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Authors
Qiang, Ji
Ryne, Robert D.
Sen, Tanaji
et al.

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Macroparticle Simulations of Antiproton Lifetime at 150 GeV in the Tevatron

J. Qiang*, R. D. Ryne, LBNL, Berkeley, CA 94720, USA
T. Sen, M. Xiao, FNAL, Batavia, IL 60510, USA

Abstract

In this paper we report on a systematic study of antiproton lifetime at the injection energy of 150 GeV in the Tevatron. Our parallel beam-beam model can handle both strong-strong and weak-strong beam-beam collisions with abitrary beam-beam separation and beam distributions. In this study, we have only used the weak-strong capability due to the fact that the antiproton intensity is much smaller than the proton intensity. We have included all 72 long-range beam-beam collisions with a linear transfer map between adjacent collision points and taken into account linear chromaticity. The effects of antiproton emittance, beam-beam separation, proton intensity, and machine chromaticity have been investigated. Initial results show that the antiproton lifetime as a function of the proton intensity from the simulation is in good agreement with that from the experimental measurements. The antiproton lifetime can be significantly improved by increasing the beam separation and by reducing the antiproton emittance.

INTRODUCTION

The Tevatron has been upgraded in recent years to increase the luminosity of the proton-antiproton collisions. One of the most important factors limiting luminosity in the past and in Run II is the antiproton availability. It has been observed that the luminosity in the Tevatron is proportional to the total antiproton intensity, where the total antiproton intensity is determined by the antiproton production rate, the transmission efficiency from the antiproton accumulator to the Tevatron, and the store lifetime. A study of the antiproton lifetime subject to the effects of a range of physical parameters will help to minimize the antiproton losses during the machine operation and to improve the luminosity. In this paper, we focus our study on the antiproton lifetime during the injection stage with energy of 150 GeV. At this stage, the major factor causing the antiproton loss is the 72 long range beam-beam interactions between the proton bunches and the antiproton bunches.

COMPUTATIONAL MODEL

The computational tool used in this paper is a parallel program, BeamBeam3D, developed at Lawrence Berkeley National Laboratory for strong-strong and strong-weak beam-beam modeling [1]. This tool calculates self-consistently the electromagnetic beam-beam forces for arbitrary distributions during each collision when a strong-strong beam-beam interaction model is used. When a strong-weak model is used, the code has the option of using a Gaussian approximation for the strong beam. BeamBeam3D uses a multiple-slice model, so finite bunch length effects can be studied. The code also includes a Lorentz boost and rotation to treat collisions with finite collision crossing angle. It handles arbitrary closed-orbit separation (static or time dependent) and models long-range beam-beam interactions using a newly developed shifted Green function approach. It can also handle multiple interaction points using externally supplied linear maps between interaction points in the strong-weak model. The linear machine chromaticity is represented using a one-turn kick. The diffusion due to the random noise is emulated using a one-turn random kick in momentum space with adjustable noise amplitude.

In the calculation of the antiproton lifetime, we have assumed a strong-weak beam-beam interaction model since the antiproton intensity is much smaller than the proton intensity (typically a factor of 10). We first perform a MAD simulation using the Tevatron lattice at the injection energy of 150 GeV. From there, we extract 73 linear transfer maps, starting at B0, for the 72 long-range beam-beam interactions. These linear transfer maps are symplectified before being used to track antiprotons in the beam-beam simulation. Information related to the proton-antiproton separation, machine bare tune, and linear chromaticity is also extracted. Fig. 1 shows the normalized proton-antiproton separation as a function of distance along the proton trajectory in the Tevatron. There are three locations where

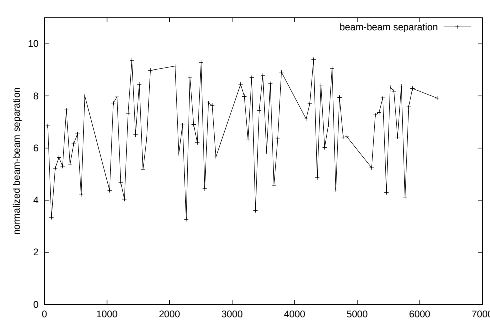

Figure 1: Normalized beam-beam separation as a function of the distance along proton trajectory in the Tevatron.

the beam-beam separations are below four sigma. Given the initial antiproton emittances and Twiss parameters, we generate an initial 6D Gaussian distribution of particles for the antiproton beam using a weighted sampling technique. Here, instead of sampling the Gaussian distribution directly, we sample a uniform distribution within the given aperture size. Then, each particle is given a weight based

* jqiang@lbl.gov

on the function value of the Gaussian distribution at the particle position. Using a weighted sampling technique, we can increase the resolution of the calculated antiproton intensity and reduce the minimum number of particle-turns required for the simulation.

The antiprotons are then transported from one long-range beam-beam collision point to the next using the symplectified linear map. Before each collision, the transverse amplitudes of each particle are checked against a specified "aperture" size. If the amplitude is larger than the aperture size, that particle is lost and no longer tracked in the simulation. At the collision point, every antiproton receives a kick from the beam-beam force generated by the proton beam. The beam-beam force is calculated assuming a Gaussian distribution for the proton beam. Within each turn, the antiproton bunch will receive 72 such long range beam-beam kicks from 36 proton bunches. After each turn, a linear chromaticity map and a random diffusion map are applied to all antiproton particles. The amplitude of the noise has been adjusted so that the emittance growth of the antiproton beam without beam-beam collisions is several pi-mm-mrad after one hour of machine operation. The intensity of the antiproton beam is calculated from the summation of the weights of individual particles. Most of our simulations, performed on an IBM SP parallel computer at the National Energy Research Scientific Computing Center (NERSC), are run for 100,000 turns, which corresponds to about 2 seconds of real machine operation. The antiproton lifetime τ is estimated from fitting the antiprotron intensity with the function $I_0 \exp(-t/\tau)$ using a least square method. Here, I_0 is the initial antiproton intensity.

PARAMETER SCAN STUDY

We have carried out a systematic parameter scan study of the antiproton lifetime as a function of the proton intensity, antiproton emittance, beam-beam separation, and the machine vertical chromaticity. We have defined a reference case for all parameter scans. In the reference case, the proton beam has an intensity of 2.2×10^{11} per bunch, a 95% emittance of 25 pi-mm-mrad, a momentum spread of 7×10^{-4}, and an rms bunch length of 0.9 meters. The antiproton beam has an emittance of 20 pi-mm-mrad, a momentum spread of 4.31×10^{-4}, and an rms bunch length of 0.6 meters. The Tevatron horizontal bare tune is 0.581, vertical tune is 0.576, horizontal chromaticity is 2, and vertical chromaticity is 8. In the simulation, we have assumed an "aperture" size of 3.25σ, where σ is the horizontal or vertical rms size at each collision point. The choice of the aperture size is based on a particle tracking study of the dynamic aperture in the Tevatron [2]. The noise amplitude is set as 2×10^{-8} which gives a few pi-mm-mrad antiproton emittance growth after one hour of machine operation. To check the sensitivity of the estimated lifetime versus the number of particles used in the simulations, we have run a test simulation using 100,000, 200,000, and 1,000,000 particles for the reference case. The variation of the estimated lifetime in these three simulations is within 2%. In this paper, we have used 1,000,000 particles for all parameter scan studies.

Fig. 2 shows a plot of the antiproton lifetime at the injection energy of 150 GeV as a function of the proton intensity from simulations and from measurements. We see that the

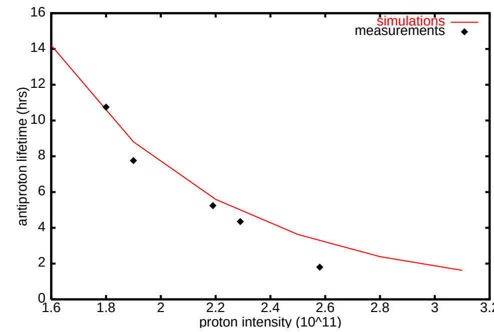

Figure 2: Antiproton lifetime as a function of proton intensity at 150 GeV in the Tevatron.

simulations have reasonably predicted the antiproton lifetime as a function of proton intensity. With a factor of 2 increase of the proton intensity, the antiproton lifetime has dropped by about a factor of 7. The rapid loss of antiprotons with increasing proton intensity observed here might overestimate the dependency of the antiproton lifetime on the proton intensity due to the fact that in the measurements the antiproton emittance had a growth from one data point to another data point. Particle tracking study of dynamic aperture size as a function of proton intensity suggests that there seems to be a threshold proton intensity above which the antiproton losses depend weakly on the intensity [3].

Fig. 3 shows the antiproton lifetime as a function of the initial antiproton emittance. With a factor 2 increasing of the antiproton emittance, the antiproton lifetime has decreased drastically by more than a factor of 100. The strong antiproton emittance dependency of the lifetime may be due to the following two effects: First, the larger antiproton emittance gives a larger antiproton beam size and results in a faster loss out of the aperture. Second, the larger antiproton beam size reduces the distance between the proton beam and the antiproton particles, which results in stronger beam-beam interactions.

Fig. 4 shows the antiproton lifetime as a function of the fractional nominal beam-beam separation. The nominal beam-beam separation is given in Fig. 1. We see that the antiproton lifetime is quite sensitive to the beam-beam separation. When the two beams are 20% closer, the antiproton lifetime has dropped by more than a factor of 2. When the two beams are further moved to approximately 50% of the nominal separation, the antiproton lifetime drops from 5 hours to about 10 minutes. The strong separation dependence of the antiproton lifetime is a result of strong beam-beam forces from the proton bunches. Fig. 5 shows the antiproton lifetime as a function of the Tevatron vertical chromaticity. The antiproton lifetime does not change sig-

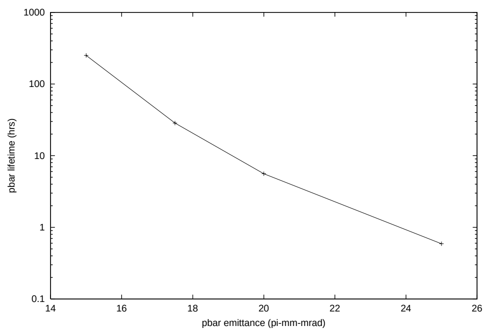

Figure 3: Antiproton lifetime as a function of antiproton emittance at 150 GeV in the Tevatron.

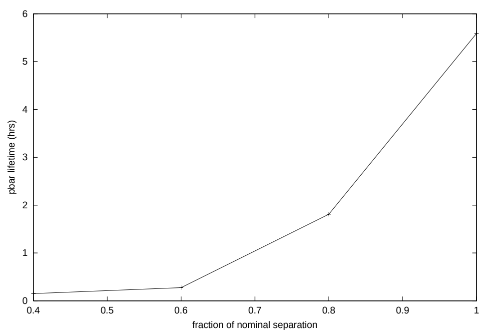

Figure 4: Antiproton lifetime as a function of fractional nominal beam-beam separation at 150 GeV in the Tevatron.

nificantly when the chromaticity varies between 2 and 8. However, in the Tevatron operation, the antiproton lifetime shows a strong dependency on the machine chromaticity. This discrepancy might be due to the fact the current computational model does not include the effects from the nonlinear external fields.

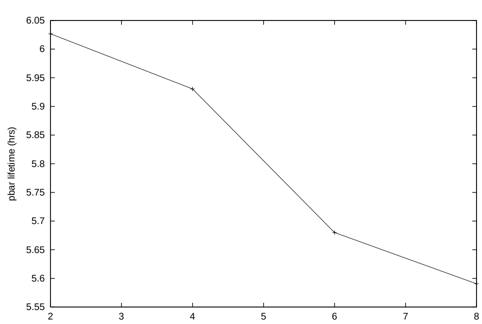

Figure 5: Antiproton lifetime as a function of machine vertical chromaticity at 150 GeV in the Tevatron.

SUMMARY

In this paper, we have presented a parameter scan study of the antiproton lifetime at the injection energy of 150 GeV in the Tevatron as a function of proton intensity, antiproton emittance, beam-beam separation, and machine vertical chromaticity. The antiproton lifetime as a function of the proton intensity from the simulation is in good agreement with the experimental measurements. For the given proton intensity, the antiproton lifetime shows strong dependence on the antiproton emittance and the beam-beam separation. This suggests that the antiproton lifetime can be significantly improved by increasing the beam separation and with smaller antiproton emittance.

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