SIMULATION OF BEAM-BEAM EFFECTS AND TEVATRON EXPERIENCE *

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Abstract

Beam-beam effects in the Tevatron have a variety of manifestations in beam dynamics presenting vast opportunities for development of simulation models and tools. In this report a summary of recent operational experience and changes is given. We explain major effects limiting the collider performance and compare results of observations and measurements with simulations.

INTRODUCTION

Peak luminosity of the Tevatron reached 3.15×10^{32} $cm^{-2}s^{-1}$ which exceeds the original Run II goal of 2.7×10^{32}. This achievement became possible due to numerous upgrades in the antiproton source, injector chain, and in the Tevatron collider itself. The most notable rise of luminosity came from the commissioning of electron cooling in the recycler ring and advances in the antiproton accumulation rate. Starting from 2007, the intensity and brightness of antiprotons delivered to the collider greatly enhanced the importance of beam-beam effects. Several configurational and operational improvements in the Tevatron have been planned and implemented in order to alleviate these effects and allow stable running at high peak luminosities.

Development of a comprehensive computer simulation of beam-beam effects in the Tevatron started in 1999 [1]. This simulation proved to be a useful tool for understanding existing limitations and finding ways to mitigate them. We have cross-checked the simulation results against various experimental data and analytical models.

This paper continues a series of reports on beam-beam effects in the Tevatron [2, 3, 4]. An updated view is provided based on the current year running. We also correlate the most notable changes in the machine performance to changes of configuration and beam conditions, and support the explanations with simulations.

OVERVIEW OF BEAM-BEAM EFFECTS

A detailed description of the Tevatron collider Run II is available in other sources [5]. Here only the essential features important for understanding of beam dynamics are provided.

Tevatron is a superconducting proton-antiproton collider ring in which beams of the two species collide at the center of mass energy of 2×0.98 TeV at two experiments. Each beam consists of 36 bunches grouped in 3 trains of 12 with 396 ns bunch spacing and 2.6 μs abort gaps between the trains. The beams share a common vacuum chamber with both beams moving along helical trajectories formed by electrostatic separators. Before the high energy physics collisions have beem initiated, the proton and antiproton beams can be moved longitudinally with respect to each other, which is referred to as cogging. This configuration allows for 72 interactions per bunch each turn with the total number of collision points in the ring equal to 138.

A typical collider fill cycle is shown in Figure 1. First, proton bunches are injected one at a time on the central orbit. After that, the helix is opened and antiproton bunches are injected in batches of four. This process is accompanied by longitudinal cogging after each 3 transfers. Then the beams are accelerated to the top energy (85 s) and the machine optics is changed to collision configuration in 25 steps over 120 seconds (low-beta squeeze). The last two stages include initiating collisions at the two main IPs and removing halo by moving in the collimators.

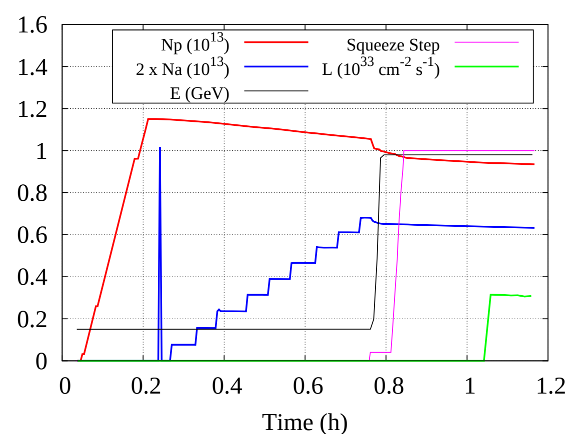

Figure 1: Collider fill cycle for store 5989.

It has been shown in machine studies that beam losses up the ramp and through the low-beta squeeze are mainly caused by beam-beam effects [3]. At HEP, the beam-beam induced emittance growth and particle losses contribute to the faster luminosity decay. Figure 2 summarizes the measured losses of luminosity during different stages of the collider cycle.

Beam-Beam Effects at Injection

During injection the long-range beam-beam effects cause proton losses (currently 5 to 10%). At the same time the antiproton life time is very good and only a fraction

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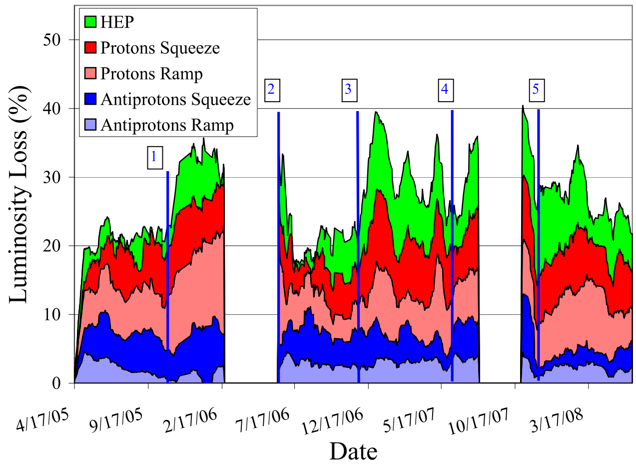

Figure 2: Luminosity loss budget over the last 3 years. The labels mark: 1. Commissioning of electron cooling. 2. Installation of extra separators and new collision helix. 3. Antiproton accumulation rate. 4. Correction of second-order chromaticity. 5. Implementation of antiproton emittance blowup.

of a per cent are lost. Observations show that mainly off momentum particles are lost (Fig. 3) and the betatron tune chromaticity has a remarkable effect. Early in Run II the chromaticity had to be kept higher than 8 units in order to maintain coherent stability of the intense proton beam, but after several improvements aimed at reduction of the machine impedance the chromaticity is about 3 units [6, 7]. Figure 3 shows an interesting feature in the behavior of two adjacent proton bunches (no. 20 and 21). Spikes in the measured values are instrumental effects labeling the time when the beams are cogged. Before the first cogging the bunches have approximately equal life times. After the first cogging bunch 20 exhibits faster decay, and bunch 21 after the second. Analysis of the collision patterns for these bunches allowed to pinpoint a particular collision point responsible for the life time degradation. The new "5 star" injection helix has been implemented late in 2007 which improved the proton life time [8, 9].

Low-Beta Squeeze

During the low-beta squeeze two significant changes occur - the β^* value is being gradually decreased from $\sim$1.5 m to 0.28 m (hence the name squeeze) and the helical orbits change their shape and polarity from injection to collision configuration. The latter poses a serious limitation since the beams separation at several long-range collision points briefly decreases from 5-6σ to $\sim$2σ. At this moment a sharp spike in losses is observed.

Another important operational concern is the tight aperture limitation in one of the two final focus regions (CDF). With dynamically changing orbit and lattice parameters the local losses are often high enough to cause a quench of the superconducting magnets even though the total amount of

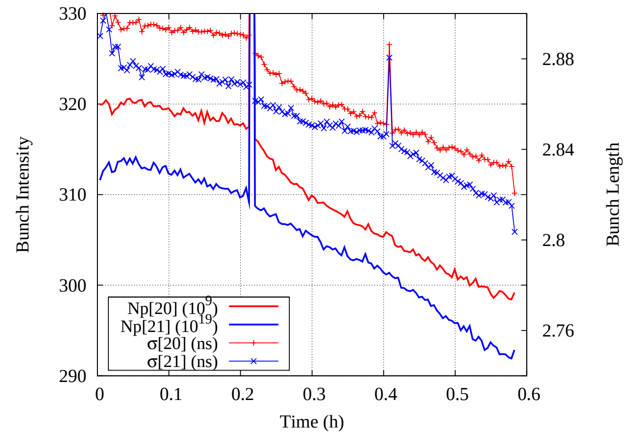

Figure 3: Intensity and length of proton bunches no. 20 and 21 during injection of antiprotons.

beam loss is small.

Besides orbit stability we have found two other factors to be important in maintaining low losses through the squeeze: antiproton beam brightness and betatron coupling. Figure 4 shows the dependence of proton losses on the antiproton beam brightness. Large amount of stores lost in this stage of the cycle caused by increase of the antiproton beam brightness after the 2007 shutdown demanded the commissioning of the antiproton emittance blowup system which is currently in operation.

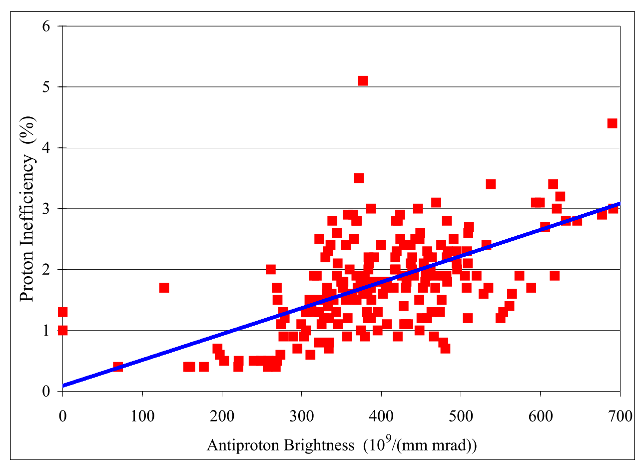

Figure 4: Proton losses in low-beta squeeze vs. antiproton beam brighness N/ϵ.

High Energy Physics

After the beams are brought into collisions at the main IPs, there are two head-on and 70 long-range collision points per bunch. Beam-beam effects caused by these interactions lead to emittance growth and particle losses in both beams.

During the running prior to the 2006 shutdown the beam-beam effects at HEP mostly affected antiprotons. The long-range collision points nearest to the main IPs were determined to be the leading cause for poor life time. Additional electrostatic separators were installed in order to increase the separation at these IPs from 5.4 to 6σ. Also, the betatron tune chromaticity was decreased from 20 to 10 units. Since then, the antiproton life time is dominated by losses due to luminosity and no emittance growth is observed provided that the betatron tune working point is well controlled.

Electron cooling of antiprotons in the Recycler and increased antiproton staching rate drastically changed the situation for protons. Figure 5 shows the evolution of head-on beam-beam tune shift ξ for protons and antiprotons. Note that prior to the 2006 shutdown the proton ξ was well under 0.01 and big boost occurred in 2007 when both beam-beam parameters became essentially equal. It was then when beam-beam related losses and emittance blowup started to be observed in protons.

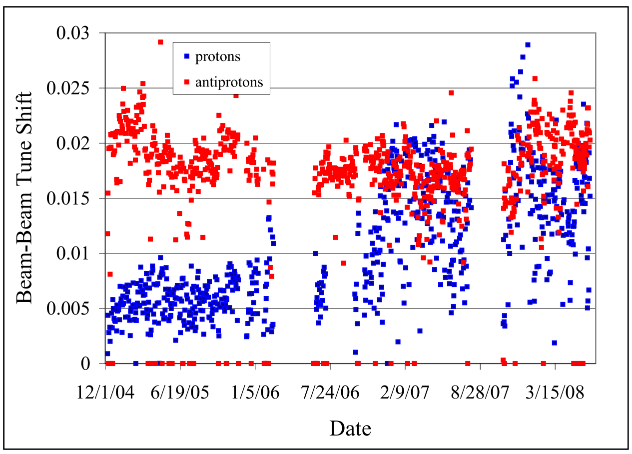

Figure 5: Head-on beam-beam tune shift vs. time.

Our analysis showed that deterioration of the proton life time was caused by a decrease of the dynamical aperture for off-momentum particles due to head-on collisions. It was discovered that the tevatron optics had large chromatic perturbations, e.g. the value of β^* for off-momentum particles could differ from that of the reference particle by as much as 20%. Also, the high value of second order betatron tune chromaticity generated a tune spread of $\sim$0.002. A rearrangement of sextupoles in order to correct the second order chromaticity was planned and implemented before the 2007 shutdown [10]. Figure 6 demonstrates the effect of this modification on integrated luminosity. Since the dependence of luminosity on time is very well fitted by a $L_0/(1+t/\tau)$ function one can normalize the luminosity integral for a given store to a fixed length T_0 by using the expression $L_0\tau \cdot ln(1+T_0/\tau)$ [11]. One can see that after the modification the saturation at luminosities above 2.6×10^{32} was mitigated and the average luminosity delivered to experiments increased by $\sim$ 10%.

Another step in the proton ξ happened after the 2007 shutdown when the transverse antiproton emittance de-

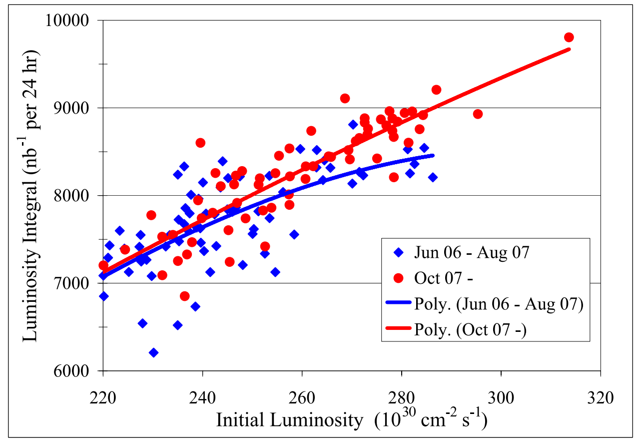

Figure 6: Luminosity integral normalized by 24 h vs. initial luminosity.

creased because of improvements in injection matching. The total attained head-on beam-beam tune shift for protons exceeded that of antiprotons and reached 0.028. This led to high sensitivity of the proton life time to small variations of the betatron tunes, and to severe background conditions for the experiments. The reason is believed to be the large betatron tune spread generated by collisions of largely different size bunches [12]. Indeed, at times the antiproton emittance was a factor of 5 to 6 smaller than the proton emittance.

To decrease the proton to antiproton emittance ratio a system has been commissioned which increases the antiproton emittance after the top energy is reached by applying wide band noise to a directional strip line (line 5 in Fig. 2). Currently, the optimal emittance ratio is $\sim$3.

SIMULATION TOOLS

In this section we describe the models and simulation tools which were used to study beam-beam effects in the Tevatron. We concentrate on incoherent effects occurring at high energy physics collisions. Discussion of long range effects at injection and coherent effects are beyond the scope of this report and can be found elsewhere [2].

Store Analysis Package

Beam-beam interaction is not the single strongest effect determining evolution of beam parameters at collisions. There are many sources of diffusion causing emittance growth and particle losses, including but not limited to intrabeam scattering, accelerating RF noise, and scattering on residual gas. Parameters of these mechanisms were measured in beam studies, and then a model was built in which the equations of diffusion and other processes are solved numerically [13]. This model is able to predict evolution of the beam parameters in the case of weak beam-beam effects. We use this approach on a store-by-store basis to monitor the machine performance in real time [14] because such calculations are very fast compared to a full numerical beam-beam simulation. Figure 7 presents an example comparison of evolution of horizontal proton emittance in an actual low luminosity store vs. calculations. They are good agreement.

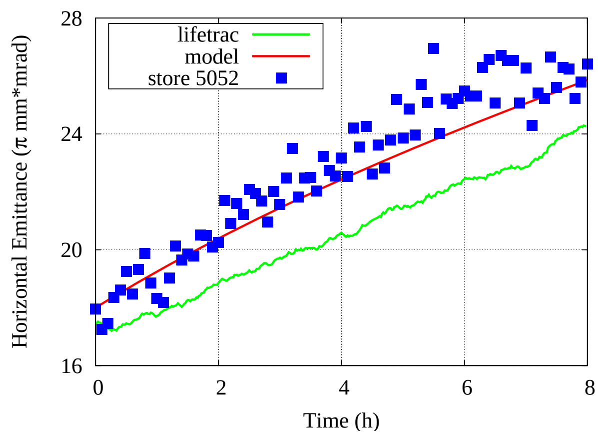

Figure 7: Comparison of proton bunch 6 horizontal emittance in store 5052 vs. two simulation methods.

Weak-Strong Code Lifetrac

Lifetrac is a parallel weak-strong macro particle tracking code [1]. The strong bunch is represented by a 3D Gaussian. The typical number of macro particles in the weak bunch is 10^4 and the number of simulation turns is 10^7, which is equivalent to 3 minutes of the real Tevatron time. In order to evaluate the dynamics of beam parameters on the time scale of $\sim$ 1-10 hours, the external diffusion rate in the simulation is artificially increased by a factor of 10 to 100 [15].

To study the dependence of beam-beam effects on various machine parameters the following features were incorporated into the code:

- Realistic machine optics via linear 6D maps calculated from actual beam measurement data, with full account of betatron coupling and optics differences on the proton and antiproton orbits.
- Collision point pattern individual for each bunch within the train, with beams separations obtained from beam measurements.
- First and second order chromaticity implemented as symplectic “chromatic drifts”.
- Beam-beam compensator (electron lens) element implemented as a thin nonlinear lens.

We have validated the code using available experimental data. As an example, Figs. 8 and 9 show a good reproduction of the two distinct effects in bunch to bunch differences caused by beam-beam effects: variation of vertical bunch centroid position due to long range dipole kicks, and variation of transverse emittance blowup caused by difference in tunes and chromaticities.

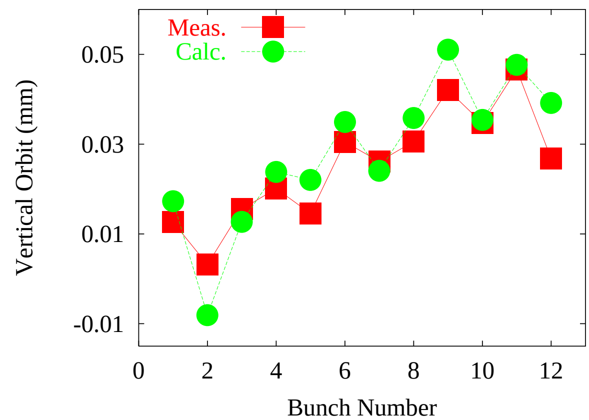

Figure 8: Bunch by bunch antiproton vertical orbit.

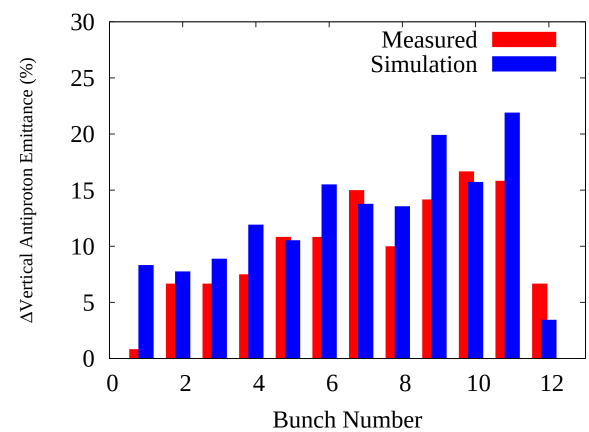

Figure 9: Bunch by bunch antiproton emittance growth. Measured in store 3554 (red) and simulated with lifetrac (blue).

The numerical simulation was used to justify the decrease of antiproton betatron tune chromaticity, reduction of the β^* from 0.35 m to 0.28 m (both in 2005). Importance of separation at the long range collision points nearest to the main IPs was also demonstrated.

Planning for the increase in amount of antiprotons available to the collider, we identified the large chromaticity of β^* as a possible source of the proton life time deterioration. Figure 10 shows the beam-beam induced proton life time for different values of ξ, and demonstrates the positive effect of corrected chromatic β^*.

Simulations revealed an interesting feature in the behavior of the proton bunch length at high values of ξ - the so-called bunch shaving, when the bunch length starts to decrease after initiating head-on collisions instead of steady growth predicted by the diffusion model (Fig. 11). This behavior was observed multiple times during HEP stores in

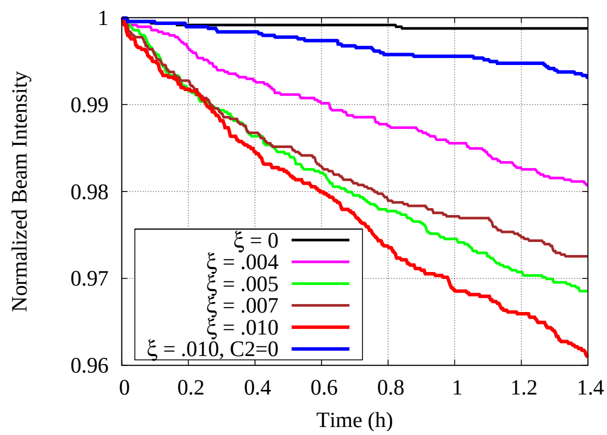

Figure 10: Proton intensity evolution for different values of beam-beam parameter per IP.

2007, being especially pronounced when the vertical proton betatron tune was set too high.

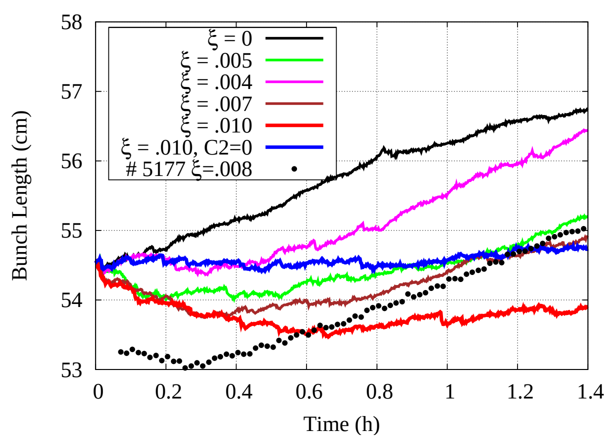

Figure 11: Effect of corrected second order chromaticity on the proton bunch length evolution.

SUMMARY

Over the past two years Tevatron routinely operated at the values of head-on beam-beam tune shift for both proton and antiproton beams exceeding 0.02. The transverse emittance of antiprotons is a factor of 3 to 5 smaller than the proton emittance. This creates significantly different conditions for the two beams.

Beam-beam effects in antiprotons are dominated by long-range interactions at four collision points with minimal separation. After the separation at these points was increased to 6σ no adverse effects are observed in antiprotons at present proton intensitites.

On the contrary, protons experience life time degradation due to head-on collisions with the beam of smaller transverse size. Correction of chromatic β-function in the final focus and reduction of betatron tune chromaticity increased dynamic aperture and improved proton beam life time.

Simulation of beam-beam effects developed for the Tevatron correctly describes many observed features of the beam dynamics, has predictive power and has been used to support changes of the machine configuration.

Further increase of the beam intensities is limited by the space available on the tune diagram near the current working point. A change of the tune working point from 0.58 to near the half integer resonance would allow as much as 30% increase of intensities but requires a lengthy commissioning period which makes it inlikely that this improvement will be realized during the time remaining in Run II.

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