IMPORTANCE OF THE LINEAR COUPLING AND MULTIPOLE COMPENSATION OF LONG-RANGE BEAM-BEAM INTERACTIONS IN TEVATRON

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Abstract

The emittance growth due to parasitic collisions in Tevatron was studied. It was found that the dominant long-range beam-beam effect is from the coupling resonance. A correction of the linear coupling of the long-range beam-beam interactions and the coupled helix orbit can significantly reduce the emittance growth. High-order multipole compensation of the long-range beam-beam interactions could further improve the beam dynamics.

INTRODUCTION

In Tevatron, serious long-range beam-beam effects are due to many parasitic collisions that are distributed around the ring [1]. Because of the non-localized nature of long-range beam-beam interactions in this case, the multipole compensation with one-turn or sectional maps aims a global compensation of long-range beam-beam interactions [2, 3, 4].

The principle of the multipole compensation of long-range beam-beam interactions is based on the fact that the linear and nonlinear beam dynamics in a storage ring can usually be described by a one-turn map that contains all global information of the system. By minimizing nonlinear terms of a one-turn map order-by-order with a few groups of multipole correctors, one could reduce the nonlinearity of the system globally [2, 3, 4]. To include long-range beam-beam interactions into the map, one should recognize that a large beam separation is typical at parasitic crossings. In Tevatron, the beam separation at most parasitic crossings is between 6 to 12 σ, where σ is the nominal beam size. There are a few “bad spots” where the separations are $\sim 5\sigma$. In the phase-space region ($< 4\sigma$) that is relevant to the beam, the long-range beam-beam interactions can thus be expanded into a Taylor series around the beam separation and be included into the one-turn map for a global or local compensation of the linear coupling and nonlinearities of the system [4]. To refine the compensation, the beam-beam interactions at those “bad spots” could be further compensated locally with the multipole compensation. To included in the map, long-range beam-beam interactions have to be expanded in the direction of the beam separation to ensure a clean order-by-order expansion [4]. In Tevatron, since the direction of the separation rotates along the helix around the ring, the transverse coordinate for the expansion has to be rotated accordingly. We have developed a differential-algebra code that expands long-range beam-beam interactions in the rotating coordinate along the helix. The map obtained with this expansion technique was found to converge very well.

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	Injection	Collision
Energy	150 GeV	980 GeV
Number of bunches	36	36
β^* at IPs	1.6 m	0.35 m
Horizontal tune (ν_x)	20.5838	20.581
Vertical tune (ν_y)	20.5753	20.571
$\xi_{\bar{p}}$	0.01	0.01
ξ_p	0.00625	0.00625
$\epsilon_{\bar{p}}$	15 μm	15 μm
ϵ_p	20 μm	20 μm

Table 1: Some beam parameters used in this study where $\xi_{\bar{p}}$ and ξ_p are the beam-beam parameter and $\epsilon_{\bar{p}}$ and ϵ_p the normalized transverse emittance (95%) for the $\bar{p}$ and p beam, respectively.

To examine the effect of the multipole compensation scheme, the emittance growth of both the proton (p) and anti-proton ($\bar{p}$) beam at injection or collision were studied with a beam-beam simulation. For Tevatron during collision, headon collisons at two interaction points (IPs) were also included in the simulation and the effect of the headon beam-beam interactions were studied self-consistently by using the particle-in-cell (PIC) method. The result of the simulation showed that the multipole compensation, especially a correction of the linear coupling from the long-range beam-beam interactions and helix orbits can significantly reduces the emittance growth of the $\bar{p}$ beam.

SIMULATION MODEL

In this study, the linear lattice for the $\bar{p}$ bunch 1 at cog 0 was used. Along the helix, the lattice is coupled. Table 1 lists some of beam parameters used in this study. There are 72 parasitic crossings for long-range beam-beam interactions in the injection lattice and 2 headon collisions and 70 parasitic crossings in the collision lattice. The beam separations at the parasitic crossings of the injection or collision lattice are given in Ref. [1]. For the multipole compensation, four independent groups of multipole correctors were assumed to be located at four locations in Tevatron where there are empty spaces larger than 5 m long. Because of large beam separations at the parasitic crossings, the long-

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range beam-beam force does not sensitively depend on the details of bunch particle distributions and, therefore, was calculated with the weak-strong model in which the bunch distributions of the two beams were assumed to be Gaussians. To increase the tracking speed, the long-range beam-beam force was calculated in two steps. First, the beam-beam kick in transverse phase space was calculated at the grid points of a mesh in configuration space for each parasitic crossing. The mesh is centered at the helix orbit of the kicked beam. The beam-beam kick is then interpolated to the positions of every macroparticles during the tracking. The grid size of the mesh was tested by comparing the kick calculated from the interpolation with that calculated directly from the numerical integration of the Green function of the beam-beam force and the bunch particle distribution. Dipole components of the long-range beam-beam kicks were subtracted during the tracking. In this study, the initial bunch particle distributions in the normalized transverse phase space were Gaussian distributions truncated at 4σ where σ is the normalized horizontal or vertical beam size at B0 for the distribution in the horizontal or vertical phase space, respectively. The initial bunch distributions were matched with the linear lattice including the linear long-range beam-beam effects. The emittance growth of the beams was studied with tracking up to 10^5 turns without momentum deviations.

SIMULATION RESULT

Long-Range Beam-Beam Effect At Injection Energy

In Tevatron, the long-range beam-beam effect is mainly on the $\bar{p}$ beam. The emittance of the $\bar{p}$ beam was therefore studied by tracking a single $\bar{p}$ bunch that consists of 10^5 macroparticles. Figure 1 plots the calculated emittance growth of the $\bar{p}$ beam due to the long-range beam-beam interactions. Without any linear or nonlinear compensation, the vertical emittance increases quickly while the horizontal one decreases with a similar rate (see curve a in Fig. 1). This coupled emittance blowup is the result of the coupling resonance. Note that the helix orbit without the beam-beam interactions is linearly coupled. Because of the feed-down effect, the long-range beam-beam interactions contribute additional linear coupling. The rotation of the beam separation along the helix makes this "beam-beam" coupling even worse. With the expansion of the long-range beam-beam interactions in a coordinate that is rotating with the helix [4], the linear terms of the map contain all the contributions of the linear coupling of the beam-beam interactions and the helix orbit. With quadrupole correctors, these unwanted contributions of the linear coupling can effectively be eliminated and, consequently, the coupled emittance blowup of the $\bar{p}$ beam was eliminated as shown by curve b in Fig. 1. The dominant long-range beam-beam effect in this case is therefore of the linear coupling due to the feed-down effect of the beam-beam interactions and the coupled helix

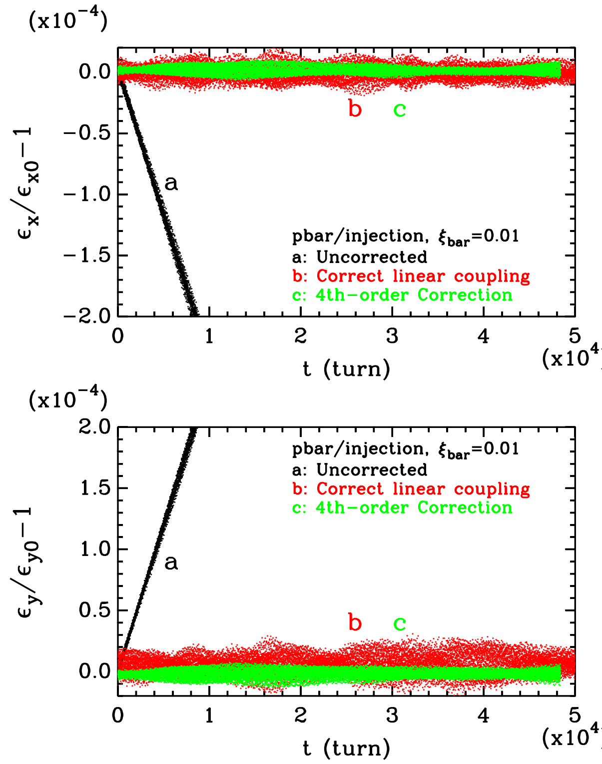

Figure 1: Evolution of the horizontal (ϵ_x) and vertical (ϵ_x) emittance of the $\bar{p}$ beam at injection energy (a) without any correction; (b) with a correction of linear coupling due to the parasitic collisions and the coupled helix orbit, and (c) with the 3rd-order multipole compensation. ϵ_{x0} and ϵ_{y0} are the initial emittances

orbit. With an additional high-order compensation by minimizing the nonlinear terms of the map order-by-order, the dynamics of the beam can be further improved as shown by curve c in Fig. 1 that is the emittance of the $\bar{p}$ beam after the 3rd-order compensation. With the 3rd-order compensation by using sextupole and octopole correctors, the overall of the 2nd- and 3rd-order terms of the map were reduced substantially. Compared with the case of only the linear correction (curve b in Fig. 1), the emittance fluctuation is much smaller now, which indicates that the dynamics of the $\bar{p}$ beam is further improved.

To apply the multipole compensation of long-range beam-beam interactions in Tevatron, one needs to consider that the two beams have to pass through common multipole correctors because they share a single vacuum pipe. The dynamics of the p beam has therefore been examined also by a beam-beam simulation. The preliminary result indicates that there is only a very small emittance growth of the p beam due to the multipole correctors.

Headon Beam-Beam Effect During Collision

To increase the luminosity in Tevatron, it has been proposed to further increase the intensity of the $\bar{p}$ beam. Consequently, ξ_p will be increased from ~ 0.0015 to ~ 0.0063. To examine the possibility of the coherent beam-beam ef-

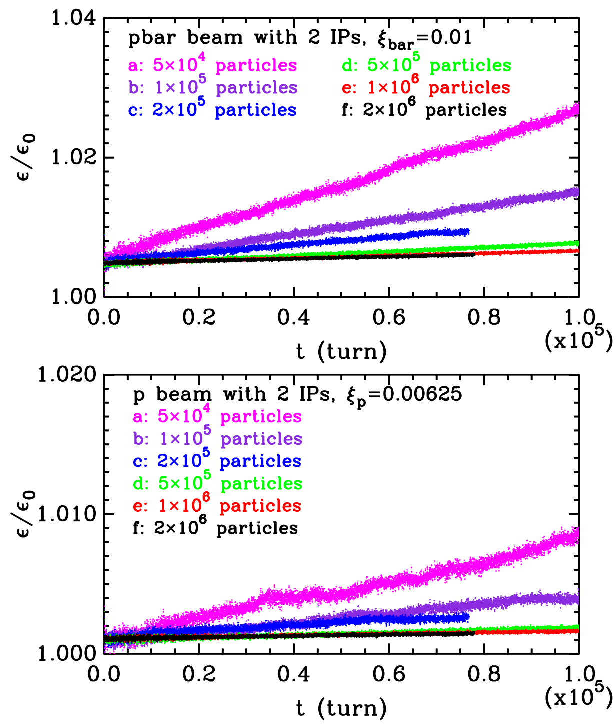

Figure 2: Emittance growth of the $\bar{p}$ and p beam due to headon collisions at B0 and D0 calculated with different number of macroparticles in each bunch, where $\epsilon = \epsilon_x + \epsilon_y$.

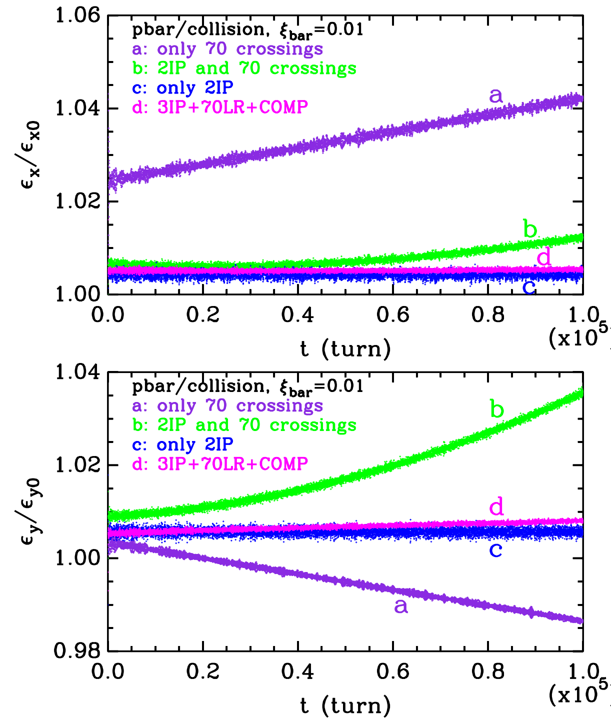

Figure 3: Emittance growth of the $\bar{p}$ beam in Tevatron during collision with (a) 70 parasitic collisions; (b) 2 headon and 70 parasitic collisions; (c) 2 headon collisions; and (d) the same as (b) but with the multipole compensation.

fect due to the headon beam-beam interactions, the dynamics of the $\bar{p}$ and p beams were studied with a self-consistent beam-beam simulation by using our PIC code [5]. Because the locations of the IPs in Tevatron are not symmetry, different pair of the p and $\bar{p}$ bunches collide at the two IPs. In order to simulate the collision pattern in Tevatron, three p and three $\bar{p}$ bunches were tracked in this study. For the consideration of computational speed, the parasitic collisions were excluded. The helix orbits of the six bunches were assumed to be the same to simplify the problem. Computational parameters in the PIC method were tested to ensure a numerical convergence. Figure 2 plots the evolution of the emittances of the two beams calculated with different number of macroparticles in each bunch. When the number of macroparticles is smaller than 5×10^5, the simulation produces a significant artificial beam-size growth. In this study, 10^6 macroparticles were therefore used for each bunch. With a study of the beam coherent oscillation in frequency space as well as phase space, no coherent beam-beam instability was observed in this case.

Long-Range Beam-Beam Effect During Collision

In this case there are 2 headon and 70 parasitic collisions. Since the coherent beam-beam effect of the headon beam-beam interactions is not important, to save the computational time, the headon beam-beam interactions were also calculated with the weak-strong model for the tracking of the $\bar{p}$ beams. Figure 3 plots the emittance growth of the $\bar{p}$ beam due to the headon and/or long-range beam-beam interactions. Similar to the situation at injection, without the headon collisions, the long-range beam-beam interactions result in a coupled emittance blowup (curve a in Fig. 3). Note that the helix orbit for the $\bar{p}$ is decoupled in this case and the linear coupling is purely from the long-range beam-beam interactions. With the headon collisions, the emittance growth is no longer coupled even though the linear coupling of the long-range beam-beam interaction still exists. The reason of this automatic decoupling is the large tune spread of the headon beam-beam interactions since the existence of a large tune spread makes it difficult to trap beam particles inside a single resonance. This is an example that having a large amplitude dependence of frequencies could benefit the stability of a nonlinear dynamic system [6, 7]. As shown by curve d in Fig. 3, the multipole compensation significantly reduces the emittance growth due to the long-rnage beam-beam interactions.

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