Long-Range Beam-Beam Interactions in the TEVATRON: Comparing Simulation to Tune Shift Data

S.SARITEPE, L.MICHELOTTI and S.PEGGS
Fermilab*, P.O.Box 500, Batavia, Il. 60510

1 Introduction

Fermilab upgrade plans for the collider operation include a separation scheme in the Tevatron, in which protons and antiprotons are placed on separate helical orbits. The average separation distance between the closed orbits will be 5σ (σ of the proton bunch) except at the interaction regions, B0 and D0, where they collide head on. The maximum beam beam total tune shift in the Tevatron is approximately 0.024 (the workable tune space between 5^{th} and 7^{th} order resonances), which was reached in the 1988-89 collider run. Helical separation scheme allows us to increase the luminosity by reducing the total beam beam tune shift.

The number of bunches per beam will be 6 in the 1991 collider run, to be increased to 36 in the following collider runs. To test the viability of this scenario, helical orbit studies are being conducted. The most recent studies concentrated on the injection of 36 proton bunches, procedures related to opening and closing of the helix, the feed down circuits and the beam-beam interaction. In this paper, we present the results of the beam beam interaction studies only. Our emphasis is on the tune shift measurements and the comparison to simulation.

2 Beam-Beam Tune Shift Measurements

The helical orbit studies were conducted in April,1990. A 31x1 store (1 antiproton bunch circulating against 31 proton bunches) was established to study the long range beam beam interactions, at a beam energy of 150 GeV. The injection lattice was used so there were no low beta sections. Two modules of electro static separators were available, at B17 and C48, providing a $85\mu rad$ horizontal kick and a $85\mu rad$ vertical kick, respectively. At 100% Helix, all 68 beam beam crossings involved long range interactions. The average separation at 100 % Helix was 4.51σ as shown in Figure 1. The helix was collapsed from 100% to 0% in 20% steps. At each step, total beam current, proton and antiproton bunch intensities, emittances, beam sizes and tunes were measured.

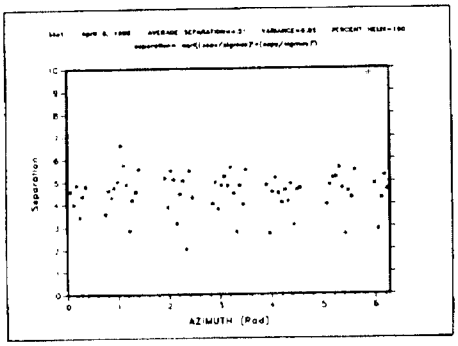

Figure 1: Normalized separation at beam-beam crossing points

The measurement of antiproton tunes presents difficulties due to low bunch intensities. During these studies antiproton beam was excited coherently in the horizontal plane, vertical excitation was not possible due to problems associated with the vertical kicker. Vertical antiproton tune measurements were made by coupling the $\bar{p}$ horizontal and vertical betatron oscillations. Tunes were read from spectrum analyzers connected to the Schotky plates. Proton and antiproton tunes are differentiated by turning on the feed-down circuits and watching the tune lines for protons and antiprotons move in opposite directions. The beam-beam tune shifts are calculated by subtracting bare tunes (tunes measured when there is no beam beam interaction while the feed down circuits are on) from actual tunes.

% Helix	Horz.Tune Shift	Vert Tune Shift
100	0.0025	0.0014
80		0.0000
60	0.0045	0.0038
40	0.0151	
20	0.0213	
0	0.0125	

Table 1: Antiproton tune shift data

% Helix	100	80	60	40	20	0
ϵ_{p_x} ($\pi mm\ \ mr$)	9.7	10.0	10.0	11.3	11.3	11.3
ϵ_{p_y} ($\pi mm\ \ mr$)	13.0	13.0	13.0	15.2	17.6	17.6
$\epsilon_{\bar{p}_x}$ ($\pi mm\ \ mr$)	6.5	7.5	8.0	8.5	9.0	9.5
$\epsilon_{\bar{p}_y}$ ($\pi mm\ \ mr$)	15.0	16.5	17.0	17.5	18.0	18.5
protons/bunch (10^{10})	3.52	2.64	2.50	2.35	2.20	2.05

Table 2: Beam parameters used in the simulation

The tune shift data is presented in Table 1. The relevant beam parameters are summarized in Table 2. Note that the emittance numbers shown in Table 2 are normalized emittances (95% phase space area definition has been used).

3 Simulation

The simulation code HOBBI[1] implements a weak strong model of the beam-beam interaction. Calculations were carried out by using the injection lattice. The only nonlinearity in the model comes from beam-beam interactions. Montaque form[4] of the beam-beam kicks were used.

The input to HOBBI is a file containing the lattice information at beam-beam crossing points, separator locations, and at arbitrary user defined points around the ring. The file also contains the linear transfer matrices between the beam-beam crossing points and other information such as the separator voltages, tunes, emittances, energy et cetera. It is prepared by a preprocessor which takes a SYNCH output as its input. The code HOBBI is designed [2] [3] to be an interactive program for exploratory orbit analysis in the presence of beam-beam interactions. All the beam parameters including base tunes can be changed during an interactive session, providing the flexibility to explore the entire parameter space. Another useful feature of HOBBI is that it tracks either protons against antiprotons or antiprotons against protons. HOBBI includes synchrotron oscillations, dispersion effects, and tune modulation. There is also a "beam review" page, where other useful information such as beam sigmas and separations at the observation site, and the average separation over all sites, are displayed. A faster version of HOBBI using tables instead of functions is under development. FASTHOBBI will be used for long term tracking simulations.

The output of HOBBI is a 4-D array of normalized phase-space variables. It is normally displayed on a specialized graphics terminal, via a graphics shell written by one of the authors (L.M.) to view the 2-D projections of the 4-D phase-space. In this note, however, we emphasize another feature of HOBBI, namely, the tune shift calculation. Tune shift for an individual particle is calculated by keeping a record of the average phase advance per turn. A separate program accesses these numbers, and uses them to plot tune shift footprints. Figures 2, 3, 4, 5, 6, 7 show such footprints for the 5 steps of the Helix. The lower plots are the tune density distributions normalized

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

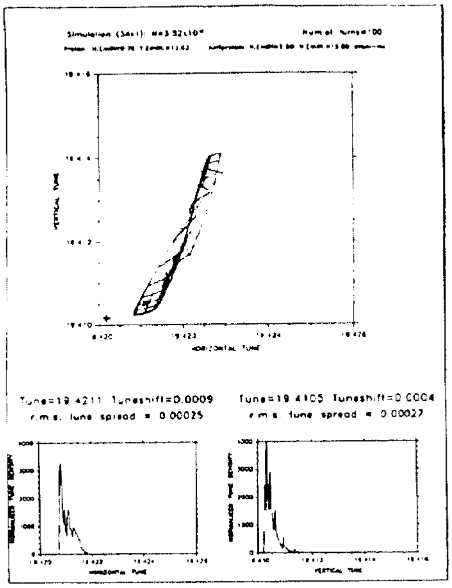

Figure 2: Tune shift footprint and tune densities at 100 % Helix.

so that the area under the distribution curve is equal to 1. The average tune shift is calculated by assuming that both beams have Gaussian transverse density distributions, i.e.

$$<\nu> = \sum \nu_i a_x a_y\, exp(-\frac{a_x^2 + a_y^2}{2}) \,/\, \sum a_x a_y\, exp(-\frac{a_x^2 + a_y^2}{2}) \qquad (1)$$

where a_x and a_y are amplitudes in units of antiproton bunch sigmas in the horizontal and vertical planes respectively. In the figures the average tune is indicated by the diagonal cross sign and the base tune by the erect cross sign. We compare the average tunes as calculated by equation 1 to the numbers in Table 1 in figures 8-9.

4 Discussion and Conclusions

The agreement between simulation and data is very good in the case of separated orbits. However, the discrepancy in the case of 0 % Helix (68 head-on collisions) is striking. The head-on tune shift, unlike the separated tune shifts, is very sensitive to beam sigmas and emittances. The accuracy of beam size measurements becomes an issue in the case of 0 % Helix. The head-on tune shift is also very sensitive to the actual transverse density distribution of the proton bunches but this effect is not taken into account in the simulation. One last comment is that in the case of 0% Helix, we may have seen the tune corresponding to the π-mode of the coherent beam beam oscillations. This explanation is plausible since beams were excited coherently during the experiment.

References

[1] The original code was written by Leo Michelotti, it was later developed by Selcuk Saritepe.

[2] L.Michelotti and S.Saritepe, "Orbital Dynamics in the Tevatron Double Helix", Proc.IEEE Particle Acc.Conf. (1989) p:1391-1393, editors:F.Bennet and J.Kopta

[3] L.Michelotti and S.Saritepe, "Exploratory Orbit Analysis of TEVATRON Helical Upgrade;One A First Look", FERMILAB Technical Note TM-1603 (1989).

[4] B.W.Montague, CERN ISR/68-38 (1968).

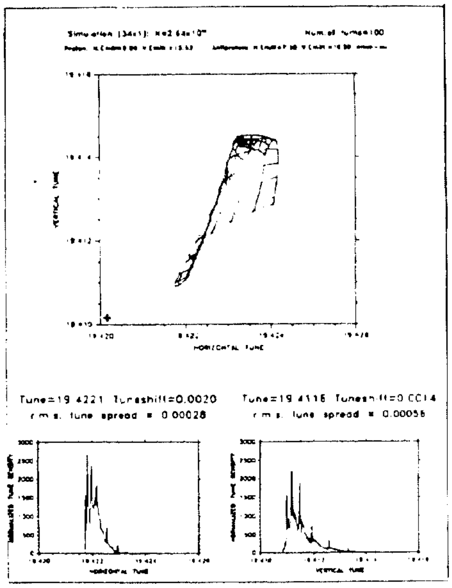

Figure 3: Tune shift footprint and tune densities at 80 % Helix.

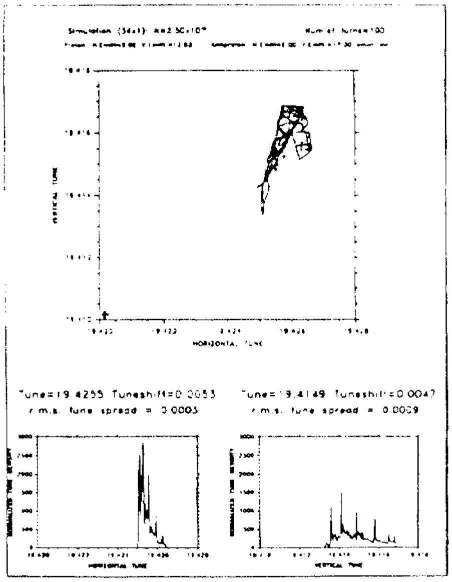

Figure 4: Tune shift footprint and tune densities at 60 % Helix.

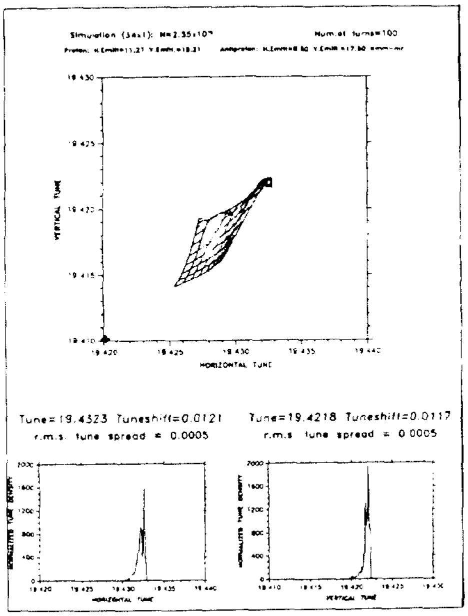

Figure 5: Tune shift footprint and tune densities at 40 % Helix.

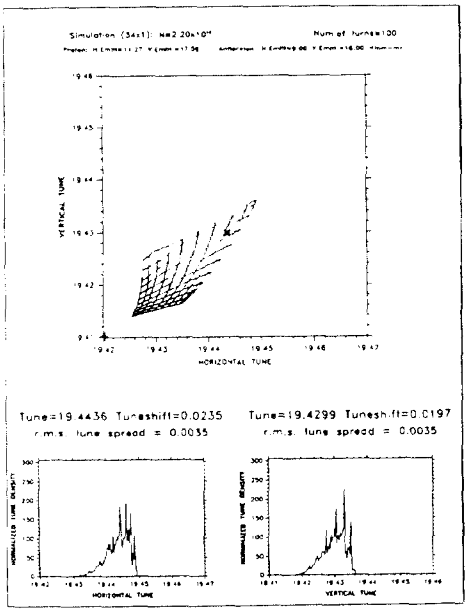

Figure 6: Tune shift footprint and tune densities at 20 % Helix.

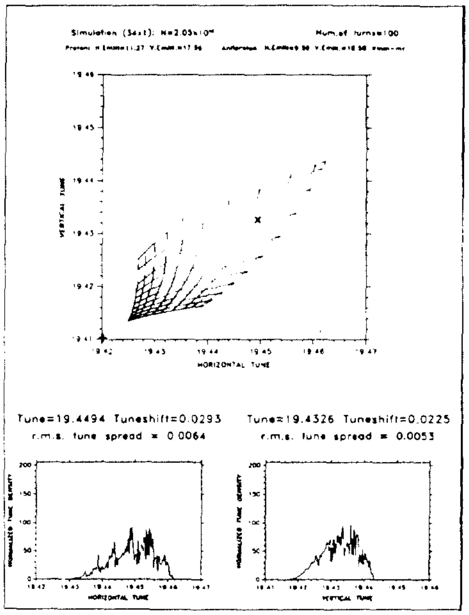

Figure 7: Tune shift footprint and tune densities at 0 % Helix.

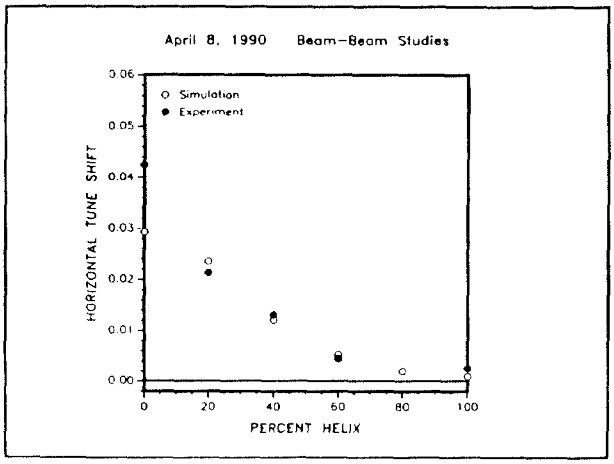

Figure 8: Comparison of tune shifts in the horizontal plane.

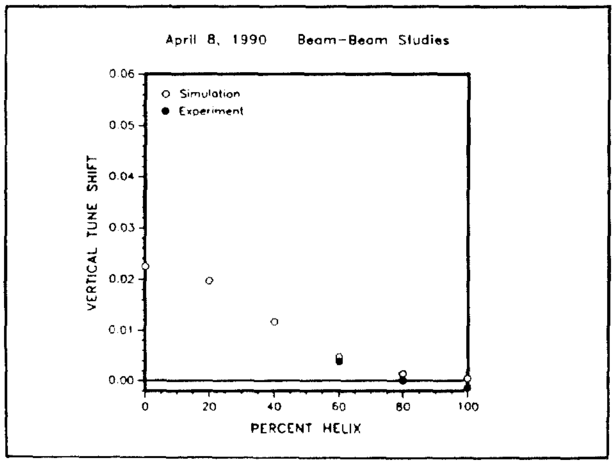

Figure 9: Comparison of tune shifts in the vertical plane.