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Beam-beam Interaction Effects for Separated Beams in a Proton-Antiproton Collider

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Abstract

An investigation of the beam-beam interaction as a function of transverse separation of colliding proton and antiproton bunches is presented. Resonant excitation (particle losses) was experimentally observed at different transverse beam separations in a large storage ring. Experimental results were compared to simulated particle losses in a beam-beam simulation model.

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I. INTRODUCTION

The electromagnetic interaction between two colliding particle distributions (the beam-beam interaction) has in the past been a dominant factor in limiting the integrated luminosity in a colliding beam storage ring. [1] Efforts to curb this measurable luminosity limitation in the Fermilab Collider led to an implementation of a helical orbit scheme; proton and antiproton orbits were separated in both transverse planes at every beam-beam collision point except for the two crossing points at the high energy physics detectors. An investigation of beam-beam interaction effects of colliding proton and antiproton distributions which are separated transversely is presented in this paper.

A weak-strong model of the beam-beam interaction is used to define the motion of a "weak" or low intensity bunch colliding with a "strong" or high intensity bunch. In the Fermilab Collider, a weak-strong picture of the beam-beam interaction translates to an antiproton bunch colliding with the static electromagnetic field generated by a round, Gaussian and short proton bunch. Antiprotons, in a weak-strong model, are the main focus of attention as test particles. Each test particle differs in their amplitude (a_x, a_y, a_s).

A two-dimensional Hamiltonian of a weak-strong colliding beam system is defined as

$$H(x,p_x,y,p_y;s) = \frac{1}{2}(p_x^2 + K_x x^2) + \frac{1}{2}(p_y^2 + K_y y^2) + V(x,y) \sum_{l=-\infty}^{\infty} \delta[s - (2\pi R l)] \quad (1.1)$$

where p_x and p_y are the canonical momenta associated with a particle's transverse positions in the horizontal and vertical planes, respectively. The summation over l is a summation of the periodic crossing points in which a particle receives a localized beam-beam kick. The focusing strengths K_x and K_y correspond to the magnetic element (quadrupole, for example) that is located at the azimuthal location s in the storage ring.

At a single crossing point, the equations of motion described by the Hamiltonian of Equation 1.1 are

$$\frac{dz^2}{ds^2} + K_z(s)z = -\frac{\partial V}{\partial z}\,\delta[s], \quad z \equiv x, y. \quad (1.2)$$

The beam-beam potential for a particle colliding with a Gaussian charge distribution is given by

$$V(x,y) = \frac{N r_p}{\gamma_{rel}} \int_0^\infty dt\, \frac{1 - \exp\left[-\frac{(x-d_x)^2}{2\sigma_x^2+t} - \frac{(y-d_y)^2}{2\sigma_y^2+t}\right]}{\sqrt{2\sigma_x^2+t}\sqrt{2\sigma_y^2+t}}. \quad (1.3)$$

The transverse rms of the Gaussian charge distribution is given by σ_x and σ_y. The parameters d_x and d_y denote the transverse separation in the horizontal or vertical plane between the closed orbit of the antiproton and the centroid of the colliding proton distribution. In the case of head-on collisions ($d_x = d_y = 0$), the symmetry of the potential expression dictates that only even ordered resonances will be driven. An expansion of the exponential term in the potential gives terms of order $x^{2n}y^{2m}$, where n and m are integers. Odd-ordered resonances require the symmetry of the potential to be broken, and are present when the beams are separated transversely or a crossing angle is present at a collision point. (For more discussion, see [2], [3] or [4], for example.) Since it of interest in this work to investigate the beam-beam interaction as a function of beam separation, resonant effects of odd-ordered resonances are examined.

Section II presents measured resonant effects due to odd-ordered resonances in the presence of a transverse separation at a beam-beam crossing point. Section III compares the experimentally measured resonant effects to that measured in a beam-beam simulation code. Inherent problems in analysis of the beam-beam simulation results are discussed. The results of the beam-beam investigation are summarized in Section IV.

II. BEAM-BEAM EXPERIMENTS IN THE FERMILAB COLLIDER

Beam separation is defined as the offset of the zero amplitude orbit of an antiproton distribution from the centroid of a colliding proton distribution. Units of beam separation are expressed in terms of the rms transverse beam size of the proton distribution and are denoted by σ. Control of beam separation and crossing angle is obtained using separator four-bumps. [5] A measurable accuracy in beam separation and crossing-angle is determined by measuring the luminosity as beam separation and crossing angle is varied. Luminosity as a function of separation and crossing angle along with a fit to the data is shown in Figures 1 and 2, respectively. The standard deviation of the Gaussian fit in Figure 1 is the convolution of individual proton and antiproton widths; $\sqrt{{\sigma_{p_y}}^2 + {\sigma_{\bar{p}_y}}^2}$ [5]. Assuming equal beam sizes, the accuracy of beam separation is estimated from the accuracy in the standard deviation obtained from the Gaussian fit.. From Figure 1, the accuracy in beam separation is thus estimated to be known within 0.05σ.

A. Identification of Beam-beam Driven Resonances

Measured proton and antiproton tunes in the Collider are nominally in an area in betatron tune space that border 7th and 5th order resonances. Under separated beam conditions, a measure of proton losses during tune scans were used to identify whether these odd-ordered resonances were beam-beam driven resonances. Figure 3 compares measured proton losses as the proton tune is moved across 5th order resonances for a proton only store of six bunches and a 6×6 colliding beam store. It is evident from the measured losses that the 5th order resonance is driven both by the Collider lattice itself and by the beam-beam interaction between colliding protons and antiprotons. Proton losses are seen to be significant only in the case of tune scans with colliding beams when crossing 7th order resonances in Figure 4. From these measurements, it is concluded that the beam-beam interaction is the sole driving term which at least initially drives 7th order resonances in the Collider. Once a particle's amplitude grows due to nonlinearities of the beam-beam interaction, it can be lost because of non-linear kicks it receives from elements in the Collider lattice itself.

B. Resonant Effects as a Function of Transverse Beam Separation

Measurements of beam-beam interaction effects as a function of beam separation were done using a 1×1 colliding beam store; one proton bunch colliding with one antiproton bunch at two locations in the storage ring. The two bunches were set to collide at the B0 high energy physics detector and consequently collided at the opposing E0 location in the Collider. In the experiment, separation of the colliding protons and antiprotons was varied at B0 while the separation at E0 remained constant at an rms separation of 4σ. Particle losses were measured at four locations in tune space, as labeled in Figure 5. The uncertainty in the measured proton tune at each location is represented in the figure. This tune error is the standard deviation of four tune measurements taken for four different beam separations at the same proton tune settings, or equivalently, correction quadrupole current settings. There exists a transient behavior of particle losses during a tune change, therefore measurements of particle losses were taken only after losses reached an equilibrium value after a tune change. [5] Figure 6 represents particle losses at each labeled tune location under conditions of four different transverse beam separations; the orbits were separated equally in each plane by $0\sigma, 1\sigma, 2\sigma$ and 3σ. The rms beam separation was thus 0σ, 1.4σ, 2.8σ and 4.2σ, respectively.

Resonant effects at each tune location are assumed to be related to the measured antiproton losses. From Figure 6, antiproton losses are minimal for head-on collisions in all cases; this result is expected in a region of odd-ordered resonances. At the tune setting of Measurement 1 in Figure 6, antiproton losses are minimal for both head-on collisions and for separated beam conditions. This is the operating tune for typical colliding beam stores in the Collider. No beam-beam driving terms are observed to strongly drive 9th or 11th order difference resonances. The presence of beam separation is seen to excite odd-ordered sum resonances at the tune locations of Measurements 2 and 3. In Measurement 2, the largest resonant effects are observed at an rms separation of 2.8σ separation. In Measurement 3, resonant effects are largest at 4.2σ separation.

III. RESONANT EFFECTS MEASURED IN A BEAM-BEAM SIMULATION

The simulation code developed to simulate resonant effects in the Fermilab Collider was based on a previously developed code. [6]

The model used for the simulation is concerned only with particle motion due to the beam-beam interaction. The motion of a particle between beam-beam crossing points is assumed to be linear motion. The particle experiences an angular kick due to the beam-beam interaction at each beam-beam crossing point. The beam-beam kick of magnitude $\Delta x^{'}$ and $\Delta y^{'}$ is calculated for non-round beams in the simulation. A vertical kick in the simulation is given by

$$\Delta y^{'} = -\frac{2N_b r_p y}{\gamma}\sqrt{\frac{2\pi}{a^2-b^2}}\cdot\mathcal{R}\left[f(x,y)\right], \qquad (3.1)$$

where

$$f(x,y) = w\left(\frac{x+iy}{\sqrt{2(a^2-b^2)}}\right) - \exp\left[\left(-\frac{x^2}{2a^2}-\frac{y^2}{2b^2}\right)\right] w\left(\frac{x\frac{b}{a}+iy\frac{a}{b}}{\sqrt{2(a^2-b^2)}}\right) \qquad (3.2)$$

for $a > b$. [7], [8] The parameters a and b denote the horizontal and vertical bunch sizes of the colliding proton distribution. The function $w(A+iB)$ is the complex error function. In Equation 3.3, the real part of the square brackets is used to calculate the vertical kick and the imaginary part would be used to calculate the horizontal kick.

In order to calculate a particle's tune q in the presence of a non-zero beam separation, it is necessary to calculate the gradient of the beam-beam kick around the closed orbit of the particle [5];

$$q \propto \frac{\partial(\Delta x')}{\partial x}. \qquad (3.3)$$

The dipole kick, apparent when the integral is evaluated for zero-amplitude particles, is present as a constant orbit kick. It is independent of a particle's amplitude. Thus the tune of a particle does not change due to the dipole kick, only the particle's closed orbit. The change in a particle's closed orbit due to the dipole kick is negligible for small kicks but is large for sizeable kicks. This orbit change can easily be computed. [9], [10] The orbit change has also been verified and observed at LEP where it eventually limited the luminosity when LEP operated with bunch trains in 1995. [11]

The change in the closed orbit reference system must be taken into account in the simulation. A subtraction of the dipole kick is necessary to bring the reference system back. The beam-beam kick used in the simulation code is obtained by subtracting out the dipole kick contribution.

$$\Delta x^{'}_{total} = \Delta x^{'}(y+d) - \Delta x^{'}(d). \qquad (3.4)$$

It is assumed in this analysis that the particle's closed orbit is essentially stable; no coherent dipole motion is driven by the beam-beam effect. Such a coherent dipole motion is excited when the coherent pi-mode is close to a low order resonance (first and second order in the case of beam-beam kicks from quasi head-on collisions) and would result in a very fast loss. [11] In any case, the pi-mode would become very prominent in the tune spectra. Such a coherent motion is therefore easy to detect and to avoid by an appropriate choice of the tune.

Figure 7 displays the simulated tune footprints for the antiproton distribution of Measurement 2 of Figure 6. Resonant effects are not shown in the figure; the footprint was obtained from simulation runs in a "resonant-free" region and overlaid on the proton tune of Measurement 2. Each plot in the figure represents the tune footprint for four different beam separations.

Note that there is a shift in the cross-hairs of Figures 6 and 7. The proton tune in the simulation represents an unshifted proton tune; protons are not beam-beam tune shifted in a weak-strong model. The proton tune of Figure 6 is a measurement of proton tune using Schottky detectors in the Collider. These detectors have been found to measure the coherent motion of protons. [12] It is assumed that the proton tune measurement in the Collider is representative of the tune of small amplitude protons. Since these protons are slightly beam-beam tune shifted in the Collider, the proton tune shown in Figure 6 must be tune shifted in the simulation in order to look at the proper resonant effects. The vertical tune in Figure 7 is shifted down and to the left by approximately 0.002 tune units to represent the unshifted proton tune of Measurement 2 of Figure 6. [5] In effect, Figure 7 is a qualitative picture of the initial tune spread of the antiproton distribution and indicates that resonant effects of the $7Q_x$ resonance are observed in the head-on case and for a beam separation of 1.4σ. Resonant effects of the $(1Q_x + 6Q_y)$ sum resonances are observed in Measurement 2 for beam separations of 2.8σ and 4.2σ.

Resonant effects were measured by monitoring the maximum amplitude reached by a particle during tracking. A particle was considered lost if it reached the tails of the Gaussian distribution; an amplitude limit of 3.5σ was defined in both the horizontal and vertical plane. In a Gaussian distribution of particles, 99.95% are within a 3.5σ amplitude range.

When simulating "lost particles", the absolute position of a particle at a given location in the ring is important. Since all amplitude particles in a particle distribution are kicked equally by the dipole kick, it is sufficient to add the orbit offset due to the dipole kick to the orbit offset measured during tracking. In the simulation runs presented, a maximum dipole kick of 4.2 μradians occurred at B0; the orbit offset due to this dipole contribution is 0.02σ which is a negligible effect.

Lost particles measured in beam-beam simulations were compared to the particle losses of the measurement points of Figure 6. A "simulated tune scan" measuring particle losses across the two seventh order sum resonances is seen in Figure 8. The horizontal axis represents a variation in the vertical proton tune. The horizontal tune remained constant. Note that there is a shift in the proton tune in which resonant effects are observed when comparing the horizontal axis of Figure 6 and Figure 8. This again takes into account the beam-beam tune shift of the small amplitude protons which was previously discussed.

The vertical axis of Figure 8 is a measure of % of particles lost, where

$$\%\,lost = 100 \times \sum_b \frac{w_b}{N_b} N_{Lb}. \qquad (3.5)$$

The factor w represents a Gaussian weighting factor imposed on the initial antiproton distribution. Particles are binned with bin index b according to initial amplitude and the number of particles per bin, N_b, is weighted using a Gaussian dependence. The range of amplitudes in each bin is 1σ. The number of lost particles in each bin is N_{Lb}.

Figure 8 displays particle losses across the particle tune spreads of Measurements 1 and 2. The figures display simulated lost particles with an imposed horizontal and vertical amplitude constraint, respectively. Each symbol in the plot represents a different transverse beam separation at B0. For completeness, simulations were also run at a beam separation of 5.7σ, which corresponds to a 4σ beam separation in both the horizontal and vertical planes. The resonant peaks in the tune scan occur at the $(1Q_x + 6Qy)$ resonance of Measurement 2.

A qualitative agreement between the simulation and the Tevatron loss measurements of Measurement 2 is observed. As is the case in the beam-beam experiment, simulated particle losses are low in the case of head-on collisions and for 1.4σ separation. Losses are predicted to be largest at a beam separation of 4.2σ. The next largest particle loss is predicted at a beam separation of 2.8σ. Figure 9 summarizes a qualitative comparison of particle losses measured at the tune setting of Measurement 2 in the Collider to peak particle losses observed in the simulation. The error in measured particle losses is a reflection of the fluctuation of losses during the measurement; each error bar represents the standard deviation of particle losses over a four to five minute period. Simulated losses is a loss rate obtained by

$$Simulated\ Losses(Hz) = \left(\frac{\%lost}{100} N_t\right)\left(\frac{1}{\Delta t}\right) \times SF. \qquad (3.6)$$

The total number of particles in the simulation is given by N_t. The time of tracking is Δt, where $\Delta t =$ (number of turns)$/f_{rev}$. The parameter SF is a constant scale factor which enables the comparison of loss measurements to be made on a unit slope ($SF = 400$ in this case). The error bars on the simulated losses is the statistical variation of the number of lost particles in the simulation.

Figure 10 summarizes a comparison of simulation results with Measurement 3. Particle losses driven by the $2Q_x + 5Q_y$ resonance are measured. Simulated losses are observed to be greatest at a beam separation of 2.8σ. The qualitative comparison of measured losses at different beam separations is in agreement with the measured losses observed in the Tevatron.

IV. SUMMARY

A comparison of beam-beam experiments with simulations led to a deeper understanding of the beam-beam interaction in the Tevatron Collider. Experimental work determined that the beam-beam interaction is the predominant nonlinear driving term which drives 7th order sum resonances in the Tevatron Collider. Odd-ordered resonances are found to be driven in the presence of a transverse beam separation or when a crossing angle at an interaction point is present.

Simulated particle losses using a beam-beam model are shown to accurately predict relative magnitudes of beam-beam resonant excitation at different transverse beam separations. At various tune settings, each representing a different resonant excitation, simulated particle losses as a function of beam separation were found to compare in a qualitative sense to measured losses in the Tevatron Collider. With such a strong correlation between experiments and beam-beam simulations, many possibilities exist for future studies. One such possibility is using a beam-beam simulation to predict minimum beam separation criteria for future bunch configurations in the Collider.

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FIG. 1. A MINUIT fit of measured luminosity vs. vertical beam separation of proton-antiproton collisions at B0.

FIG. 2. A MINUIT fit of measured luminosity vs. horizontal crossing angle of proton-antiproton collisions at B0.

FIG. 3. A comparison of proton losses measured at B0 while crossing 5th order resonances for protons only and a colliding beam store. The tune scan was "diagonal" in that the vertical tune was also varied during the tune scan from 20.545 to 20.645.

FIG. 4. A comparison of proton losses measured at B0 while crossing 7th order resonances for protons only and a colliding beam store. The horizontal tune remained constant at 20.585.

FIG. 5. Locations in tune space in which resonant effects were measured. The measured proton tune along with its uncertainty is depicted.

FIG. 6. Antiproton background losses at B0 when the proton tune is near 7th, 9th and 11th order resonances. Each symbol represents a different proton-antiproton bunch separation at B0.

FIG. 7. Antiproton beam-beam tune shift due to beam-beam detuning overlaid on the tune of Measurement 2. Tune shifts due to resonant effects are not shown. The proton intensity is 120×10^9. Beam-beam footprints represent collision points at both B0 and E0. Each plot represents a different beam separation at B0.

FIG. 8. Simulation of a 1×1 store measuring lost particles in a vertical tune scan. Lost particles in the top and bottom figure are defined with a horizontal and vertical amplitude limit, respectively.

FIG. 9. A comparison of measured particle losses to simulated particle losses for Measurement 2 of Figure 6. Each data point represents a different transverse beam separation at B0.

FIG. 10. A comparison of measured particle losses to simulated particle losses for Measurement 3 of Figure 6. Each data point represents a different transverse beam separation at B0.