PROGRESS WITH TEVATRON ELECTRON LENS HEAD-ON BEAM-BEAM COMPENSATION *

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Abstract

Tevatron electron lenses have been successfully used to mitigate bunch-to-bunch differences caused by long-range beam-beam interactions. For this purpose, the electron beam with uniform transverse density distribution was used. Another planned application of the electron lens is the suppression of tune spread due to head-on beam-beam collisions. For this purpose, the transverse distribution of the e^- beam must be matched to that of the antiproton beam. In 2009, the Gaussian profile electron gun was installed in one of the Tevatron electron lenses. We report on the first experiments with non-linear beam-beam compensation. Discussed topics include measurement and control of the betatron tune spread, importance of the beam alignment and stability, and effect of electron lens on the antiproton beam lifetime.

INTRODUCTION

Electron lenses have been proposed as a tool for mitigation of beam-beam effects in the Tevatron collider [1]. A mode of operation, in which the pulsed electron current produces different betatron tune shift in different proton or antiproton bunches, thus cancelling bunch-to-bunch difference generated by long-range beam-beam effect, was successfully demonstrated in 2007 [2]. In that experiment, the electron beam had uniform transverse density distribution, and the beam size was appreciably larger than the size of the circulating beam. In such conditions the effect of the electron lens is limited to linear betatron tune shift.

The second, more promising application of the electron lens is the compensation of head-on beam-beam effect in the antiproton beam. For this, the transverse density distribution in the e^- beam must mimic that of the proton beam, so that space charge seen by antiprotons is canceled. A Gaussian profile electron gun was developed [3] and installed in the Tevatron electron lens no. 2 (TEL-2) during the 2009 Summer shutdown.

Another major advance of the TEL beam-beam compensation (BBC) project resulted from the development and commissioning of the new gun modulator, capable of pulsing the e^- beam on individual circulating bunches [5].

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This paper reports on the commissioning and first studies of beam-beam compensation with the Gaussian TEL-2 beam. We describe the upgrade and calibration of TEL-2 beam position monitoring (BPM) system, discuss the procedure of alignment of e^- and antiproton beams, and present the first results of TEL-2 BBC during a high energy physics (HEP) store, along with the future plans.

IMPROVEMENT OF THE BPM SYSTEM

A detailed description of the TEL BPM system can be found in [3]. The recent developments include a new BPM software, which allows faster readout of the beam coordinates, and a thorough calibration of the whole system.

A significant factor contributing to the improved accuracy of reporting of the electron beam coordinates is a much shorter (400 ns) e^- pulse generated by the new modulator. It was shown by bench measurements that the BPM response is affected by the difference of the characteristic frequencies of circulating bunch and electron beam signals [6]. Our measurements have demonstrated that with the new modulator the offset between the coordinates reported for electron and antiproton beams is less than 0.2 mm, even with a faster readout time of the new BPM software.

Calibration of the BPM system was performed based on the known position bumps of the circulating beam. The circulating beam was moved inside TEL-2 using the ring dipole correctors, and the magnitude of the shift was controlled by the ring BPM system. From these measurements it was found that the TEL-2 BPM calibrations are within 3% of expected, and the position measurement resolution is approx. 30 μm. The BPM calibration data was then used

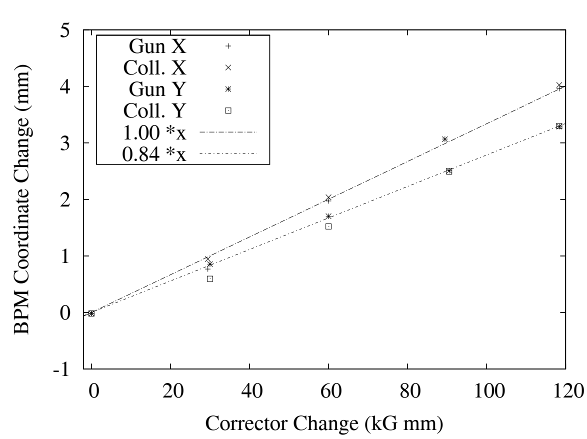

Figure 1: TEL-2 BPM and magnetic corrector calibration.

to verify the TEL-2 magnetic corrector calibration (Fig. 1). It was found that in the horizontal plane the measured effect of correctors is in good agreement with expectations, while in the vertical plane there is a 15% systematic discrepancy. This discrepancy is currently not understood.

BEAM ALIGNMENT

Previous TEL BBC studies demonstrated the importance of relative transverse alignment of electron and antiproton beams. This is especially critical for the case of highly nonlinear Gaussian e^- profile. We have verified the alignment using the following method. The transverse position of electron beam was set to be on axis of the antiproton beam with the use of TEL-2 BPM system. The transverse position and angle of the e^- beam was then scanned in the horizontal and vertical plane, and antiproton losses recorded. This scan produces a characteristic double-hump in the shape of losses vs. beam offset (Fig. 2). The scan was performed at a late stage of a HEP store, when the antiproton beam-beam parameter was 0.012 (about 1/2 of the initial). TEL was acting on a single bunch, producing the tune shift of 0.007. Remarkably, the lens would not generate any losses even for misaligned beams if the vertical betatron tune stays far from 7th order resonance. In order to produce the loss in Fig. 2 the vetrical working point was lowered by 0.003. The solid curves in Fig. 2 represent a fit of the experimental data with two Gaussians with amplitudes of opposite sign. For the horizontal scan, the sigma of the inner Gaussian (σ_1) is 0.74 mm, of the outer Gaussian (σ_2) is 0.9 mm. Fo the vertical scan, $\sigma_1 = 0.585$ mm, $\sigma_2 = 1.05$ mm. One would expect $\sigma_1 = \sigma_e$, and $\sigma_2 = \sqrt{\sigma_e^2 + \sigma_a^2}$, which for the vertical plane produces an agreement to within 20%. The somewhat larger width of the horizontal profiles may be explained by the fact that the e^- beam enters and exits the interaction region horizontally.

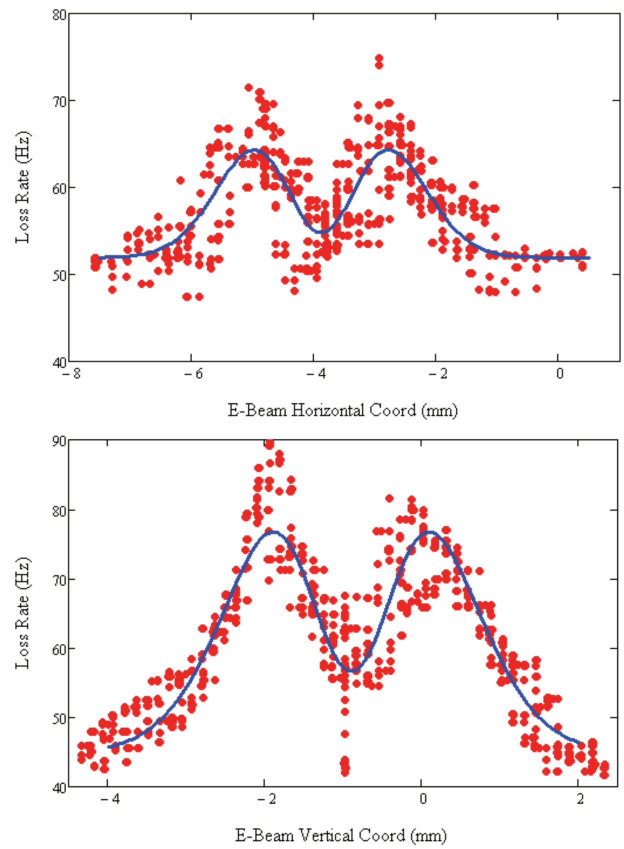

Figure 2: Antiproton losses as a function of relative e^--antiproton beam position. $\sigma_e = 0.52$ mm, antiproton $\sigma_x = 0.45$ mm, $\sigma_y = 0.6$ mm.

TUNE SPREAD GENERATION

The nonlinear density distribution of the electron beam should produce a betatron tune spread in the antiproton beam, which is determined by the electron-antiproton beam-beam parameter

$$\xi_{x,y} = -\frac{r_0 I L (1+\beta_e)\beta_{x,y}}{4\pi\gamma e c \beta_e \sigma_e^2},$$

where r_0 is the proton classical radius, I is the electron current, L is the interaction length, $c\beta_e$ is the electron velocity, γ is the antiproton relativistic factor, β is the lattice beta-function, and σ_e is the size of e^- beam, and the minus sign denotes the defocusing interaction between electrons and antiprotons.

We have observed the effect of the Gaussian TEL-2 beam on the antiproton tune spread in a dedicated beam study, where only 4 antiproton bunches were circulating in the machine. In such conditions, the conventional 21 MHz Shottky spectrum is a good indicator of the antiproton tune spread, since there is no contamination by the proton signal. In Figure 3 the vertical Shottky spectrum is plotted for three values of electron beam current. The observed tune shift and enhancement of the tune spread is in good agreement with expectations.

For observation of the effect of TEL on antiproton tune during a HEP store, a system was developed for bunch-by-bunch detection of transverse coherent oscillations based on the signal from a single BPM [7].

EFFECT ON ANTIPROTON BEAM

Currently, the large difference between transverse emittances of protons and antiprotons (caused by the electron cooling of antiprotons) results in the absence of head-on beam-beam effect in the antiproton beam [8]. Hence, it was not possible to observe a positive effect of head-on BBC during normal collider operation. However, the experiments were carried out in order to demonstrate the absence of detrimental effects of Gaussian TEL-2 beam on the antiproton dynamics. The e^- beam was pulsed on a single antiproton bunch during a few HEP stores in order to evaluate the effect of nonlinear BBC on the antiproton beam intensity and emittance life time. In Fig. 4 the in-

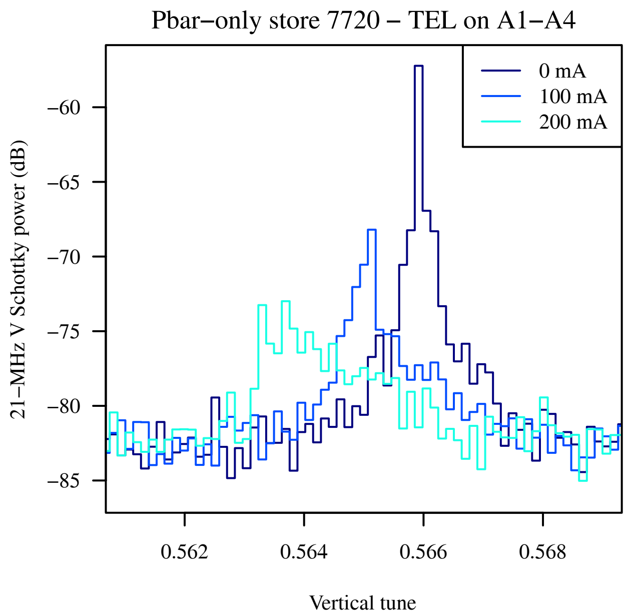

Figure 3: Vertical betatron tune spread in antiproton beam as a function of TEL-2 current.

tensities of antiproton bunches no. 6 and 18 are plotted as a function of time at the beginning of the Tevatron store 7661, which had an initial luminosity of $3.5 \cdot 10^{32}$ cm^{-2} s^{-1}. TEL-2 was acting on bunch no. 18. There is no life time degradation up to the peak current of 150 mA. At higher current, the vertical tune of bunch 18 approaches the known 7th order resonance (generated by long-range beam-beam interaction), which is known to cause particle losses. As the store progresses, the strength of the resonance decreases, and the threshold TEL current reaches 500 mA. It was also demonstrated that TEL-2 does not cause antiproton emittance growth.

SUMMARY

The Tevatron beam-beam compensation project have seen significant progress over the past year, owing to the successful commissioning of the Gaussian profile electron gun. The accompanying improvements in the TEL-2 beam diagnostics allowed better control of the e^- beam position. Together with the development of the Tevatron orbit stabilization system this results in a reliable and accurate alignment of electron and antiproton beams.

In a single beam study it was demonstrated that the Gaussian TEL-2 beam creates the expected betatron tune spread in the antiproton beam. Current beam conditions at the Tevatron do not produce a significant head-on beam-beam effect in the antiproton beam, which the electron lens could compensate. The TEL-2 beam does not cause beam intensity or emittance life time degradation.

In the nearest future we plan to demonstrate the ultimate usefulness of the head-on BBC in a dedicated HEP store. In this store, the beam parameters would be made such that

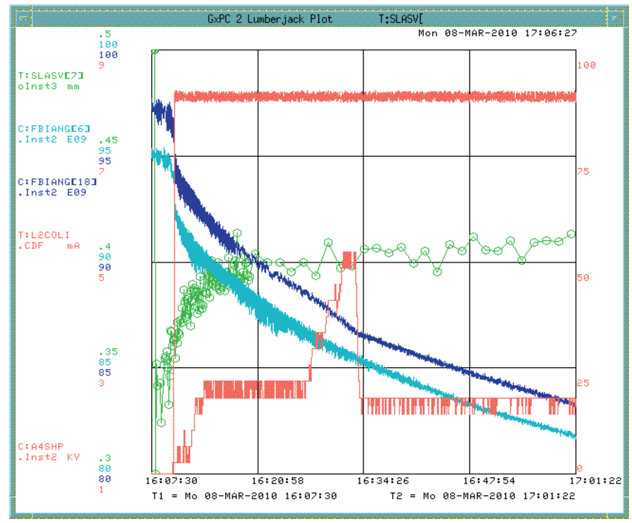

Figure 4: Dynamics of antiproton beam parameters in-store with and without TEL. Blue and cyan traces are the intensities of bunch 18 and 6, correspondingly. Red - average TEL-2 current.

the long-range beam-beam effect in antiprotons would be weak, while the head-on interaction would be enhanced. This can be easily achieved by injecting fewer bunches (e.g. 3 instead of 36 per beam), and disabling electron cooling of antiprotons, which would result in essentially equal proton and antiproton emittances.

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