Helical Orbit Studies in the Tevatron

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Abstract

The Tevatron is currently running vary close to the beam-beam limit. Therefore, in order to increase the luminosity the proton and antiproton beams have to be separated to eliminate unwanted beam crossings. To achieve this beam-beam separation the proton and antiproton beams must travel on separate helical orbits, except at the collision areas. Particles moving on helical orbits in the Tevatron have both their tune and coupling changed with no measurable change in their chromaticity or lifetime. The tune and coupling changes are due to b_2 multipole errors in the main bending magnets. The size of the changes depends on the phase of the helical orbit relative to the distribution of b_2 errors around the ring. For the upgraded Tevatron with separated orbits the protons and antiprotons live on different helical orbits. Therefore, the antiprotons are tune shifted relative to the protons by ~ 0.01 in both the horizontal and vertical planes, and experience a different skew quadrupole field (Q_s) of $\sim 0.2 \times 10^{-2}$ m^{-1}. These differences can be removed by suitably located sextupoles whose feed down normal and skew quadrupole terms cancel the equivalent effect produced by the b_2 feed down of the main bending magnets.

Introduction

For a given β^* one can raise the Tevatron luminosity by increasing N/ϵ in the bunch, or by having more bunches circulating in the ring. In either case, the proton antiproton bunches have to be kept apart, except at the collision areas, in order to minimize the antiproton beam-beam tune spread or equivalently the linear beam-beam tune shift ($\Delta\nu_{bb}$). The size of the beam-beam tune shift is proportional to the number of crossing points. Currently the Tevatron operates with 6 bunches of protons and antiprotons and therefore 12 crossing points around the ring. When separators are installed the number of crossing points will go from 12 down to 2. Thus reducing the beam-beam tune shift to $1/6^{th}$ of its present value. This number can be further reduced by increasing the number of bunch while decreasing the bunch intensity. Beam separation can be provided by electrostatic deflectors or "separators" distributed around the ring.

The arrangement of electrostatic separators in the Tevatron has been discuss elsewhere[1]. The intent of this paper is to report on a series of experiments preformed in the Tevatron, to study the beam dynamics of particles traveling on orbits similar to ones the separators are expected to produce. First, helical orbits are discussed and a simple model is presented to estimate the change in the behavior of a beam when placed on such an orbit. Second, the results of the experiments are reported and compared to this model. Finally, a scheme for correcting these effects is proposed.

Helical Orbits

Particles moving on a helical orbit in the Tevatron experience normal and skew quadrupole fields in addition to those produced by the tune and coupling circuits. These quadrupole fields are generated by the multipole field errors in the Tevatron magnets feeding down onto the nonzero closed orbit. The magnitude of these quadrupole fields depends on the distribution of multipole errors around the ring and the phase of the orbit distortion relative to the multipole errors (phase of helix). When the proton and antiproton closed orbit is one and the same orbit these additional fields are of little concern for they can easily be compensated with existing quadrupole circuits around the ring. However, when the orbits are separated the particles on each orbit experience different normal and skew quadrupole fields and quadrupole circuits cannot remove these differences.

To simplify the discussion it is assumed that the only multipole field error of importance is b_2 in the main bending magnets in the Tevatron. This is a good assumption for the amplitudes of the helix that are being considered here. This field is expressed as:

$$B_y + iB_x = B_0 b_2 (x + iy)^2 \tag{1}$$

where B_0 is the dipole field strength, and (x, y) is a position of the beam in the magnet relative to the center of the magnet. This location can be recast in terms of the closed orbit relative to the magnet center (x_c, y_c) and the betatron oscillation amplitude about the closed orbit (x_β, y_β).

$$x = x_\beta + x_c \tag{2}$$

$$y = y_\beta + y_c \tag{3}$$

Then the effect of b_2 can be expressed in terms of a four-by-four transfer matrix by substituting equation (2) and (3) into equation (1) and keeping only those terms which are linear in x_β and y_β. Thus giving:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ -2\frac{B_0 L}{B_\rho} b_2 x_c & 1 & 2\frac{B_0 L}{B_\rho} b_2 y_c & 0 \\ 0 & 0 & 1 & 0 \\ 2\frac{B_0 L}{B_\rho} b_2 y_c & 0 & 2\frac{B_0 L}{B_\rho} b_2 x_c & 1 \end{pmatrix}$$

where L is the length of the magnet. The tune change ($\Delta\nu$) can be extracted from the normal quadrupole term of the matrix.

$$\Delta\nu_{x,y} = \frac{1}{2\pi}\frac{B_0 L}{B_\rho}\int \beta_{x,y}(s) b_2(s) x_c(s) ds \tag{4}$$

$\beta_{x,y}(s)$ being the beta function around the ring. When discussing skew quadrupole effects it is convenient to define a quantity:

$$Q_s = \int ds B'/B_\rho \tag{5}$$

where $B' = dB_x/dx$. The change in Q_s can be extracted from the skew quadrupole term of the matrix.

$$\Delta Q_s = 2\frac{B_0}{B_\rho}\int b_2(s) y_c(s) ds \tag{6}$$

In the next section these predicted changes are compared with the measurements. The values used for $b_2(s)$ are the measurements made at the Magnet Test Facility on each magnet before it was installed together with it's location in the ring.

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Results of Helical Orbit Studies

The experimental procedure throughout the study period is to inject a single bunch of $\sim 60 \times 10^9$ protons into the Tevatron and store it at 150 GeV. Then the tunes, coupling, chromaticity, and emittance are monitored. The coupling is minimized (minimal tune split $\nu_x - \nu_y \leq 0.002$) using the skew quadrupole circuit which consists of 48 skew quadrupole symmetrical located around the ring. The horizontal and vertical tune circuits are adjusted so that the horizontal and vertical tunes as measured by shottky plates are 0.42 and 0.41, respectively. The chromaticity is adjusted to be ~ 2 units using the chromaticity sextupoles. The emittance of the bunch is typically 15π mm-mrad.

The experiment consisted of creating a helical closed orbit in the Tevatron using correction dipoles. A horizontal correction dipole at B48 and a vertical correction dipole at C23 are used to produce the orbits show in Figure 1. These orbits are similar to the injection orbits that the protons and antiprotons will have when the separators are installed. They also represent the orbits with the largest orbit distortions. Since as the beams are accelerated the magnitude of the orbit distortion becomes smaller. Since $\Delta\nu$ and ΔQ_s in our simple model scale with the magnitude of the orbit distortion, this orbit should show the largest variation in these parameters.

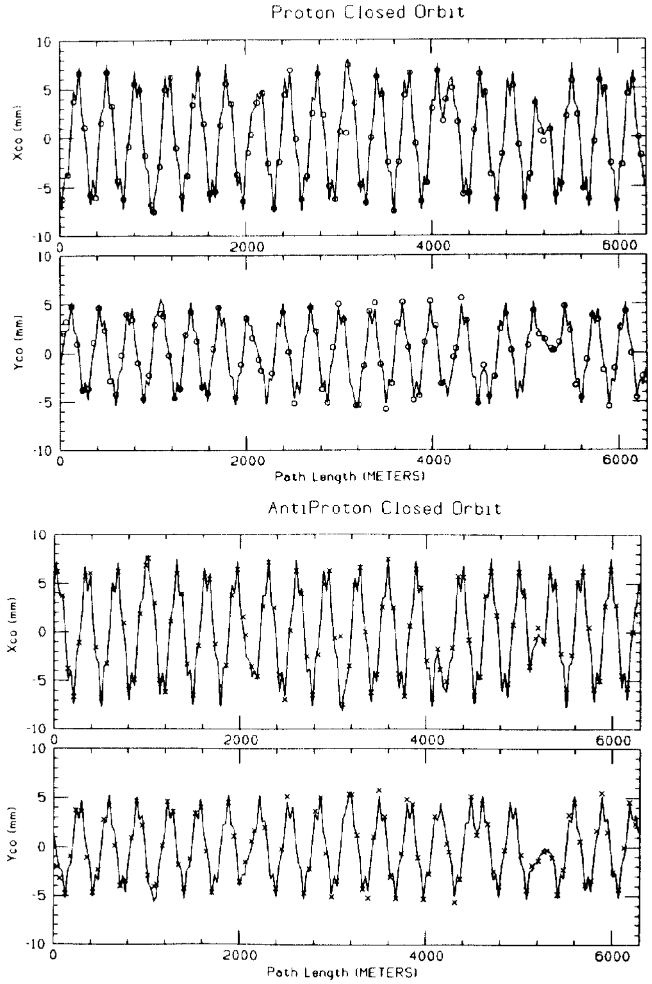

Figure 1: 150 GeV orbit for the protons and antiprotons: solid line is from a SYNCH simulation, and the dots and x's are the BPM readings of the actual orbitin the Tevatron.

The magnitude of these two bumps are then scaled by a common factor. Thus producing a helical orbit whose amplitude (x_c, y_c) is proportional to this scale factor (the plot refers to this scale factor as "fraction of helix"), but the phase of the helix remains fixed relative to the random error distribution.

For each scale factor setting between 1 and -1 the coupling is minimized and the skew quadrupole setting (Q_s) is recorded. Then the tune circuit is adjusted so that the measured horizontal and vertical tunes are 0.42 and 0.41, respectively. The settings ($\Delta\nu_{x,y}$ is equal to the change in these settings) of the horizontal and vertical tune circuits are recorded. The chromaticity and emittance are also measured. The results of these measurements are shown in figure 2. The points are the measured values and the curves are the predictions of our simple model. Inclusion of higher order multipoles (up to and including decapole) and chromaticity sextupoles into our model changed the predicted values of $\Delta\nu$ and ΔQ_s by less than 10% which is comparable to the measurement error.

The phase of the helix relative to the random errors was changed by choosing a different pair of correction dipoles which shift the phase of the helix by $\sim 60°$. The measurements are then repeated using this phase shifted helix. The results of this experiment are also shown in figure 2. The dashed curves show the prediction of our model and the x's are the measurements.

As is indicated by the measurements and equations (4) and (6) $\Delta\nu_{x,y}$ and ΔQ_s are proportional to the amplitude of the orbit distortion (helix). The proportionality constant is related to the phase of the helix.

For the proposed separation scheme the model predicts a horizontal and vertical tune shift for particles on the proton orbit with respect to particles on the antiproton orbit of ~ 0.01, and a change in Q_s of 0.2×10^{-2} m^{-1} at 150 GeV. The chromaticity of the beam on these helical orbits was measured and the change if any was less than the measurement error which is estimated to be $\sim \pm 2$ units. The calculated change in the chromaticity due to octupole feed down is less than 1 unit. The beam lifetime on these helical orbits was compared to that of a smoothed closed orbit where the beam went down the center of the magnets, and no differences were observed. It was found to be $\sim 14 \pm 1$ hours at 150 GeV.

Correction Scheme

The variation in the tune and coupling is directly proportional to the amplitude of the helix (fraction of helix). Therefore, the effect on the antiproton orbit is equal in magnitude but opposite in sign to that on the proton orbit. Thus making it impossible to compensate for these differences with quadrupole circuits. However suitably placed sextupoles can produce the needed compensation. This can be seen by examining the form of a normal sextupole field. The field created by a normal sextupole can be written as:

$$B_y + iB_x = 2B''(x + iy)^2 \qquad (7)$$

where $B'' = d^2B_y/dx^2$. As one would expect this is identical to equation (1) if $B_0 b_2$ is substituted for $2B''$. Therefore, if sextupoles are placed at locations such that the so called feed down normal and skew quadrupole terms cancel similar terms created by b_2 feed down, the tunes and coupling on both the proton and antiproton orbits will be the same. At the time this paper is being written experiments are being carried out to see how well such a correction scheme will work in the Tevatron. Preliminary results indicate that existing sextupoles in the Tevatron should be able to compensate the effect of b_2 feed down.

References

1. E. Malamud,"Tevatron Orbit Separator Design", Snowmass, 1988

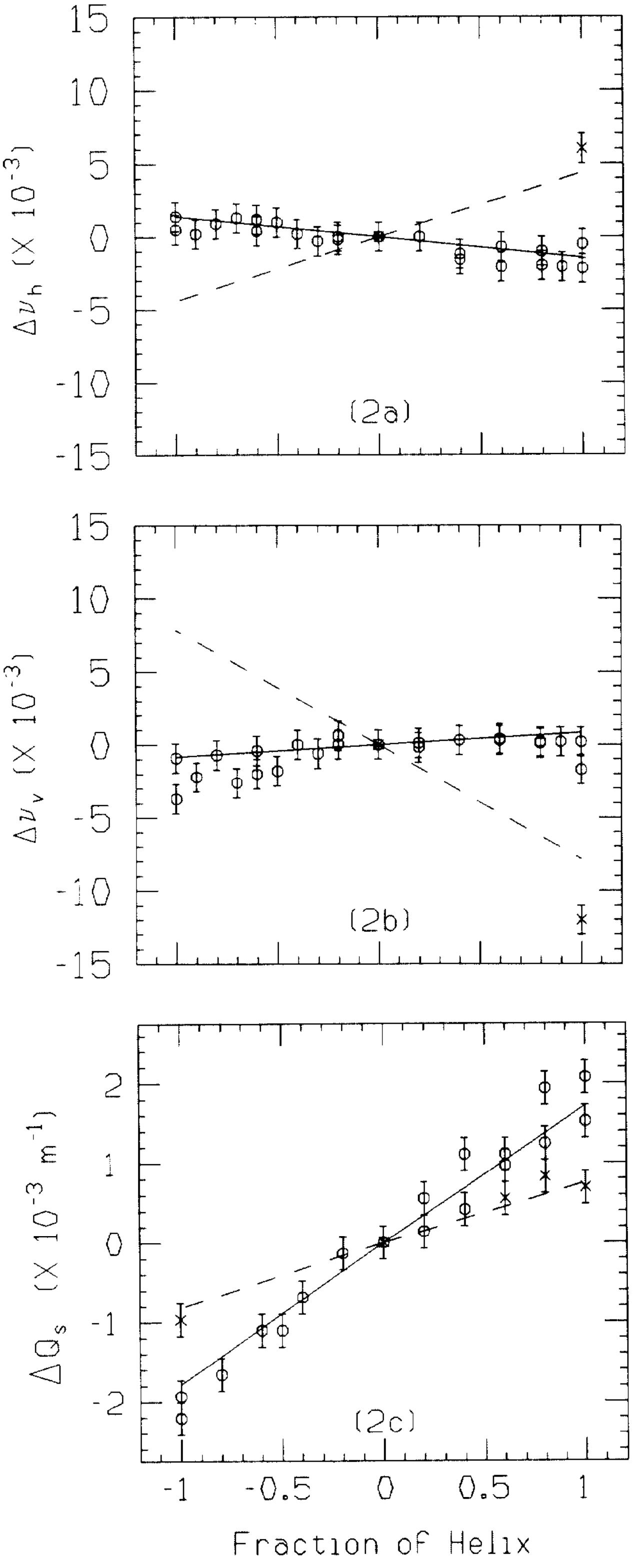

Figure 2: Figures 2a, 2b, 2c are the changes in horizontal tune, Vertical tune, and skew quadrupole, respectively, vs fraction of helix. The solid curve is the prediction from our simple model and the dots are the measured values. The dashed line and associated x's are the predicted and measured values when the phase of the orbit distortion is changed.