered. Finally, we will describe some future experiments.

DESCRIPTION OF THE TEVATRON

The behavior of protons in the 6-dimensional phase space of a synchrotron is determined by the character of the magnetic guide field (transverse, or betatron motion) and the rf accelerating fields (longitudinal, or synchrotron motion). These fields are basically simple, providing linear restoring forces to particles with small displacements from the ideal, synchronous orbit. The behavior of the machine is analytically calculable in this approximation, often expressed in the familiar language of simple harmonic motion.

The 774 bending magnets (dipoles) and 216 quadrupoles which make up the Tevatron lattice are superconducting magnets with a rich harmonic content. Unlike many earlier accelerators, each magnet in the 1 km radius ring has been carefully measured and the detailed multipole components (15 normal and 15 skew) of each element in the lattice are computer catalogued.

Beam is injected into the Tevatron at 150 GeV (.15*4.2 kGauss) and accelerated to 1000 GeV. This energy range of a factor of 7, a conservative choice by the designers of the Tevatron, was influenced by two considerations. One was the availability of an injector with no real energy limit (the Main Ring has run at 500 GeV). The other consideration was the effect of persistent currents in the dipoles which lead to large sextupole fields. This same consideration is one of the most interesting for the design of the SSC where the energy range is 20 and the choices of magnet bore diameter and lattice have large economic consequences.

Correction and Adjustment Magnets

Certain of the multipole errors in the main dipole and quadrupole magnets can be compensated using special auxiliary magnets which are distributed around the ring. Many of these magnets also carry out necessary adjustments of accelerator parameters. There are five such circuits which are used to compensate the lowest order effects of the multipole errors discussed above. Two circuits of correction quadrupoles allow the independent control of the two transverse oscillation frequencies, the betatron tunes. Here and below by the betatron tune we mean the ratio of the transverse oscillation frequency divided by the revolution frequency. For the Tevatron, the tune is about 19.4 and the revolution time is 21 μsec.

One circuit of skew quadrupoles is used to control the coupling between the horizontal and vertical planes. Two circuits of sextupoles are used to adjust the chromaticity, the change in betatron tune as a function of momentum offset, in the two planes. The sextupole moment in the main dipoles is a major contributor to the chromaticity.

There are also some additional circuits which are used primarily for the resonant extraction of the beam from the synchrotron. These can be used for accelerator experiments. But more important for our discussion here are the many correction elements which were installed in the ring, as yet unpowered, which can be selected for specific machine experiments. For the sextupole experiment described below, it was only necessary to select the magnets and add the necessary power supplies and controls.

RF Acceleration

Up to 8 rf cavities each operating at 53 MHz and providing 360 KV of accelerating voltage per turn are available. For most of the experiments considered so far, the beam is at constant energy. While the presence of the rf fields is something of a complication for the analysis of the beam behavior, longitudinally bunched beam is essential for many of the diagnostic devices. As well, since the SSC is also to be operated in the bunched beam mode, it may be desirable to include rf effects in some of the experiments.

BEAM DIAGNOSTICS

Beam Position Monitors

At each quadrupole location there is an electromagnetic beam position monitor of the appropriate x or y plane. These monitors give the position of the centroid of the beam to 100 μm. They can be operated in several different modes. In the simplest mode they are used to measure the closed orbit traversed by the beam.[1]

One basic test of an accelerator model is the comparison of the calculated linear lattice functions with those measured with the beam position monitors. For example, the dispersion, or dependence of the position of the beam on the momentum relative to the central orbit, can be easily measured by subtracting the orbit positions for two different rf frequencies. Fig. 1 shows the measured and calculated dispersion function for the Tevatron at 800 GeV with the optics used for normal, fixed target operation. Similar data for the low β configuration show good agreement between the calculated and measured values.

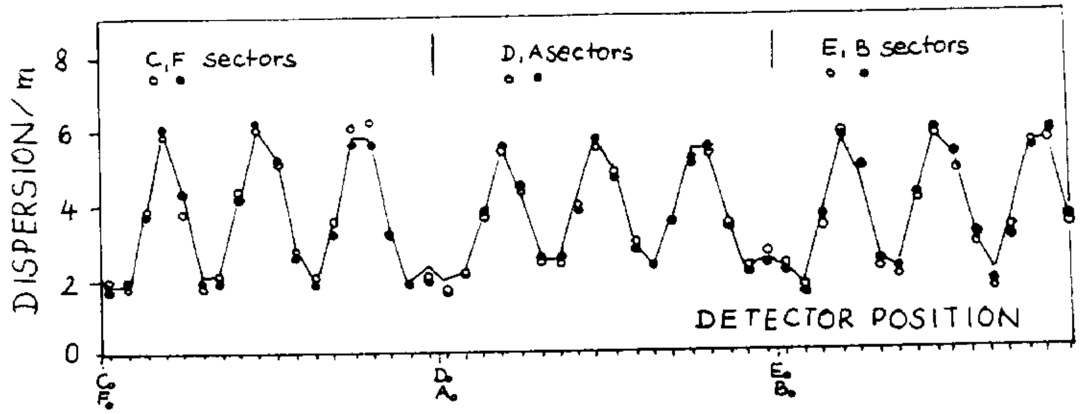

FIGURE 1 Comparison of measured and predicted dispersion function for the Tevatron at 800 GeV. The points are the measured values, the lines connect the predicted values at the position monitors. The abscissa is the approximate azimuthal position of the monitors. The twofold superperiodicity of the 6 sectors of the lattice is exhibited by the way the values repeat after 1/2 the circumference.

At selected locations, the beam position can be measured on 1024 successive turns. This turn-by-turn mode is often used to measure the betatron tune of the beam. The technique involves a pulsed magnetic kicker, or pinger, which applies a transverse kick to the beam, creating a coherent betatron oscillation. A Fourier analysis of the beam position at a single detector then gives the fractional part of the betatron tune in the plane of the transverse kick.

Figure 2a shows the position at one of the horizontal detectors on 1024 successive turns. After the ping, the oscillations continue for many thousands of revolutions. Over the 1024 turns shown in figure 2a) the maximum amplitude is seen to diminish for the first 500 turns, then return to almost the original value by the end of the figure. This amplitude change is understood as due to the combined effects of the synchrotron motion and the machine chromaticity. Namely, the original longitudinal or energy distribution modulated by the synchrotron motion will cause a time-varying tune spread due to the machine chromaticity. The part of the decoherence caused by the synchrotron motion will then oscillate with the synchrotron period which is about 1000 times greater than the revolution period.

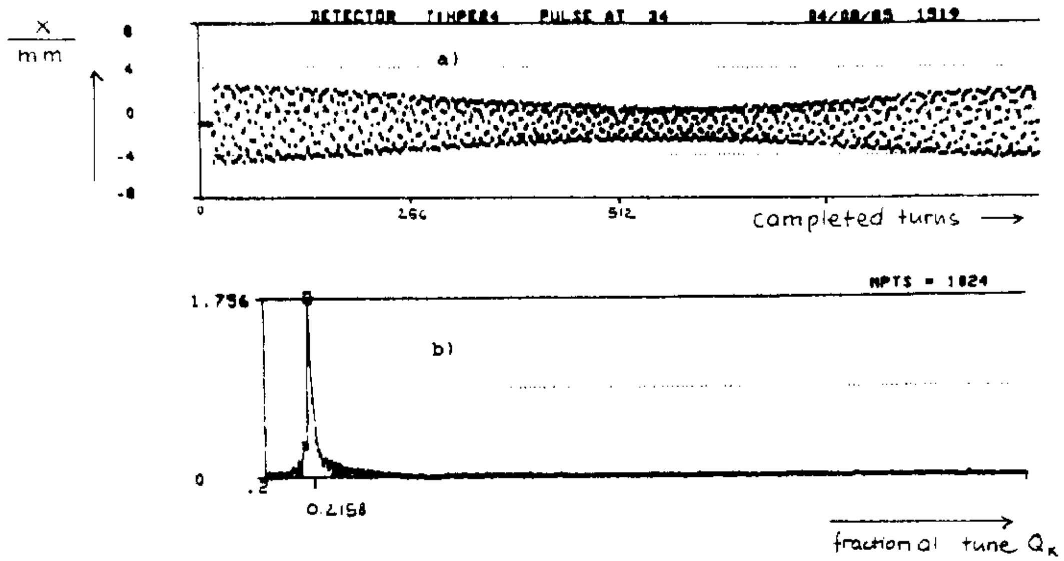

FIGURE 2 a)The beam position at one of the horizontal detectors on 1024 successive turns. Each dot is a measurement taken every 21 μs.
b) The Fourier spectrum of fig. 2a.

The Fourier spectrum of figure 2a is shown on figure 2b where the fractional tune is shown explicitly as .215. By varying the strength of the pinger it is possible to measure the amplitude dependent tunes caused by the average value of even-order multipoles and higher-order odd multipoles.

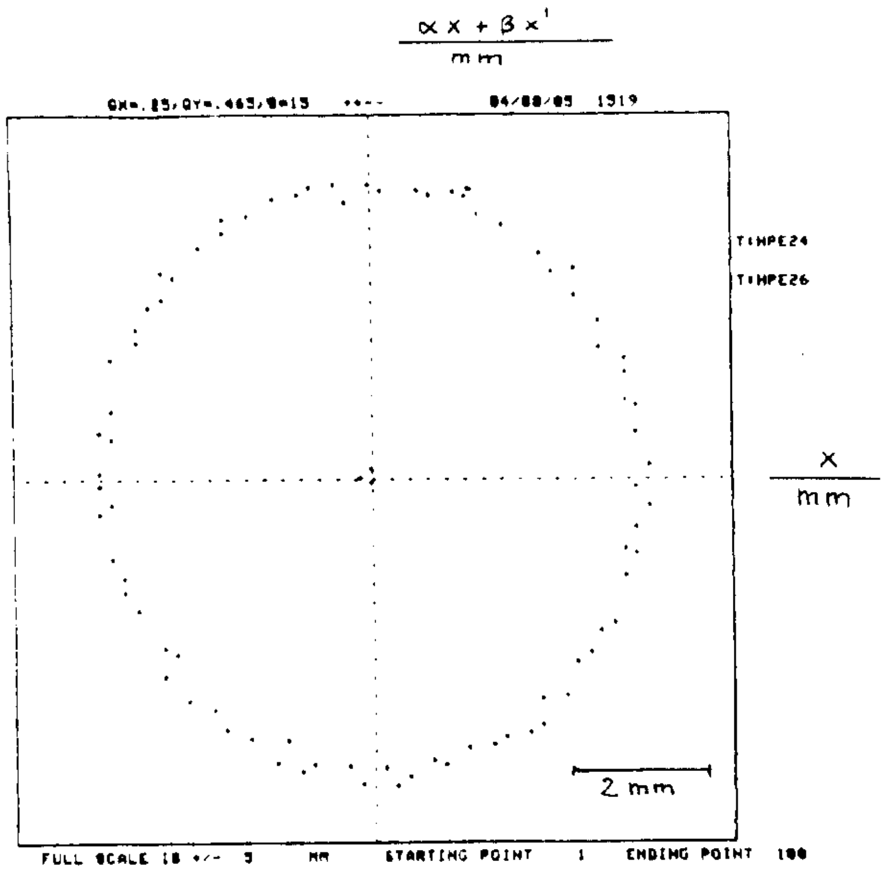

FIGURE 3 The phase space evolution of the beam shown in figure 2 for the first 100 turns after the ping. This plot is the synthesis of data from two position monitors placed 68 degrees in betatron phase advance from each other. The abscissa is the transverse position of the centroid of the beam at the first detector, the ordinate is a combination of data from the two detectors.

A more novel mode, particularly interesting for studies of orbital dynamics, involves the simultaneous recording of 2 nearby detectors in the turn-by-turn configuration. This allows one to measure the evolution of the beam in phase space coordinates, x and x'. The 2 by 2 transfer matrix between the detector positions and the 2 measured positions give 2 equations and 2 unknowns. To the extent that the transfer matrix is well known and that nonlinearities cause negligible deviation from linear behavior over the short path involved, x and x' are obtained at both detectors on successive turns.

Traditionally, one transforms the angular phase space coordinate x' using the lattice functions α and β. Phase space trajectories in x, $\tilde{x}' = \alpha(s)x + \beta(s)x'$ space lie on circles for a linear machine. Figure 3 shows the phase space evolution of the same beam shown in figure 2 for the first 100 turns after the ping. To understand su ch data quantitatively it is necessary to correct for the finite emittance and momentum spread of the beam.[2]

Flying Wire Profile Monitors

To measure the transverse profile of the beam, a thin wire is passed (flown at speeds up to 10 m/s) through the beam. In one pass, the wire scatters about 1.E-5 of the circulating protons. The debris from these interactions is monitored with a scintillation counter. The counting rate versus the wire position is a measure of the beam size and shape. The invariant emittance follows from the rms width and the lattice β function at the position of the wire ($\epsilon = (\sigma^2_{rms}/\beta)\ \pi$ mm-mr).

Figure 4 shows the change of the beam profile over a 1.5 hour period while the beam was stored at 800 GeV. The increase in transverse size is some 20 times larger than that expected from scattering by residual gas in the vacuum chamber. It is believed that the emittance growth in this instance was due to fifth order betatron resonances.

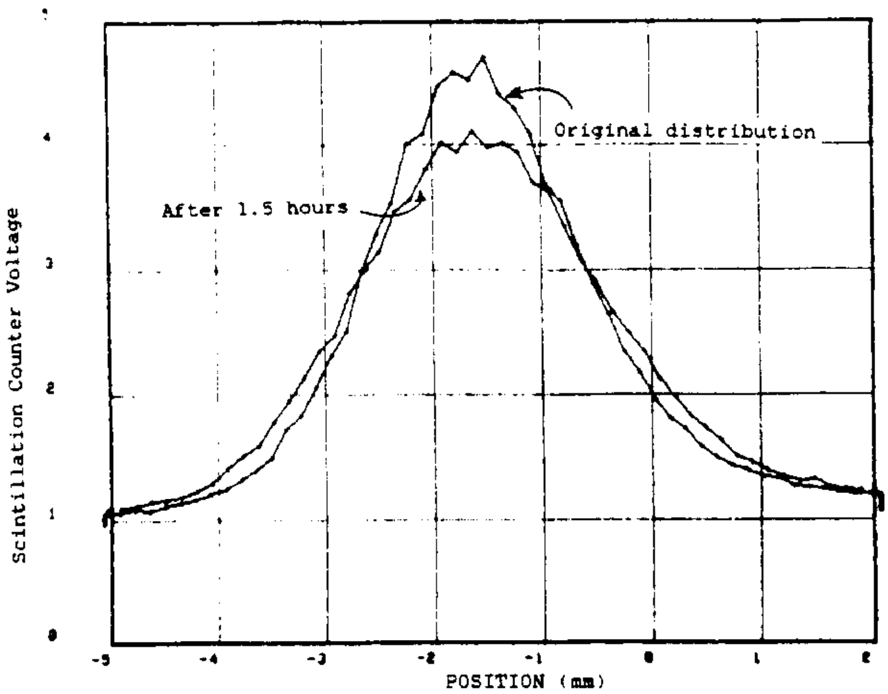

FIGURE 4 Flying wire measurement of the horizontal beam profile at the beginning and end of a 1.5 hour store. The abscissa is the position of the wire and the ordinate is the signal from a scintillation counter which is sensitive to the debris from the beam collisions with the wire.

Betatron Tune Measurements

There are several ways to measure the natural transverse oscillation frequencies. The method using the beam position monitors and pinger, described above, is not appropriate in cases where it is important to keep the emittance small for subsequent measurements. Very small oscillations induced by noise in magnetic circuits or by active (anti)damping feedback systems can be monitored with sensitive pickups and spectrum analyzers.

Using a spectrum analyzer it is possible to measure the fractional part of the transverse tunes to .00002. Precise measurements of tune versus momentum offset have been used to verify tracking models of the Tevatron.

Figure 5 shows a comparison of a RACETRACK[3] prediction with data taken at 800 GeV in the Tevatron. The predicted curve is largely determined by the higher order multipole errors of the superconducting dipole magnets.

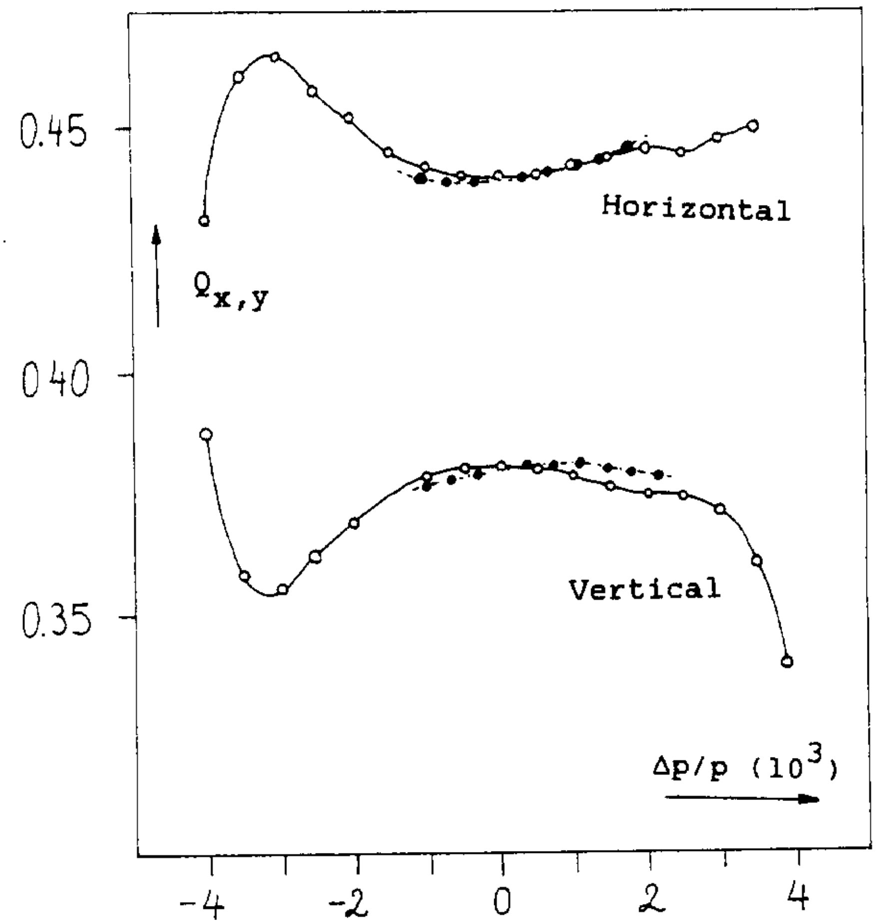

FIGURE 5 A comparison of predictions (open dots) with measurements (dots) of tune versus momentum offset. The errors on the measurements are approximately the size of the dots. The slope, or chromaticity, is artificially made slightly positive with the correction sextupoles for the real data (to avoid collective instabilities).

These precise tune measurements have been used to measure other characteristic parameters of the Tevatron. The chromaticity, $\xi = \Delta\nu/(\Delta p/p)$, is the change in tune as a function of momentum; the momentum of the beam can be varied by changing the rf frequency. Local values of the β function can be measured by measuring the tune change as a function of the strength of a single quadrupole.

EXPERIMENTS

Computational Fidelity

One of the primary interests in using the Tevatron is as a testing ground for computational techniques. The major questions to be investigated include the accuracy of predictions made by tracking and perturbation codes, especially for beam behavior at large amplitudes and after many turns. The answers to these questions may depend on the exact specifications of the nonlinear elements and any real confrontation between a calculation and an experiment must begin by establishing that the code correctly describes the basic machine.

To a large extent the character of the comparisons described above in the discussion of the diagnostic devices is good evidence that the Tevatron behaves as expected. Another test of the understanding of the actual distribution of multipole errors in the machine was the comparison of the measured 1/2-integer horizontal resonance stopband width with predictions based on tracking and an analytical calculation.

A SIMPLE SEXTUPOLE EXPERIMENT

Perhaps the simplest thing one can do to investigate nonlinear effects, both computationally and experimentally, is to add one sextupole to the machine. By choosing the correct machine parameters, essentially splitting the horizontal and vertical tunes sufficiently to suppress coupling, one can consider the motion to lie in just one plane. On each turn, a particle gets a transverse kick proportional to the square of its displacement from the center of the vacuum chamber. The trajectory of the beam in x,x′ space is then modified from the original circle to one which is distorted according to the value of the tune and the strength of the sextupoles relative to the original betatron amplitude.

The tune of the machine can be altered by changing the values of the correction quadrupoles. The sextupole strength can be altered both by increasing the current or the number of sextupoles. The betatron amplitude of the beam centroid (essentially the starting x′ coordinate) can be varied by changing the strength of the pinger magnet.

Another variable at our disposal is the periodicity of the sextupoles in the lattice. By using more than one sextupole, we can place them such that their lowest order effects can be either enhanced to create effects which are more easily measured or cancelled to allow the higher order effects to be more easily viewed. Figure 6 shows the x,x′ plot for the case of a tune near a third integer (19.333) with sextupoles powered to drive the third integer resonance. The triangle drawn on the figure is the calculated limit of stability, the separatrix.

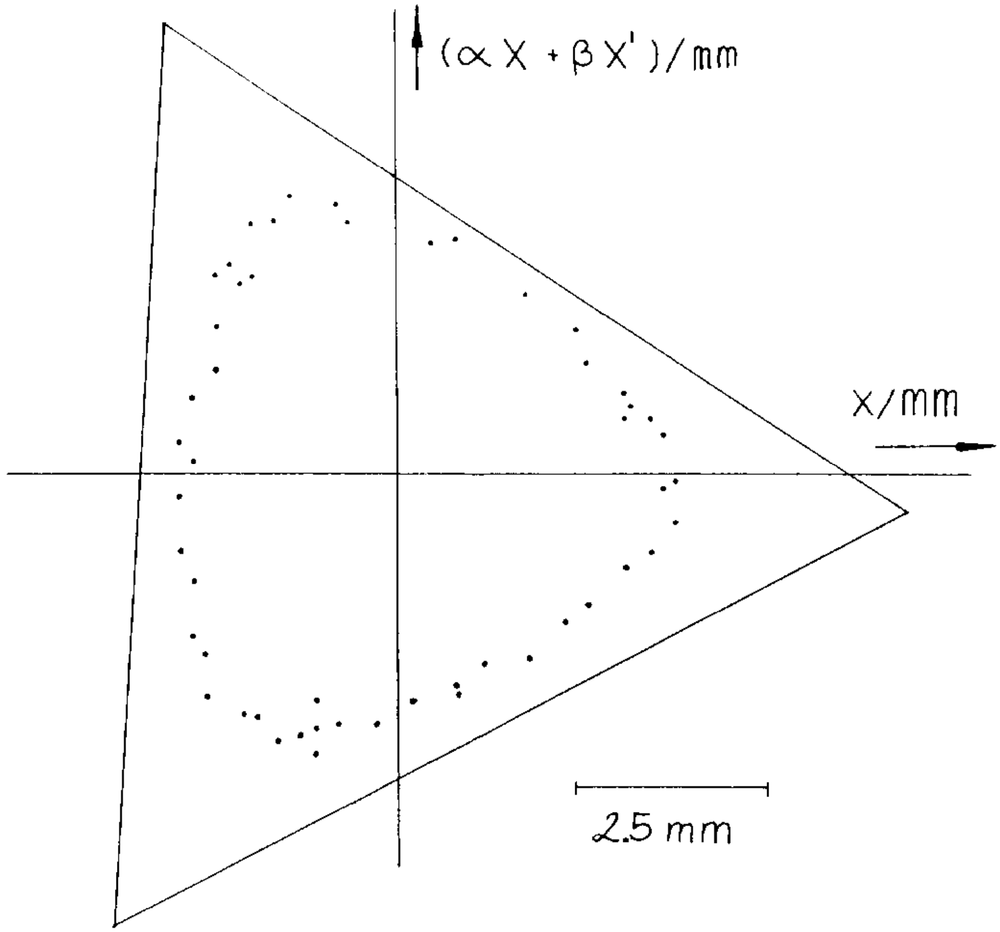

FIGURE 6 The x,x′ plot for the case of a tune near a third integer (19.333) with sextupoles powered to drive the third integer resonance. The triangle drawn on the figure is the calculated limit of stability, the separatrix.

With the horizontal tune near 19.25, the distortion of the phase space trajectories due to the sextupoles can be measured and compared to predictions, among which is a contribution to the quarter-integer resonance width that is second order in the sextupole strength. These comparisons are only just beginning and detailed results are not yet available. As an indication of the technique, figure 7 shows the phase space trajectories for the case where the sextupoles are powered in such a way as to compensate 1/3 integer driving terms.

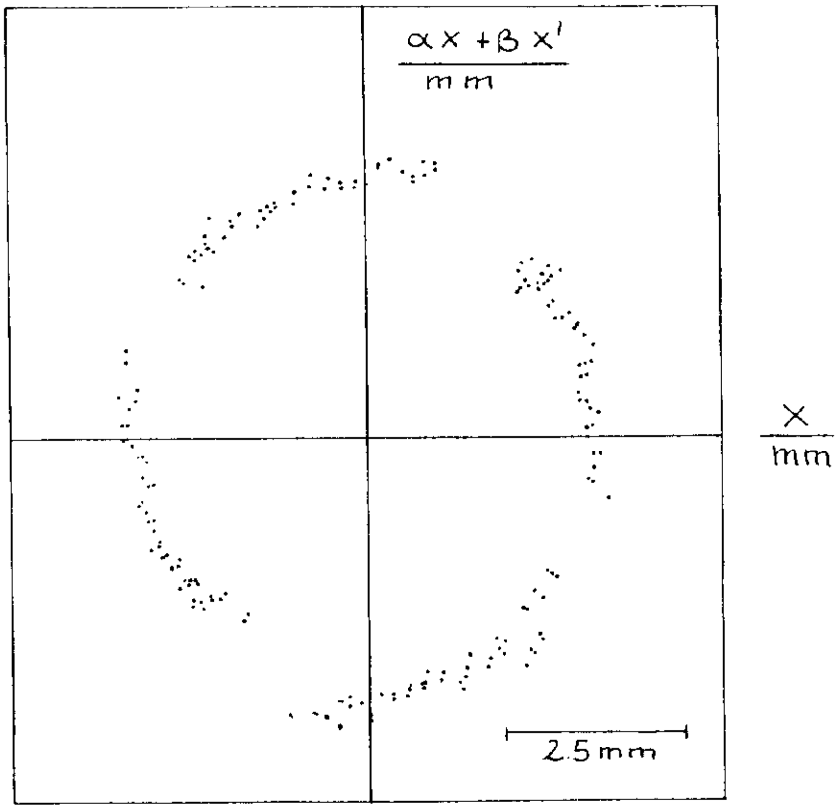

FIGURE 7 The phase space trajectories for the case where the sextupoles are powered in such a way as to compensate 1/3 integer driving terms and enhance 1/4 integer driving terms. The tune is near 19.25.

The distortion of the circle to the observed square shape is the expected result of the additional sextupole fields. The usual definition of the "dynamic aperture" is the largest inscribed circle on the x,x' plot which contains no unstable trajectories. In this square distortion of the trajectories due to the sextupoles one can see that the radius of the inscribed circle diminishes. This is a direct way to see the higher order effects of sextupoles on the dynamic aperture.

Detailed, quantitative comparisons of the measured and calculated phase space distortions due to sextupole fields are yet to be made. They will involve understanding the actual emittance and momentum distribution of the beam. Eventually, and this is the real point of the exercise, we must understand the interplay of these experimental sextupole fields with the existing multipole errors of the magnets in the Tevatron.

CONCLUSIONS AND FUTURE PLANS

Although our technique for studying the evolution of trajectories in multi-dimensional phase space is in its infancy, the preliminary results are very encouraging. At the very least, we have started making detailed comparisons of measurements and calculations of orbital dynamics involving nonlinear elements in a proton synchrotron. We have also seen that the data from the Tevatron are easily interpreted, requiring little processing to demonstrate the consequences of changes in the tunes and sextupole fields. Further refinements in experimental technique have been suggested and are being investigated. One such suggestion is that the phase space trajectories for the horizontal and vertical planes be acquired and displayed to investigate coupling phenomena.

We are exploring other experimental methods to be used to compare the results of tracking or perturbation calculations on the expected performance of accelerators. These are more indirect than measuring phase space trajectories and usually involve measurements of lifetimes of stored beams as a function of betatron amplitude. Some interesting results have been obtained using the flying wire profile monitor in conjunction with beam current monitors.

We expect to make specific experiments to test the programs which are being used in the SSC design effort. These will be directed toward understanding how the dynamic aperture is determined by the magnetic multipole errors of the superconducting magnets. As well, questions of numerical accuracy for iterative calculations will be examined by using the Tevatron as an analog computer with the power to track 10^{13} particles at almost 50,000 turns per second.

ACKNOWLEDGEMENTS

We thank David Finley, Rod Gerig, and Karl Koepke for assistance in acquiring the data presented here. We are indebted to Al Russell for a variety of calculations using his program TEVLAT. We thank Helen Edwards, Leo Michelotti and Sho Ohuma for valuable discussions.

REFERENCES

1. R. E. Shafer and R. E. Gerig, Proceedings of the 12th International Conference on High Energy Accelerators, 1983, p609.
2. F. Willeke, "Using the Tevatron Beam Position Monitor System to Examine Transverse Phase Space", Fermilab TM-1309 (April 1985).
3. RACETRACK, a tracking program developed by A. Wrulich, DESY, and F. Willeke,"Study of the Tevatron Nonlinear Acceptance by Computer Simulation", Fermilab TM-1220 (November, 1983).