OBSERVATIONS AND MODELING OF BEAM-BEAM EFFECTS AT THE TEVATRON COLLIDER *

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Abstract

This report summarizes recent experience with beam-beam effects at the Tevatron collider. Improvements in the beam lifetime resulting from the implementation of the a helical orbit are analyzed. The effect of second order chromaticity correction is studied.

INTRODUCTION

Since the start of the Tevatron collider Run II [1], the peak luminosity of the machine experienced steady growth and reached 2.92×10^{32} cm^{-2} s^{-1}. Together with the instantaneous luminosity the rate at which the luminosity integral is accumulated has been increasing and the level of 45 pb^{-1} per week was attained [2]. This progress became possible because of numerous improvements in the accelerator complex. Much of the luminosity gain came from the growth of antiproton production rate and commissioning of the electron cooling in the Recycler. Still, a big part of the increase in luminosity was the result of better understanding of the beam dynamics in the Tevatron collider and carefully planned improvements of the machine.

Two notable changes commissioned at the Tevatron after the last long shutdown which ended in June 2006 are the new collision helix and correction of the second-order betatron tune chromaticity.

In this report we describe our experience with beam-beam effects in the Tevatron operations before and after the 2006 shutdown. Only operation in the collision mode is covered, leaving effects at injection and energy ramp beyond the scope of this study. We discuss the motivation for implementation of the new helical orbits and second-order chromaticity correction, and present results of numerical simulations and experimental data chracterizing the results of modifications.

SUMMARY OF BEAM-BEAM EFFECTS

A comprehensive analysis of beam-beam effects in the Tevatron can be found in Ref. [3]. Here we will briefly describe the major effects and the most important changes in the collider operation since 2005.

The Tevatron is a proton-antiproton collider in which 36 bunches of each species collide at two interaction points occupied by the CDF and D0 detectors. Each beam consists of 3 12-bunch trains with equal gaps between the trains. An essential feature of the Tevatron is that protons and antiprotons share common vacuum chamber, thus generating multiple collision points along the circumference. To avoid these parasitic collisions the beams are directed along separated helical orbits by means of electrostatic separators. Because of this property two types of beam-beam effects can be distinguished: head-on and long-range collisions. Both types of collisions have an adverse effects on beam intensity lifetime and beam emittance.

The head-on beam-beam effects are characterized by the beam-beam parameter ξ which for the antiproton beam is equal to 0.011 per IP (both beams have round cross-sections). Before the commissioning of electron cooling in the Recycler, antiprotons in the Tevatron had transverse emittances of $\sim 12\,\pi$ mm mrad (95% normalized) at the top energy and beam-beam parameter for protons was $\sim .005$ per IP. Hence, beam-beam effects in the proton beam were dominated by the parasitic collisions.

After switching to the Recycler-only operation the antiproton emittance at 980GeV decreased to $\sim 9\,\pi$ mm mrad which together with the larger available antiproton intensities lead to growth of the proton ξ up to $\sim .008$.

Since the transverse emittance of protons is noticeably larger (18 π mm mrad) than that of antiprotons, most particles in the antiproton bunch does not experience nonlinear transverse beam-beam force. Essentially, the head-on interaction for antiprotons is limited to the linear tune shift which does not complicate tuning of the machine because store-to-store variation of the proton brightness is small. Situation for protons is quite different. A significant fraction of particles in the proton bunch have betatron amplitudes equal or larger than 1 sigma of the antiproton bunch. Thus, strong nonlinear fields tend to deteriorate the proton beam lifetime.

The betatron tune working point of the collider sits between the 5-th and 7-th order resonances which are driven by beam-beam effects. The available tune space between these resonances is about 0.028. This is comparable with the total proton beam-beam parameter which characterizes the tune spread in the beam. This reason demands a precise control of the proton beam betatron tunes and coupling. Our experience says that in order to keep the collider performance at the optimal level, the tunes should be stabilized to better than 0.002 which is complicated by varying intensity of antiprotons available for collisions.

A remarkable feature of beam-beam effects in the Tevatron is strong coupling between the transverse and longitudinal motion. In order to maintain coherent stability of the high intensity beams, the betatron tune chromaticity has to be kept at about 8 units. Another chromatic effect is the significant modulation of the beta-function for off-momentum particles. This results in a modulation of the beam-beam force by longitudinal motion and a deteriora-

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tion of momentum aperture. An often observed signature of the effect is a shortening of the bunch instead of the natural IBS-dominated bunch length growth.

NEW COLLISION HELIX

As mentioned, the strong betatron resonances affecting the collider performance are caused by beam-beam effects. It was shown that the strength of the 7-th order resonance is determined by the long-range collisions [4]. Also, analytical calculations and numerical simulations predicted that increasing the beam separation at the parasitic collision points nearest to the main IPs would give the largest benefit. To achieve this, two extra electrostatic separators were installed during the 2006 shutdown. As the result of their commissioning, the separation at the IPs upstream and downstream of CDF and D0 increased by 20% (Fig. 1).

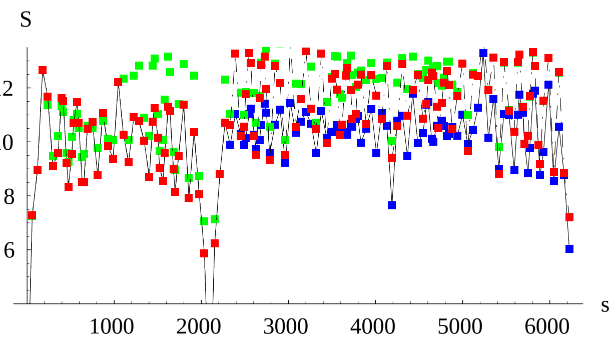

Figure 1: Radial beam separation at the collision helix in units of the beam size vs. azimuth starting from CDF IP. Blue - design helix, red - before installation of the new separators, green - present.

The increased separation showed itself in improved proton lifetime. Figure 2 shows a comparison of the single bunch proton intensity for two HEP stores before and after commissioning of the new helix. Initial intensities and emittances of antiprotons in these stores were close which allows direct comparison.

A noticeable change in the bunch length behavior can be observed in Fig. 3. Note that on the old helix protons experienced significant bunch shortening.

Single bunch luminosity and luminosity integral for the same two stores are shown in Fig. 4. As one can see, luminosity lifetime in the new configuration has improved substantially. The overall gain can be quantified in terms of luminosity integral over a fixed period of time (e.g. 24 hours) normalized by the initial luminosity. The value of this parameter has increased by 16%.

SECOND ORDER CHROMATICITY

Increasing the beam separation mitigated the long-range beam-beam effects. However, with advances in the antiproton production rate, the initial antiproton intensity at collisions has been rising continuously. Head-on beam-beam

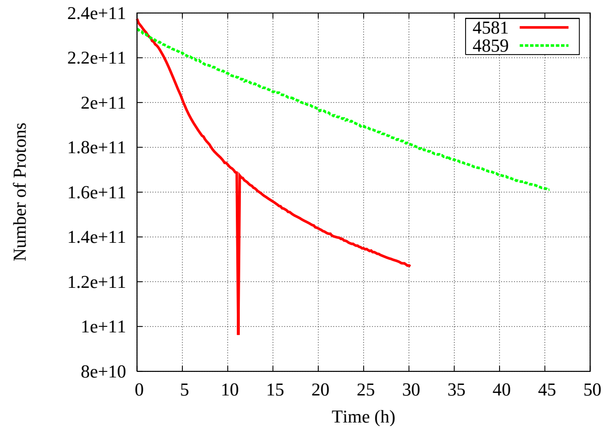

Figure 2: Single bunch proton intensity in two HEP stores. 4581 with the old helix, 4859 with the new helix.

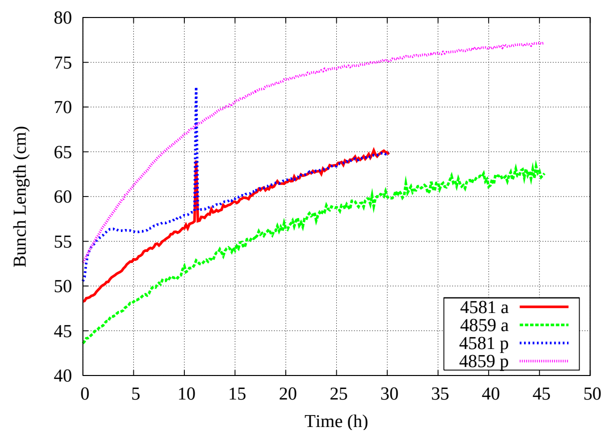

Figure 3: Proton and antiproton bunch length in two HEP stores. 4581 with the old helix, 4859 with the new helix.

parameter for protons was pushed up to 0.008 per IP which made the head-on beam-beam effects in the proton beam much more pronounced. One of the possible ways for improvement is a major change of the betatron tune in order to increase the available tune space. This, however, requires significant investment of the machine time for optics studies and tuning. A partial solution may be implemented by decoupling of the transverse and longitudinal motion at the main IPs, i.e. by reducing the chromatic beta-function.

The value of chromatic beta-function $(\Delta\beta/\beta)/(\Delta p/p)$ at both IPs is -600 which leads to the beta-function change of 10% for a particle with 1σ momentum deviation [5]. Thus, a large variation of focusing for particles in the bunch exists giving rise to beam-beam driven synchrobetatron resonances.

Numerical simulations with weak-strong code [6] predicted that elimination of the chromatic beta-function at the main IPs would mitigate the deterioration of proton lifetime at the present values of antiproton intensity even without switching to the new betatron tune working point. In Fig. 5 the simulated proton bunch intensities are plotted for the cases of corrected and uncorrected chromatic beta-

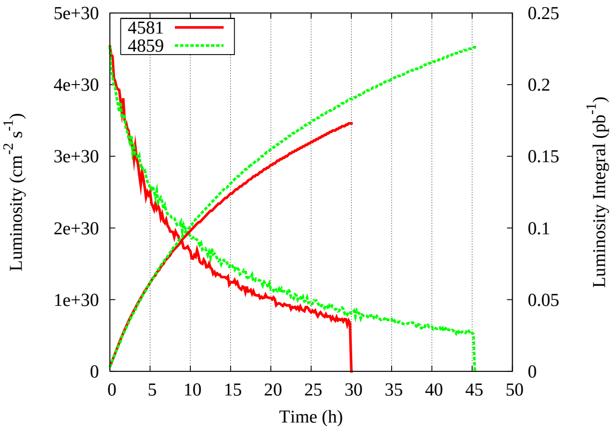

Figure 4: Single bunch luminosity and luminosity integral for stores 4581 and 4859.

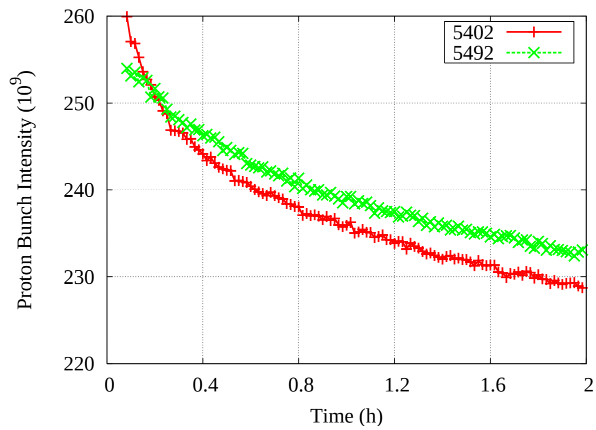

Figure 6: Intensity of the proton bunch no. 6 in the first two hours of a store. Store 5402 - before the correction of chromatic beta-function, store 5492 - after correction.

function.

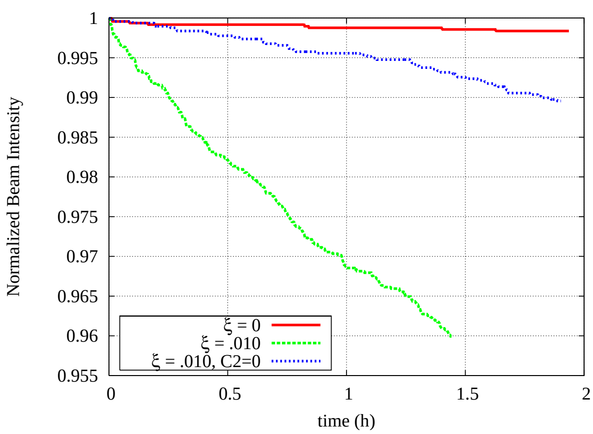

Figure 5: Normalized intensity of one proton bunch vs. time. Green line - $\xi = 0.01$, chromatic beta-function = -600. Blue line - $\xi = 0.01$, chromatic beta-function = 0. Red line - $\xi = 0$. Numerical simulation.

In order to achieve the desired smaller beta-function chromaticity, a new scheme of sextupole correctors in the Tevatron has been developed and implemented in May 2007. The scheme uses the existing sextupole magnets split into multiple families instead of just two original SF and SD circuits. The effect of introducing the new circuits is illustrated in Fig. 6. Again, the two stores chosen for comparison had close initial luminosities (5402 - $2.45 \cdot 10^{32}$ and 5492 $2.44 \cdot 10^{32}$ cm^{-2} s^{-1}). About 40% increase of the proton lifetime is observed in this case.

CONCLUSIONS

Beam-beam effects in the Tevatron are one of the limiting factors for further increase of the peak and integrated luminosity. Presently, the most remarkable effects occur in the proton beam experiencing lifetime degradation which becomes more pronounced as the intensity and brightness of the antiprotons are pushed up by advances in the antiproton source.

An increase of the radial separation of the two beams at the most critical parasitic collision points was achieved by commissioning of the new collision helix. This solved the problem with the proton losses at the luminosity level up to $2 \cdot 10^{32}$ and gained about 16% in the luminosity accumulation rate.

As the peak luminosity reached $2.5 \cdot 10^{32}$ deterioration of the proton intensity lifetime caused by head-on interaction became significant. The new sextupole scheme was implemented aimed at correction of the chromatic beta-function at the main IPs in order to eliminate the synchrobetatron resonances. Correction of the beta-function chromaticity has a clear positive effect of the proton lifetime.

At the same time, correction of the chromatic focusing errors presents the opportunity to move the betatron tune closer to the half integer resonance. The new working point would allow up to 30% increase in the proton beam intensity and corresponding gain in luminosity without growth of the antiproton production rate.

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