RESULTS OF HEAD-ON BEAM-BEAM COMPENSATION STUDIES AT THE TEVATRON*

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Abstract

At the Tevatron collider, we studied the feasibility of suppressing the antiproton head-on beam-beam tune spread using a magnetically confined 5-keV electron beam with Gaussian transverse profile overlapping with the circulating beam. When electron cooling of antiprotons is applied in regular Tevatron operations, the head-on beam-beam effect on antiprotons is small. Therefore, we first focused on the operational aspects, such as beam alignment and stability, and on fundamental observations of tune shifts, tune spreads, lifetimes, and emittances. We also attempted two special collider stores with only 3 proton bunches colliding with 3 antiproton bunches, to suppress long-range forces and enhance head-on effects. We present here the results of this study and a comparison between numerical simulations and observations, in view of the planned application of this compensation concept to RHIC.

The nonlinear forces between colliding beams are one of the main performance limitations in modern colliders. Electron lenses have been proposed as a tool for mitigation of beam-beam effects [1]. It was demonstrated that the pulsed electron current can produce different betatron tune shifts in different proton or antiproton bunches, thus cancelling bunch-to-bunch difference generated by long-range beam-beam forces [2]. In these experiments, the electron beam had a flat transverse current-density distribution, and the beam size was larger than the size of the circulating beam. To first order, the effect of the electron lens was a linear betatron tune shift.

The present research goes a step further. We are studying the feasibility of using the magnetically confined, nonrelativistic beam in the Tevatron electron lenses to compensate head-on beam-beam effects in the antiproton beam. For this purpose, the transverse density distribution of the electron beam must mimic that of the proton beam, so that the space charge force acting on the antiprotons is partially canceled. The betatron phase advance between the interaction points and the electron lens should also be close to an integer multiple of π.

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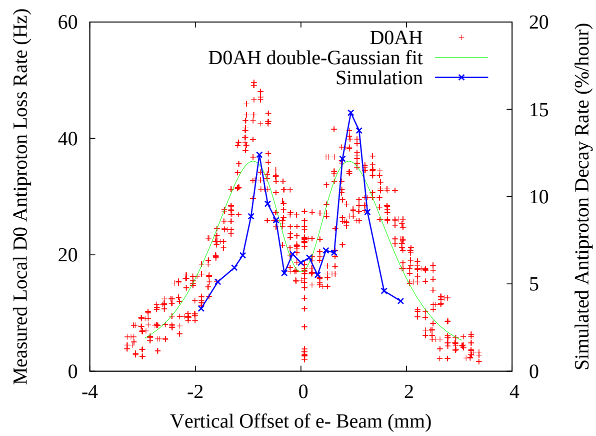

Figure 1: Measured and calculated loss rates during a vertical beam scan.

Currently, during regular Tevatron operations, both stochastic and electron cooling are used to reduce the transverse emittance of antiprotons. Under these conditions, antiprotons are transversely much smaller than protons, making head-on effects essentially linear. Antiproton losses due to beam-beam are caused by long-range interactions and rarely exceed 5% per hour. While an improvement of the Tevatron performance by head-on beam-beam compensation is not foreseen, we are interested in the feasibility of the concept and in providing the experimental basis for the simulation codes used in the planned application of electron lenses to the RHIC collider at BNL [3].

A 10.2-mm-diameter electron gun with a current density profile close to a Gaussian distribution was designed and built [4]. Its r.m.s. width is 2.0 mm at the gun, and its size in the overlap region is controlled by the ratio between gun and main solenoid fields. The gun was installed in the second Tevatron electron lens (TEL2) in June 2009. Experiments were carried out between September 2009 and July 2010. Preliminary results were discussed in Ref. [5].

Because of the nonlinear fields, alignment between electrons and antiprotons is critical. We performed several position scans to ensure that the response of the beam position monitors is reliable for both fast antiproton signals and for slower electron signals. These position scans were also useful to assess the effects of misalignments on losses and to compare the experimental results with numerical calculations. We simulated losses during a vertical alignment scan using the weak-strong numerical tracking code Lifetrac [6]. The model included the full collision pat-

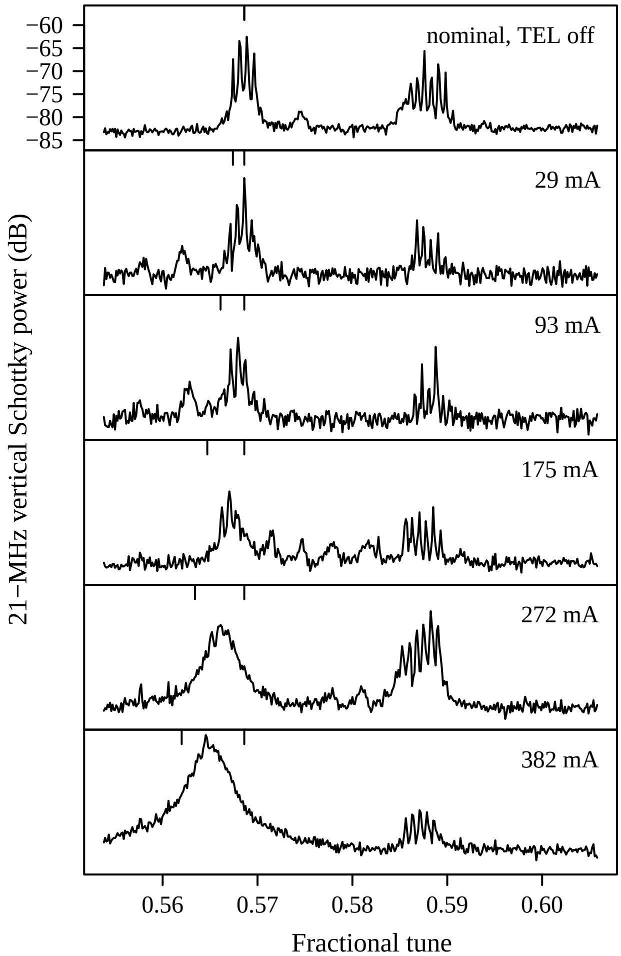

Figure 2: Schottky spectra vs. electron lens current.

tern for the relevant antiproton bunch and a thin-kick Gaussian electron beam implemented via an analytical formula. The beam parameters corresponded to the conditions at the time of the measurement at the end of Store 7718. We tracked a bunch of 5,000 macroparticles for 3×10^6 turns for various vertical electron beam misalignments and evaluated the intensity loss rate. The simulation reproduced two features observed in experiments. First, the simulation performed at the nominal antiproton working point ($Q_x = 0.575$, $Q_y = 0.581$) predicted no losses for all values of the vertical misalignment. Similarly to the experiment, the verical tune in the simulation had to be lowered by 0.003 to produce particle losses. Second, the simulation at the modified working point demonstrated the characteristic double-hump structure of the loss rate with the position of peaks in good agreement with the measurements. Fig. 1 shows the measured loss rates (red crosses) and the simulated decay rates (blue crosses and lines). Both electron and antiproton vertical r.m.s. beam sizes in the overlap region were equal to 0.6 mm.

The effect of the electron lens on the incoherent tune distribution could be observed directly during dedicated antiproton-only stores, when there was no contamination

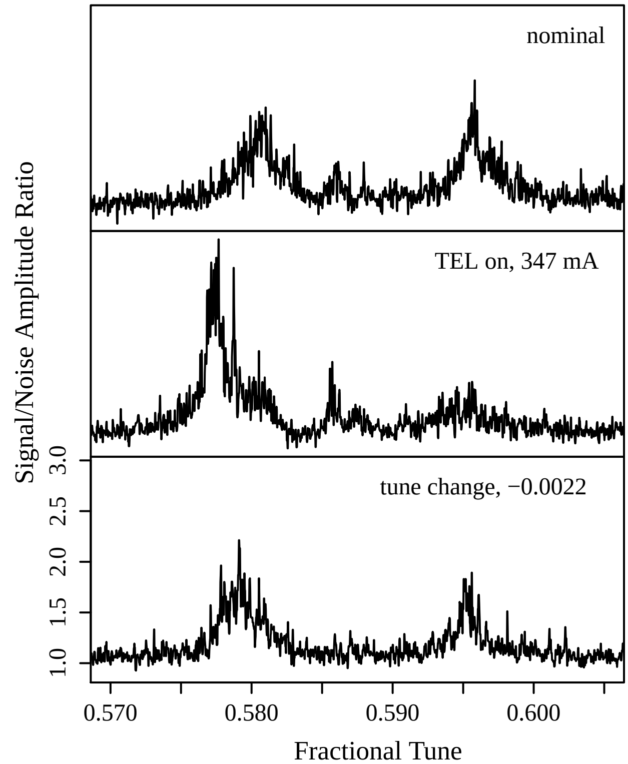

Figure 3: Spectra of transverse coherent modes.

from protons in the 21-MHz Schottky signal. Figure 2 shows the vertical Schottky signal as a function of electron lens current. The vertical tick marks indicate the expected linear beam-beam parameter ξ_e due to N_e electrons with Gaussian standard deviation σ_e and velocity $\beta_e c$ at a location where the amplitude function is β:

$$\xi_e = -\frac{N_e r_p \beta (1+\beta_e)}{4\pi\gamma_p\sigma_e^2}. \quad (1)$$

Here, r_p represents the classical radius of the proton and γ_p is the relativistic factor of the circulating beam. The width of the vertical tune line agrees well with the hypothesis that ξ_e represents the maximum tune shift.

A system for bunch-by-bunch measurements of transverse coherent beam-beam oscillations was also developed [7]. It is based on the signal from a single beam position monitor in a region of the ring with high amplitude functions. Because of its frequency resolution and its single-bunch capability, this system complements the existing Schottky detectors and direct-diode-detection baseband tune monitor. Figure 3 shows the signal from a single antiproton bunch towards the end of a regular collider store (Store 7719). The top plot shows the spectrum of coherent modes under nominal conditions. The linear beam-beam parameter per interaction point was 0.0050 for antiprotons and 0.0023 for protons. The middle plot corresponds to the electron lens acting on the bunch, with $\xi_e = -0.006$. For comparison, the bottom plot shows the effect of lowering the vertical antiproton tune by 0.0022. In the middle

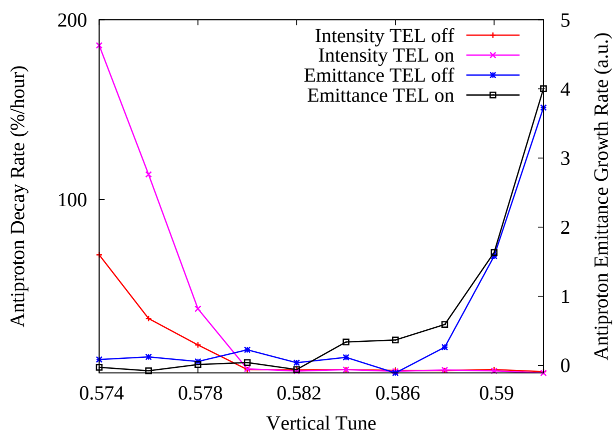

Figure 4: Numerical simulation of a diagonal tune scan.

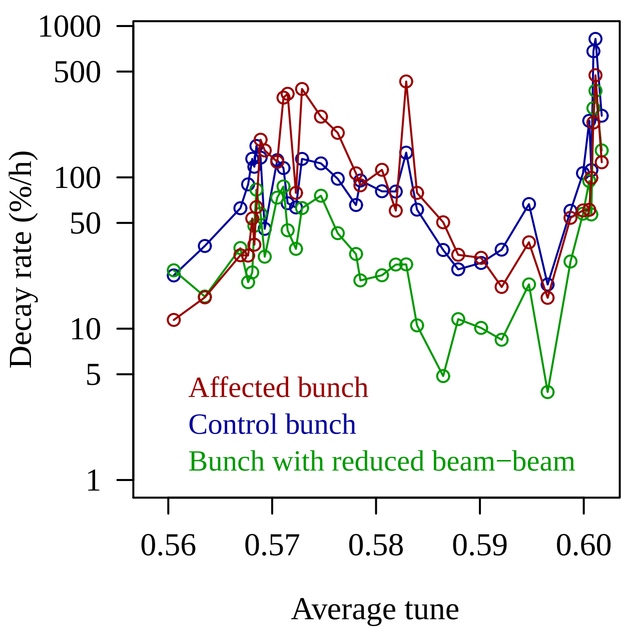

Figure 5: Measured decay rates during diagonal tune scan.

plot, one can see a downward shift of the first eigenmode and a suppression of the second. This suppression could be caused in part by the antiproton tune moving away from the proton tune. Relating the reduced width of a coherent mode to a smaller tune spread requires further investigation.

To enhance head-on effects and to suppress long-range forces in the Tevatron, two special collider stores were attempted. In these stores, 3 proton bunches collided with 3 antiproton bunches. The bunches were equally spaced around the machine. Antiprotons were intentionally heated to increase their emittance. Unfortunately, during the first experiment, the emittances of two proton bunches increased dramatically between the beta squeeze and collisions, before the beginning of the study. Hence, the store could not be used for our purposes.

A smaller blow up of proton emittances occurred before the second study as well, making conditions far from ideal: the antiproton beam-beam parameter was less than 0.015, electron sizes could not be matched to proton sizes, and we had to sacrifice compensation strength ($\xi_e = -0.002$). Nevertheless, several tune scans were performed, both vertically and diagonally in the tune diagram. They provided useful information on the available tune space for comparisons with simulation codes. Figure 4 shows the calculated antiproton decay rates and emittance growth rates from Lifetrac as a function of tune in a diagonal scan. The horizontal scale is the bare lattice tune plus half of the beam-beam parameter. As the tune approaches the 7th order resonance (0.571) from above, loss rates increase dramatically. Increasing the tune causes emittance growth. According to this calculation, with the simulated experimental conditions described above, the electron lens does not cause harm in the stable region and it makes things worse outside.

Figure 5 shows the measured decay rates for the 3 antiproton bunches as a function of the average tune (from the 1.7-GHz Schottky detector) during a diagonal scan: the bunch affected by the electron lens (A25, red), the control bunch (A13, blue), and the bunch colliding with the two least dense proton bunches (A1, green). Lifetimes and tune space are obviously better for A1. The affected bunch is shifted compared to the control bunch by approximately the correct amount (0.002). Nonlinear resonances are stronger with the lens on, except the 3/5. There are regions where the affected bunch has better lifetime, but this special 3-on-3 store was not enough to clearly see a reduction or an improvement in the choice of working point. On the other hand, the region of available tune space is well reproduced by the simulations.

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REFERENCES

[1] V. Shiltsev et al., Phys. Rev. ST Accel. Beams 2, 071001 (1999).

[2] V. Shiltsev et al., Phys. Rev. Lett. 99, 244801 (2007); V. Shiltsev et al., New J. Phys. 10, 043042 (2008); V. Shiltsev et al., Phys. Rev. ST Accel. Beams 11, 103501 (2008).

[3] W. Fischer et al., 'Status of RHIC Head-on Beam-beam Compensation Project,' these proceedings, THP055.

[4] V. Kamerdzhiev et al., Proc. 2008 Eur. Part. Accel. Conf. (EPAC08), Genoa, Italy, p. 3500, THPP058.

[5] A. Valishev et al., Proc. 2010 Int. Part. Accel. Conf. (IPAC10), Kyoto, Japan, p. 2084, TUPD070.

[6] D. Shatilov, et al., 'Lifetrac Code for the Weak-Strong Simulation of the Beam-Beam Effects in Tevatron', Proc. 2005 Part. Accel. Conf. (PAC05), Knoxville, TN 2005, p. 4138.

[7] G. Stancari et al., Proc. 14th Beam Instrum. Workshop (BIW10), Santa Fe, New Mexico, p. 363, TUPSM077; G. Stancari and A. Valishev, in preparation.