Beam-beam Experiments in the Tevatron

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Abstract

The working point tunes in the Tevatron at 900 GeV are nominally in an area in betatron tune space that borders the 7th and 5th order resonances. An attempt will be made in this 1992 collider run to measure whether the beam-beam interaction plays an important role in driving resonances in this region of tune space. Experimental results which identify the beam-beam driven resonances are presented. An experimental method of ensuring head-on collisions in order to minimize odd-ordered resonance effects in the Tevatron is also presented.

INTRODUCTION

The tune shift and the tune spread caused by the beam-beam interaction dictated the installment of separators in the Tevatron for the 1992 collider run. The electrostatic separators separate the proton and antiproton orbits such that head-on collisions occur only at the location of the two high energy physics detectors. This reduced the tune shift for a store of 6 protons colliding with 6 antiprotons by a factor of 6. The analytical beam-beam tune footprint shown in Figure 1 represents the tune shift and tune spread of the antiprotons colliding head-on at the two collision sites in the Tevatron. The proton base tune is 20.58 in the horizontal plane and 20.575 in the vertical plane. The tune footprint is calculated using parameters representing the normal operating conditions of the collider run. A normalized emittance of 20π mm-mrad (using the 95% definition of emittance) for the protons and 16π mm-mrad for the antiprotons was used in the calculation, along with a momentum spread of 124 MeV for the 900 GeV beam. Bunch intensities of 120×10^9 and 50×10^9 are typical intensities for the protons and antiprotons, respectively.

This is the first collider run where the Tevatron collides protons and antiprotons at two interaction regions and separates the beams in two dimensions at all other crossing points in the storage ring. The experiments presented below were done in an effort to understand what adverse effects the beam-beam interaction may have in this new operational state of the Tevatron.

*Operated by the Universities Research Association under contract with the U. S. Department of Energy

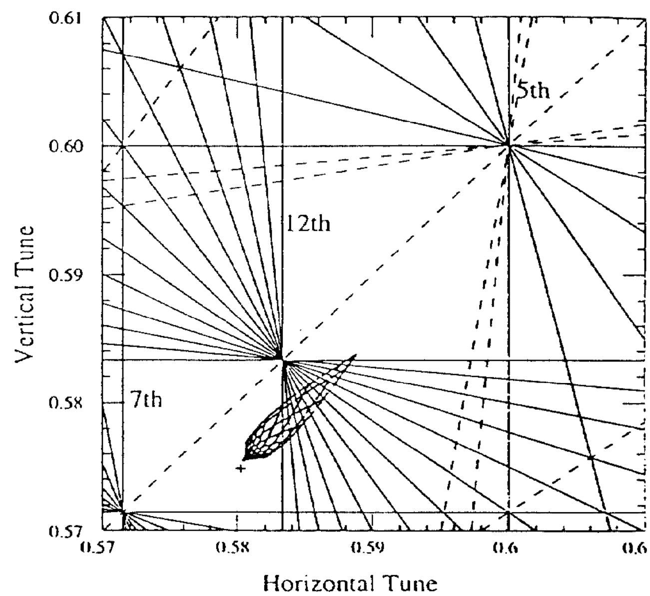

Figure 1: Antiproton beam-beam tune footprint in the Tevatron

BEAM-BEAM DRIVEN RESONANCES

In order to identify resonances driven by the beam-beam interaction, the proton tune was moved across resonances in both a proton only store and a store in which protons and antiprotons were colliding. Proton background losses were measured as a function of proton tune. The focusing and defocusing correction quadrupole circuits were used to change the tunes linearly at a constant rate of 0.01 tune units per minute. The tune signals were measured using Shottky plate signals sent into a spectrum analyzer.[1] Measurements of the tunes were taken at both end points of the tune scan. Loss monitors located at the physics detectors were used to measure proton background losses. The

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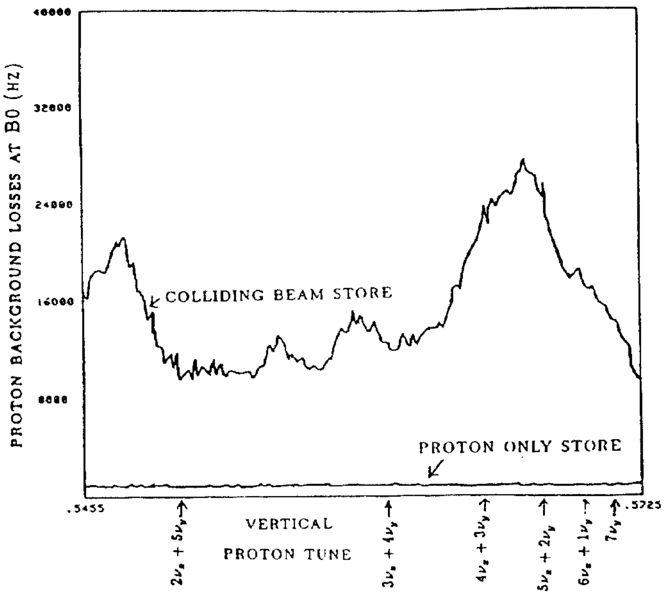

Figure 2: Proton losses crossing 7th order resonances for a proton only and a colliding beam store

colliding beam tune scans were done at the end of stores, when the proton and antiproton emittances were 25π and 18π, respectively.

A typical comparison of tune scans in which the proton vertical tune was moved across the 7th order resonance is shown in Figure 2. The horizontal tune of 20.58 was held constant during the scan. The result of the vertical tune scan show background losses to be large when the tune scan is done with protons and antiprotons in the machine, and negligible when protons only cross the 7th order resonance. Thus, in the Tevatron, the 7th order resonance gives measurable losses only when the beam-beam interaction is present.

When similar tune scans were done across 5th order resonances, background losses were seen when crossing some 5th order resonances during the proton only store. The losses became much larger when protons and antiprotons were colliding. This indicates that, along with a beam-beam driven response, there are nonlinearities in the Tevatron lattice which drive 5th order resonances.

A tune scan across the 12th order resonance, located in the midst of the Tevatron operating region, was found to cause minimal background losses under either proton only or colliding beam conditions. Proton and antiproton lifetimes, though, may be affected by the 12th and were not measured in this experiment.

Ensuring Head-on Collisions

The theory of the beam-beam interaction predicts that beams colliding with a separation or crossing angle will excite odd-ordered resonances[2]. The results of the tune scans, indicating that the $\frac{4}{7}$ resonance is strongly driven by the beam-beam interaction, led us to investigate the possibility that the beams were colliding with a small separation or crossing angle at the interaction points. In order to measure the effects of collisions which were not quite head-on, separator four bumps were used to control the proton and antiproton orbits as they crossed the interaction regions.

The separators provide an electrostatic field which causes the protons and antiprotons to get kicked in opposite directions. By using four separators as elements in a closed bump (one that is local to the region between the bump elements), we are able to control both the separation and crossing angle at which the protons and antiprotons collide. The locality of the bump and the location of the separators in the Tevatron enabled collisions at each of the physics detectors to be controlled individually. This is the method by which head-on collisions are obtained in the Tevatron.

An experiment was done in which separator four bumps were used to vary the transverse separation of the colliding protons and antiprotons. The luminosity was measured as a function of the beam-beam separation. A simple one-dimensional dependance of luminosity, $\mathcal{L}$, on the transverse separation, d, of the centroids of two gaussian particle distributions can be written as [3]

$$\mathcal{L} = \mathcal{L}_0 \exp\left(-\frac{d^2}{2\left(\sigma_p^2 + \sigma_{\bar{p}}^2\right)}\right) \tag{1}$$

$\mathcal{L}_0$ is the luminosity when the collisions are head-on and σ_p and $\sigma_{\bar{p}}$ are the transverse rms beam size of the proton distribution and antiproton distribution, respectively.

A typical separation scan is shown in Figure 3. In this separation scan, the magnitude of a separator four bump across B0 is varied to allow the vertical separation of the centroid of colliding protons and antiprotons to change. The magnitude of the bump is smaller than the resolution of the beam position monitors in the ring. It is predicted here using a model of the Tevatron, TEVCONFIG[4], which calculates an orbit for a given lattice configuration of the ring. By including the angular kicks of the separators used in the four bump, a predicted orbit is calculated. The magnitude of the voltage change of the separators can thus be translated into a beam-beam separation at B0. The luminosity is plotted in Figure 3 as a function of the beam-beam separation. A gaussian fit to the data calculates an rms σ of 62μ, where $\sigma = \sqrt{\sigma_p^2 + \sigma_{\bar{p}}^2}$ as seen in equation 1. The separation scans were done both in the horizontal and vertical planes at each of the interaction sites.

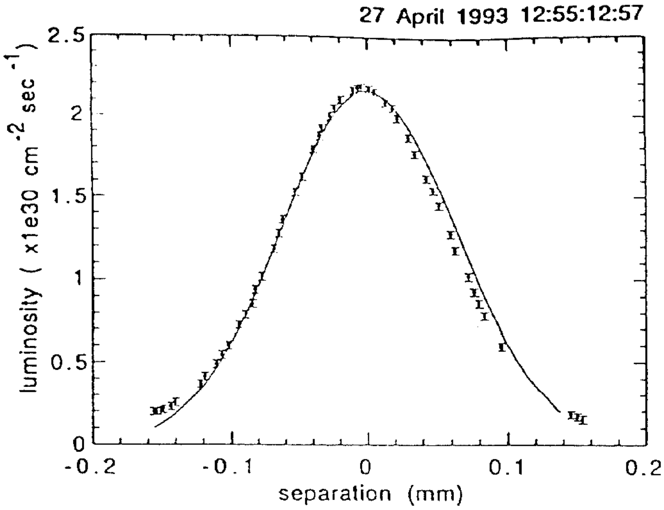

Figure 3: Separation Scan in the Vertical Plane at B0

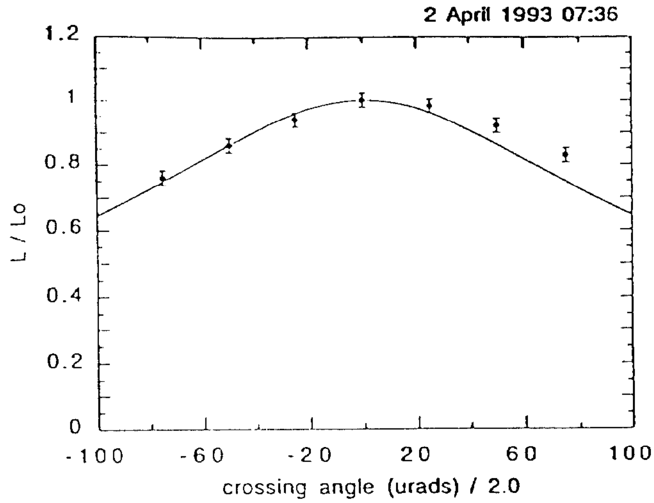

Figure 4: Crossing Angle Scan in the Horizontal Plane at B0

The measurement of σ can be compared to one which is done using the flying wires in the Tevatron.[5] Using the rms beam sizes which are obtained by this method, an rms σ of 57μ was calculated. The 8% discrepancy may be due to an inaccuracy in the lattice functions used in the calculations.

The luminosity was then measured as a function of the crossing angle at each of the interaction sites. A typical crossing angle scan is shown in Figure 4. In this case, the orbit distortion in the arcs is of the order of 1 mm, and the real orbit in the Tevatron can be compared to the TEVCONFIG prediction of the orbit. The data agrees within one LSB of the beam position monitors. A fit to the data is also shown, using a one-dimensional formula for the luminosity as a function of crossing angle[6].

$$\mathcal{L} = \mathcal{L}_0 \left(\sqrt{1 + \frac{\sigma_z^2}{\sigma_x^2} \delta^2} \right)^{-1} \qquad (2)$$

The crossing angle, δ, is defined as one half of the total crossing angle. The transverse sigma, $\sigma_x = \frac{1}{2}\sqrt{\sigma_{p_x}^2 + \sigma_{\bar{p}_x}^2}$, used as a parameter in the fit is 57μ. The longitudinal sigma, $\sigma_z = \frac{1}{2}\sqrt{\sigma_{p_z}^2 + \sigma_{\bar{p}_z}^2}$, is dependant on the longitudinal rms beam size of the protons and antiprotons. The value of σ_z used in the fit is 65 cm, comparable to a typical measurement of the rms of the longitudinal distribution in the Tevatron.

The results of the crossing angle scans indicate that under normal operation, the protons and antiprotons collide at the minimum measurable separation, but that there is a crossing angle of 50 urads (full crossing angle) at B0. This 50 urad crossing angle corresponded to a 5 percent loss in luminosity. After the separator voltages were adjusted for head-on collisions, a 5 percent increase in the initial luminosity was achieved.

Conclusions

We have found that when operating the Tevatron with two-dimensional helical orbits, the luminosity is optimized by varying the separation and crossing angle at each individual interaction region. In the future, we plan to use this method of orbit control to investigate how the $\frac{4}{7}$ resonance is driven by beam-beam effects when the protons and antiprotons collide with small separations or crossing angles.

References

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We would like to acknowledge David Finley for his helpful discussions and Paul Derwent for his help with the data analysis.