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SIMULATIONS OF BEAM-BEAM EFFECTS IN TEVATRON AND NONLINEAR MODE COUPLING ANALYSIS

C.S. MISHRA and S. ASSADI

Fermilab, Batavia, IL 60510, USA*

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The Fermilab accelerator complex is in the middle of an upgrade plan, Fermilab III. In the last phase of this upgrade the number of protons and antiproton bunches will increase from 6×6 to 36×36 and finally to 108×108 bunches. The luminosity of the Tevatron will increase by at least one order of magnitude. The Tevatron beam dynamics has been studied from the "Weak-Strong" representation of the beam-beam effects. A single particle is tracked using TEAPOT in the presence of the other beam.The nonlinearities introduced by beam-beam force introduces two unwanted effects: (a) It excites nonlinear resonances; (b) It introduces a dispersion of the tunes with amplitude. The strength of nonlinear three mode coupling satisfying the sum rules $Q_3 = Q_1 + Q_2$ is measured. These higher orders spectral analysis results will be presented.

Keywords: Beam-beam effects; computer simulations.

1 INTRODUCTION

The Fermilab Tevatron is a 1.8 TeV/c center of momentum proton-antiproton collider, delivering a peak luminosity greater than 2.E31 $\text{cm}^{-2}\text{sec}^{-1}$. In the current collider operation, six proton and antiproton bunches collide at B0 (CDF) and D0 interaction points. The two beams are kept separated in a helical orbit at ten other possible interaction locations by electrostatic separators, with average 5σ separation. During the Run 1b the average intensities of proton and antiproton bunches were increased by about a factor of two to 25E10 and 8E10 respectively.[1] Every attempt were made to keep the lifetime of the colliding beam high by adjusting the feed-down sextupoles.

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This allowed us to keep the tunes of proton and antiproton away from nearby resonances.

The calculations presented in this paper were started at the time when we had only one model[2] to study the Beam-Beam effects in the Tevatron. Preliminary results from these two model calculations for the Run II running conditions has generated considerable interest in the measurements and simulations of Beam-Beam effects at Tevatron.

The Fermilab III accelerator complex upgrade, including the Main Injector will increase the peak luminosity to 2E32 $\text{cm}^{-2}\text{sec}^{-1}$. Higher luminosity will be achieved by injecting more proton and antiproton bunches with similar intensities to present bunches. Number of bunches will increase from 6×6 to 36×36 and eventually to 108×108, to keep the number of interactions per crossing at each high energy physics detector at a manageable level. We have studied the change in tunes of particles, change in closed orbit and beam size as a function of bunch intensity and beam separations. We have studied this for 6×1 and 36×1 case. In this paper we present some general features of our calculation and introduce a new technique to analyze the non-linearity in the particle motion.

2 NUMERICAL SIMULATIONS

The beam dynamics of particles in the Tevatron has been studied from the Beam-Beam effect point of view in a "Weak-Strong" representation. This is modeled by tracking a single particle in the presence of a constant field of the other beam like those of any other fixed beam-line elements. All the calculations presented here are performed at 900 GeV for the setting when two beams are not colliding head-on at B0 and D0. The thin element tracking program TEAPOT[3] has been used for these simulations. The code TEAPOT simulates the passage of a single particle in the presence of an oncoming beam by a BEAM-BEAM element. The code takes as an input the transverse beam size, number of particles in the fixed beam, horizontal and vertical offset from the ideal orbit.

2.1 Tevatron Lattice

The Tevatron Lattice includes standard magnetic elements dipoles, quadrupoles, sextupoles, correction elements, and measured higher order multipoles

TABLE I Magnetic multipole errors used in the simulations

		Normal Errors		*Skew Errors*	
Magnet Type	*Multipole Order*	$\langle b_n \rangle$	σb_n	$\langle a_n \rangle$	σa_n
Dipole	quad	0.10	0.50	0.20	0.60
	sext	0.48	2.66	0.12	1.19
	8	–0.20	0.81	–0.10	1.42
	10	–0.64	1.33	–0.10	0.45
	12	–0.06	0.32	–0.06	0.55
	14	5.35	0.46	–0.12	0.29
	18	12.46	0.30	–0.08	0.36
Arc Quadrupoles	quad	–	19.2	0.25	0.45
	sext	1.98	3.69	2.83	3.41
	oct	1.25	0.93	–0.45	1.97
	10	–0.26	0.74	–0.72	0.80
	12	–1.91	1.70	0.21	0.44
	14	0.05	0.28	0.18	0.29
	18	–0.03	0.26	–0.10	0.22
	20	–1.66	0.32	0.19	0.29
Low Beta Quadrupoles	quad	–	19.2	0.25	0.45
	sext	0.62	1.88	–0.43	3.11
	oct	0.13	0.76	–0.30	0.99
	10	0.15	0.48	–0.25	0.65
	12	–3.38	1.62	–1.91	1.70
	14	0.05	0.30	0.11	0.37

for dipoles and quadrupoles. The higher order multipoles include both normal and skew components up to 18 poles for dipoles,[4] 20 poles for arc quadrupoles[5] and up to 14 poles for low beta quadrupoles.[6] The higher order multipoles are distributed about its mean value with a sigma, cut off at 3σ. Table I shows the magnetic multipoles as used in the lattice.

In TEAPOT there is no direct provision for electrostatic separator, so its function is achieved by providing a horizontal and vertical kick to the particles at separator locations. The Tevatron has four RF cavities per beam, each operating at Vrf = 0.2125 MV. The RF frequency is set to 53 MHz corresponding to a harmonic number of 1113. We introduce the RF cavity in the lattice to study the coupling between the transverse betatron oscillations and the longitudinal synchrotron oscillations. These coupling resonances get excited by single beam effects arising from dispersion in accelerating cavities, transverse fields that vary over the bunch length and beam-beam effects.

Misalignment of all the magnetic elements and beam position monitor has been included in these calculations. The sigma of the alignment error with respect to closed orbit is 0.25 mm in both horizontal and vertical directions. The dipoles and quadrupole magnets have a roll angle deviation of 0.5 mrad. The horizontal and vertical correctors are used to correct for closed orbit error due to these errors.

Quadrupole strengths and separator kicks are input from the Tevatron controls page. The strengths of the trim quadrupoles were adjusted to set the Tevatron tune to the desired value (Qx,Qy) = (20.583,20.574), as is done in the experiment. The two sextupole families are used to set the chromaticity of the Tevatron to (Cx,Cy) = (20,24). All the launched particles have $\Delta p/p = 0.0001$. The Tevatron has four sets of skew quadrupoles. Coupling is introduced in the lattice error fields present in dipole and quadrupole magnets and rolled quadrupoles. Skew quadrupoles are used to globally decouple the Tevatron. Decoupling at the interaction regions are also performed using the skew quadrupoles present near the interaction regions and other skew quadrupoles in the lattice.

2.2 Calculations and Results

The beam size in the Tevatron is measured at E17 location using flying wire. At 900 GeV the beam dimensions are measured to have a RMS of 0.35 mm in both planes. We have used the beta-function of the Tevatron to calculate the beam size at all the points where two beams crosses each other. The separation of the two beams is maintained on the helical orbit by offsetting the beam-beam element as if it was an opposing beam. We study the effect of antiproton bunches on a single proton. In 6×1 and 36×1 calculations the single tracked proton crosses the antiproton bunches at 12 and 72 locations respectively. The particles are launched with these amplitudes at maximum beta of 125 meters and with x amplitude equal to y amplitude. The large amplitude particles are closer to the fixed beam beam elements and particles with small amplitudes radially move away from it. Simulations of the 36×1 case takes into account one of the present loading scheme planned for Run II operations.

Figure 1 shows the change in horizontal and vertical tunes of a small amplitude (1.0 mm at maximum beta) particle as a function of beam intensity.

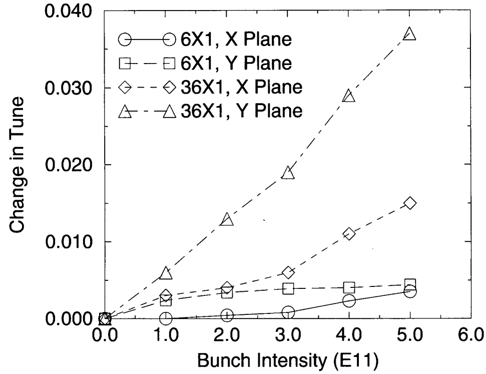


FIGURE 1 Change in betatron tune as a function of bunch intensity.

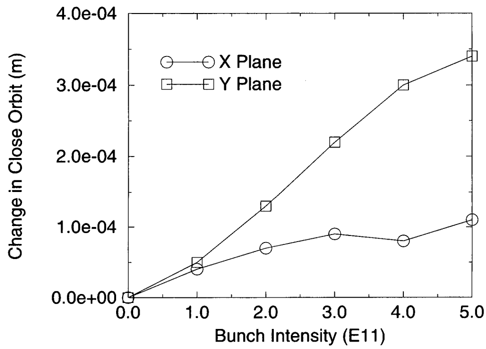


FIGURE 2 Change in closed orbit as a function of bunch intensity.

These changes in tunes are measured with respect to the calculated tune of the same particle for no beam-beam case. The change in tune is first order due to beam-beam effects. As expected the beam-beam tune shifts is considerable larger in 36×1 case, compared to 6×1. This large tune shift will require us to adjust the tune of the Tevatron during the opposing beam injection process. We have also studied the change in tune as a function of beam separation. The change in tunes of the particle increases as we reduce the two beam separation indicating a possible need of higher separation of the two beams.

Figure 2 shows the change in closed orbit in x and y plane due to beam-beam force for 36×1 case. At a bunch intensity of 3E11 the change in y closed orbit is of the order of half the beam size. The beam-beam interaction distorts the phase space and increases the emittance of the beam. We have studied the change in transverse beam size as a function of intensity and find that it increases with the bunch intensity of opposing beam.

3 NONLINEAR MODE COUPLING ANALYSIS IN THE TEVATRON

The analytic theory of synchro-betatron motions was first studied in connection with chromaticity. The dispersion in RF cavities was found to cause beam loss by coupling, and this effect has been studied analytically and computationally by a number of physicist. However, no experimental evidence of considerable wave-wave coupling of the broad band turbulence has been reported so far. Whereas the standard linear spectral analysis (power spectrum) provides experimental information on the amplitude and phase behavior of the individual Fourier components and the transport induced by fluctuations, it does not give any information about the coupling among different spectral components. The use of the bispectral analysis allows one to discriminate between oscillations spontaneously excited by the beam and those generated by nonlinear coupling.

We investigate the combined effect of long range interactions and higher order multipoles to calculate the non-linearly generated frequency spectrum. In this paper we discuss three cases. First we restrict ourselves to synchro-betatron and betatron-betatron coupling of a single beam with betatron tunes close to 7/12 resonance when higher order multipoles are present. Second, beam-beam without error fields are considered. Finally beam-beam with multipoles are analyzed. Turn by turn data was generated using the Tevatron Lattice described above. The bicoherence spectrum has been computed to study the strength of the three-wave coupling contributing to the characteristics of beam-beam coupling in the Tevatron.

The bicoherency is defined as

$$b^2(\nu_1, \nu_2) = B(\nu_1, \nu_2)^2/[\langle |X_{\nu_1} X_{\nu_2}|^2 \rangle P(\nu)].$$

Where $B(\nu_1, \nu_2)^2$ is the bispectrum defined as $B(\nu_1, \nu_2) = \langle X_{\nu_1} X_{\nu_2} X_{\nu^*} \rangle$, $P(\nu)$ the autopower spectrum $P(\nu) = \langle X_{\nu_1} X_{\nu_2 *} \rangle$, X_ν is the Fourier transform of the turn by turn data, X(t) and $\langle \rangle$ means ensemble averaging over many statistically similar realizations. The bicoherency measures the fraction of the fluctuating power at a frequency ν that is phase correlated with the spectral components at frequency ν_1 and ν_2 obeying the summation rule $\nu = \nu_1 + \nu_2$. The bicoherency thus quantifies the degree of coupling among three waves. The bicoherency is bound between 0 and 1: When $b^2(\nu_1, \nu_2)$ is equal to 1 then the oscillations at frequency ν are completely coupled with frequency components at frequency ν_1 and ν_2 and completely decoupled for the zero value. The use of the bicoherence as a measure of three-wave coupling is independent of any closure assumptions. The bicoherence is nonzero if there is a statistically significant phase relation between the three modes. Such bispectral analysis has been advanced by Ritz, Powers, and Bengston for plasma research, and applied in the frequency domain to electrostatic fluctuations.[7]

In order to predict a particle's behavior in the presence of the beam-beam interaction in the Tevatron, modified TEAPOT simulation code was run under three conditions. The predicted position and phase of a particle after a designated 20000 turns is used to calculate the bicoherencies. In all cases, the base tunes for all conditions are (Qx,Qy) = (20.5836,20.5826). The two sextupole families are used to set the chromaticity of the Tevatron to a desired value (minimum chromaticities to keep the beam stable at 900 GeV); the chromaticity setting is adjusted to Qx = 20 and Qy = 24. The launched particle has $\Delta p/p = 1.0$ E -3. Beam intensity used in these simulations were 3.0E11 per bunch. The initial position and phase are the same for all cases. In a first approximation, when the intensity of the opposite beam is relatively low and the tunes are far enough from the low order resonances, the beam-beam effects appear as a nonlinear dependence of the frequencies of transverse oscillations on their amplitude. For larger intensity, or when the tunes are close to the low-order resonances, isolated nonlinear resonances, creating a periodic energy exchange between the transverse planes, come into play. This is the regime we have performed the simulations. For still larger intensity, the resonances can overlap to form stochastic regions where the particle dynamic is diffusive.

Figure 3 shows the normalized phase space plot for the single beam. The only source of nonlinearity is the higher order multipoles. The above standard normalized phase space plot does not show any structure that could reveal the sources of nonlinearities if any exist. Figure 4 shows the normalized phase-space plot for the beam-beam with the long range kicks for 6×1 case. The higher order multipoles are not present. Twelve islands associated

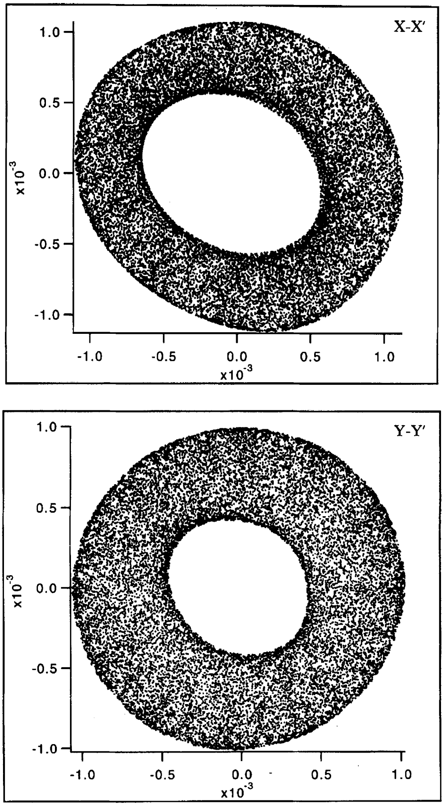


FIGURE 3 Single beam normalized phase space plots with higher order multipoles.

with 12 parasitic crossing is observable. This non-linearity is small for small amplitude particles.

The same turn by turn data is analyzed to calculate bicoherency. Figure 5 shows the calculated bicoherence which clearly shows the three waves coupling. The horizontal axis denote horizontal and vertical tunes. The vertical axis denotes the bicoherence for $\nu_3 = \nu_1 + \nu_2$. Peak "A" is the only significant non linearity observed which is due to the dispersion present in the cavities. This synchro-betatron coupling can be removed from the simulation by removing dispersion. This type of analysis is not possible by simple study of traditional normalized phase space plots.

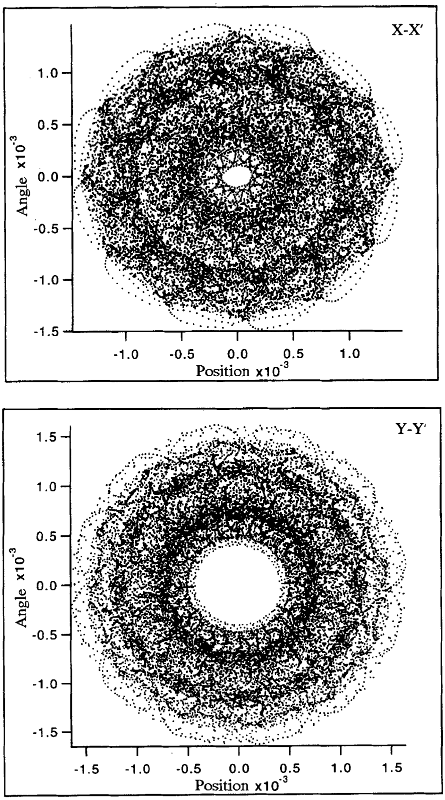


FIGURE 4 Normalized phase space plot for beam-beam without higher order multipoles.

Figure 6 represents the bicoherence spectrum of particle tracked in the presence of beam-beam elements without the higher order multipoles. We observe nonlinearly generated modes due to dispersion and also along the difference resonance $\nu_H - \nu_V$. When both the beam-beam interaction and higher order multipoles are present together some resonances gets excited with higher amplitude and other gets suppressed. Figure 7 shows that the phase space of the particle get fully diluted when both the higher order multipoles and beam-beam effects are present. No obvious non-linearity is observed in the normalized phase space plot. When the same data for 6×1 beam-beam with 3E11 particles per bunch and higher order multipoles is

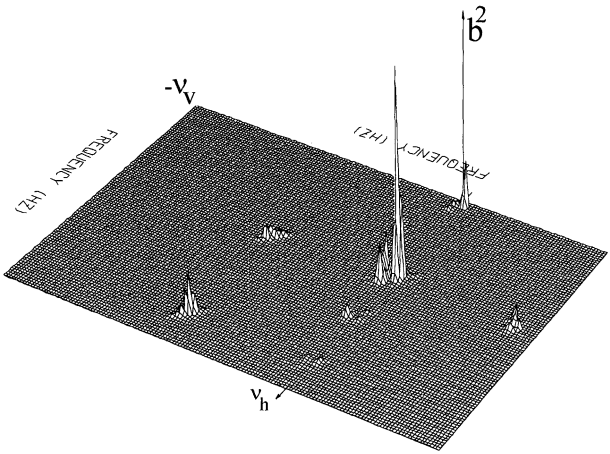


FIGURE 5 Bicoherence, $b(\nu_1, \nu_2, \nu_3)$, of single beam with all higher order multipoles present.

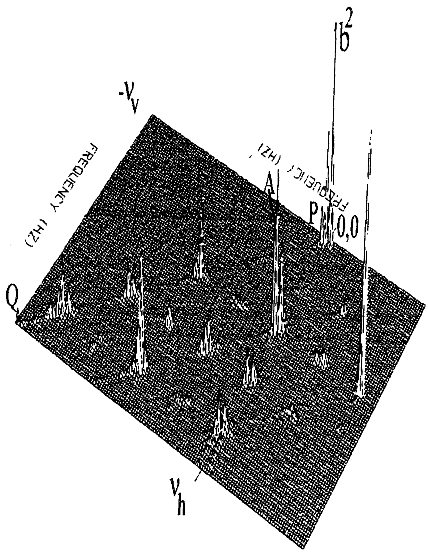
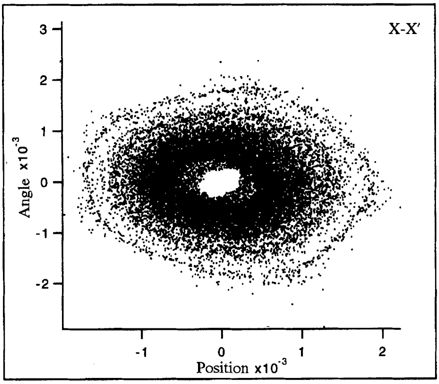


FIGURE 6 Bicoherence, $b(\nu_1, \nu_2, \nu_3)$, of beam-beam without all higher order multipoles.



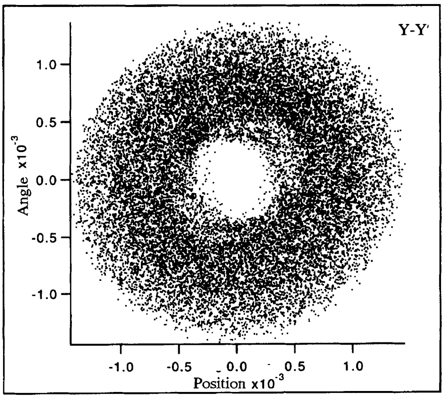


FIGURE 7 Normalized phase space plots for beam-beam with higher order multipoles.

analyzed for Bicoherence analysis Figure 8, we observe resonances which were not present either in the case of single beam with higher order multipoles Figure 5 or just the beam-beam Figure 6.

4 SUMMARY

In this paper we have presented initial results from a study to understand the beam-beam effects in the Fermilab Tevatron. A closer attention needs to be paid by changing the Tevatron operating procedures to overcome the effects of increasing beam-beam force. We have also introduced a new technique to analyze the particle dynamics.

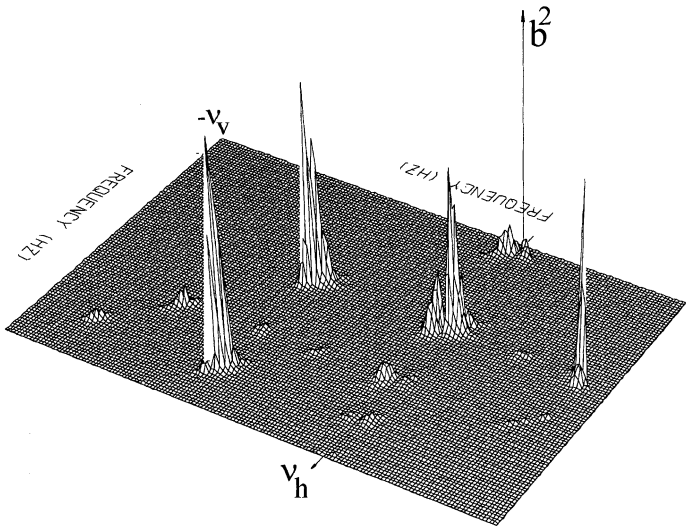


FIGURE 8 Bicoherence, $b(\nu_1, \nu_2, \nu_3)$, of beam-beam with all higher order multipoles.

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