TEVATRON ELECTRON LENS AND IT'S APPLICATIONS*

X.L. Zhang, V. Shiltsev, A. Valishev, FNAL, Batavia, IL 60510, U.S.A.
V. Kamerdzhiev, FZ-Jülich, IKP, Germany.
A. Romanov, BINP, Novosibirsk, Russian.

Abstract

The Tevatron Electron Lenses (TELs) are designed for the purpose of the Beam-beam tuneshift compensation. Now they are the vital parts of the Tevatron. In this report, their daily operations and beam study results are presented. Their possible future applications are discussed as well.

INTRODUCTION

Fermilab's Tevatron is a 980 GeV particle collider ring in which tightly focused beams of protons and antiprotons collide in two dedicated interaction points (IPs). Both beams share the same beam pipe and magnet aperture by placing the beams on separated helical orbits everywhere except the main IPs using high-voltage (HV) electrostatic separators. However, the effects due to electromagnetic beam-beam interactions at the main IPs together with long-range interactions between separated beams limit the collider performance, reducing the luminosity integral per store (period of continuous collisions) by 10-30%[1]. The long-range effects which (besides being nonlinear) vary from bunch to bunch are particularly hard to treat. To compensate these beam-beam effects, the electron lenses were proposed [2] and installed at the Tevatron [3]. An electron lens employs space-charge force of a low-energy beam of electrons that collides with the high-energy bunches over an extended length L_e. Such a lens can be used for linear and nonlinear force compensation depending on electron current-density distribution $j_e(r)$ and on the ratio of the electron beam radius a_e to the rms size σ of the high-energy beam at the location of the lens. The electron transverse current profile (and thus the radial dependence of electromagnetic (EM) forces due to electron space-charge) can easily be changed for different applications. The electron-beam current can be adjusted between individual bunches, equalizing the bunch-to-bunch differences and optimizing the performance of all bunches in a multi-bunch collider by using fast high voltage modulator [6].

A shift of the betatron frequency (tune) of high-energy particles due to EM interaction with electrons is a commonly used "figure of merit" for an electron lens. A perfectly steered round electron beam with current density distribution $j_e(r)$, will shift the betatron tunes $Q_{x,y}$ of small amplitude high-energy (anti-)protons by [2]:

$$dQ_{x,y} = \pm \frac{\beta_{x,y} L_e r_p}{2\gamma ec} \cdot j_e \cdot \left(\frac{1 \mp \beta_e}{\beta_e} \right) \qquad (1),$$

where the sign reflects focusing for protons and defocusing for antiprotons, $\beta_e = v_e/c$ is the electron beam velocity, $\beta_{x,y}$ are the beta-functions at the location of the lens, L_e denotes the effective interaction length between the electron beam and the protons or antiprotons, $r_p = e^2/mc^2 = 1.53\times10^{-18}$ m is the classical proton radius, and $\gamma_p = 1044$ the relativistic Lorentz factor for 980GeV protons.

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#zhangxl@fnal.gov

TEVATRON ELECTRON LENSES

Both Tevatron Electron Lenses (TELs) direct their beam against the antiproton flow. The TELs operate at up to 10kV electron energy and can shift the betatron tune by as much as $dQ_{x,y}^{max} \approx 0.008$ [4] depending on the type of the electron gun design. The layout of the Tevatron Electron Lens 2 (TEL2) is shown below. TEL2 is installed in the Tevatron at the location where β_x/β_y=68m/150m whereas TEL1 is installed at the different location where β_x/β_y=104m/29m. The design difference between the two lenses is that the TEL1 bending section has a 90° angle between the gun solenoid and the main solenoid while this angle is about 57° in TEL2.

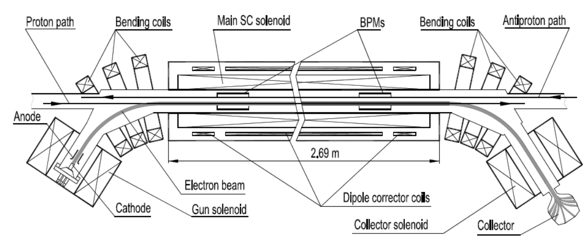

Figure 1: TEL2 layout.

The designed and measured electron beam profiles are flattop, smooth edge flattop (SEFT) and Gaussian, which are shown below:

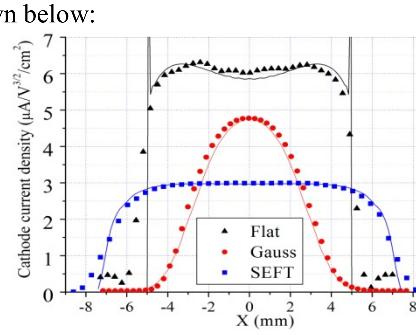

Figure 2: Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data are scaled to refer to an anode–cathode voltage of 10 kV.

The SEFT gun has been designed and built in order to generate much less nonlinearity than the flattop gun at the transit edges so that it causes much less proton loss when electron beam is not perfectly aligned with proton beam it acted on. The Gaussian gun was installed recently and hasn't been studied for beam-beam compensation effects yet.

BEAM-BEAM COMPENSATION STUDIES

The experimental beam-beam compensation (BBC) studies[4] were carried out at the Tevatron for either dedicated machine time or parasitically during the High Energy Physics (HEP) store and mostly done with protons. The tune shift, beam lifetime and halo loss rate at both physics detectors are measured and some typical data is presented in the following sections.

Tune Shift

Figure 3 presents the vertical tune shift induced by the TEL2 electron current from the SEFT gun. There is an excellent agreement between the tune shift measured by the 1.7 GHz Schottky tune monitor and the theory. The dependence of the tune shift on the electron energy also agrees with the theoretical predictions

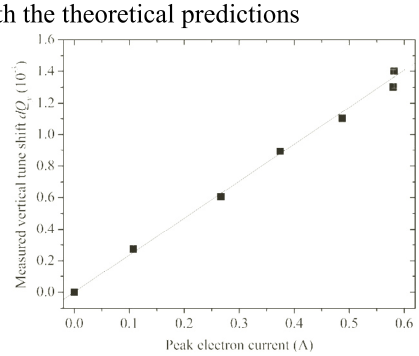

Figure 3: Vertical betatron tune shift of the 980 GeV proton bunch vs. the peak electron current in TEL2.

The results displayed in Figure 4 show the 980 GeV antiproton tune shift measurements at various cathode voltages U_c, ranging from -6 to -13 kV. As the total electron beam current (which is determined by the gun cathode–anode voltage difference and shown by the dashed line) was kept constant, the total electron space-charge Q_{SC} grew for smaller values of U_c, inducing correspondingly larger tune shift.

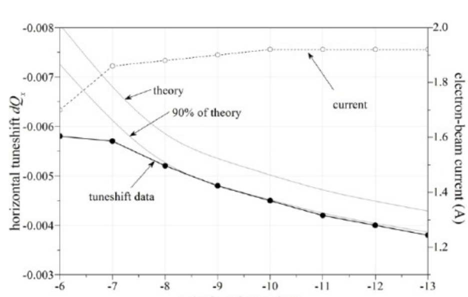

Figure 4: Horizontal tune shift of 980 GeV antiprotons versus TEL1 cathode voltage (electron energy). This data was obtained using the flattop electron gun.

Beam Lifetime

Improvement of the proton intensity lifetime (up to 40%) has been observed in experiments performed with TEL1. TEL1's large horizontal beta-function produce mostly horizontal proton tune shifts up. As the proton horizontal tunes are lower by $\Delta Q_x \approx$ -(0.002 - 0.003) for the bunches at the beginning of the bunch trains, P1, P13, and P25 [1], the TEL1 can effectively compensate for those. Figure 5 shows the dependence of D0 proton halo loss rate on the TEL1 electron current. These halo loss rates are measured bunch-by-bunch and are inversely proportional to the proton bunch lifetime. In this experiment, TEL1 was acting on P13 which has the lowest horizontal tune. Bunch neighbour bunch P14 unaffected by TEL1 was chosen as a reference bunch because its behaviour in terms of halo and lifetime was very similar to P13 in case without TEL. The loss rate of P13 dropped by about 35% once a 0.6 A-peak electron current was turned on, while the P14 loss rate stayed unaffected. After about 12 min the e-current was turned off which made the P13 loss rate return to the reference level. The loss reduction has been repeated several times over the next 4 h in this store and it was confirmed in several other HEP stores

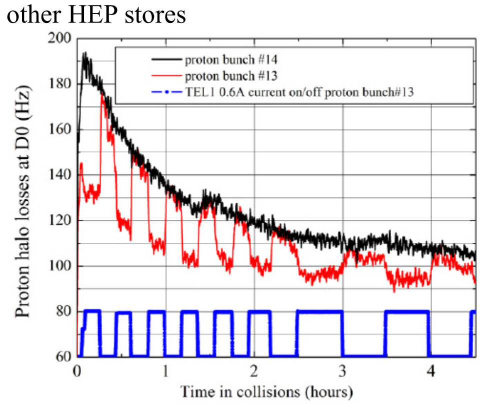

Figure 5: Proton beam halo rates as measured by D0 counters: black, for reference bunch 14; red, for bunch no. 13 affected by TEL1 (first 4 h in store #5352 L=197 × 10^{30} $cm^{-2}s^{-1}$).

The TEL-induced improvements in the luminosity lifetime of about 10% are significantly smaller than the corresponding changes in the proton intensity lifetime (about a factor of 2) because the luminosity decay is driven mostly by other factors, the strongest being the proton and antiproton emittance increase due to intra-beam scattering and the antiproton intensity decay due to luminosity burnout.

Usually, the proton lifetime, dominated by beam–beam effects, gradually improves with time in a HEP store and reaches about 50–100 h after 6–8 h of collisions. This is due to the decrease of the antiproton intensity and increase of antiproton emittance. In store #5119, we studied the effectiveness of the BBC by repeatedly turning on and off TEL2 on a single bunch P12 every half-an-hour for 16 h. The relative bunch intensity lifetime improvement R is plotted in Figure 6.[5]

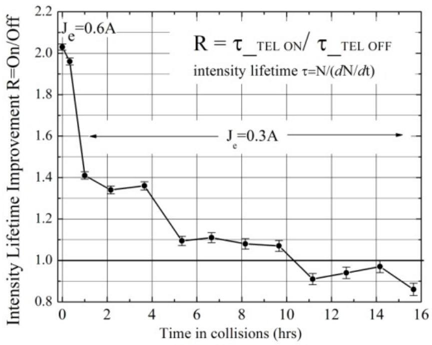

Figure 6: Relative improvement of the TEL2 induced proton bunch #12 lifetime vs. time (store #5119, Dec. 12, 2006, initial luminosity $L = 159 \times 10^{30}$ cm^{-2} s^{-1}).

The first two data points correspond to $J_e = 0.6$ A, but subsequent points were taken with $J_e = 0.3$ A to observe the dependence of the compensation effect on the electron current. The change of the current resulted in a drop of the relative improvement from $R = 2.03$ to 1.4. A gradual decrease in the relative lifetime improvement is visible until after about 10 h, where the ratio reaches 1.0 (i.e. no gain in the lifetime). At this point, the beam–beam effects have become very small, providing little to compensate. Similar experiments in several other stores with initial luminosities ranging from 1.5×10^{32} to 2.5×10^{32}cm^{-2}s^{-1} reproduced these results.

Collimation Effect

There are always particles with amplitudes beyond the electron beam cross section. For such particles with oscillations larger than the size of the electron beam, the electric field due to the electron space charge is no longer linear with the transverse displacement and the resulting nonlinearities may significantly change the particle dynamics depending on the electron current distribution. As we found experimentally, in the worst case of the flattop electron beam, the electron beam edges act as a `gentle' collimator, since the outlying particles are slowly driven out of the bunch until they eventually hit the collimators.

In Figure 7, one bunch was monitored over 100 min as the TEL1 was `shaving' the bunch size. The current of the TEL was initially set to 1 A for the first 45 min. After a 10 min respite, the current was increased to 2 A (these settings are shown above the plot). After about 85 min, the TEL1 was purposefully mis-steered in order to observe a `blowup' in the bunch sizes. The upper data in Figure 7 show the horizontal and vertical beam sizes measured many times during this process. Also indicated is the longitudinal bunch size.

The open circles show the intensity of the bunch during this process. One can see a fast initial decreasing of sizes, but after about 10 min, the rate of decrease drops significantly; this implies that the large-amplitude particles have been removed, and the core is more stable inside the electron beam. In addition, the increase of the TEL1 current to 2 A was expected to worsen the bunch-size lifetime, but the smaller bunch was well preserved for the remaining time that the TEL1 electron beam was on and centered on the proton beam. The stability of the bunch size is remarkable, suggesting that the flattop profile was ideal for the small bunch size.

The bunch intensity decay rate also decreases significantly after a short interval of faster losses, and when the electron current is doubled, the decay rate is nearly unchanged. After the bunch was observed for a while, the electron beam was moved transversely so that the bunch intercepted the edge of the electron beam. As expected, the particles were suddenly experiencing extremely nonlinear forces, causing emittance (and size) growth, shown by the bump in the upper plot of Figure 7, and heavy losses, shown by the fast decline of the lower plot.

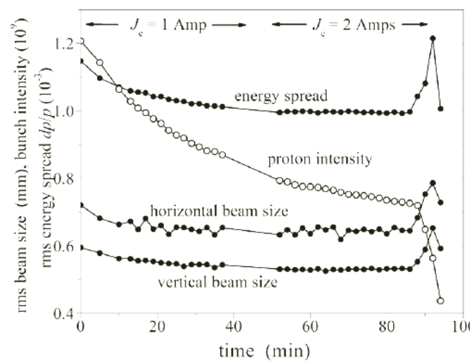

Figure 7. Scraping of a proton bunch due to interaction with the TEL1 electron beam (flattop electron current distribution).

OTHER APPLICATIONS

There have been a few studies carried out trying to use the unique and powerful electron beam creatively [8], such as to excite or scrap away the proton beam in more controlled fashion. But the most important application of the TEL is removing the un-captured beam from the abort gaps.

Removing Uncaptured Beam

Coalescing in the MI typically leaves a few percent of the beam particles outside RF buckets. These particles are transferred together with the main bunches. In addition, single intra-beam scattering, diffusion due to multiple intra-beam scattering (IBS), and phase and amplitude noise of the RF voltage, drive particles out of the RF buckets. The uncaptured beam is lost at the very beginning of the Tevatron energy ramp. At the top energy, uncaptured beam generation is mostly due to the IBS and RF noise while infrequent occurrences of the longitudinal instabilities or trips of the RF power amplifiers can contribute large spills of particles to the uncaptured beam. Uncaptured beam particles are outside of the RF buckets, and therefore, move longitudinally relative to the main bunches to fill the beam abort gap. If the number of particles in the uncaptured beam is too large and eventually lost due to energy ramp, beam abort or fallout, usually causing large background in physics detector, damage their components even lead to quenches of the superconducting (SC) magnets by the corresponding energy deposition.

To remove the uncaptured beam, the TEL electron beam is timed to the abort gaps and placed 2-3 mm away from the proton beam orbit horizontally and about 1 mm down vertically [7]. Then the TEL1 is turned on and train of three electron pulses is generated every 7^{th} turn for the purpose of excitation of the 4/7 resonance to effectively remove the uncaptured proton beam particles quickly. The electron pulse width is about 1 μs and the peak amplitude is about 250 mA in operation.

In Figure 8, the TEL was turned off during a store (average electron current is shown in black) at about *t* = 20 min. Accumulation of the uncaptured beam started immediately and can be measured as an excess of the total uncaptured beam current with respect to its usual decay. The blue line shows the excess measured by the Tevatron DCCT, $\delta N_{DCCT}(t)=N_{TEL\ on}(t) - N_{decay\ fit\ TEL\ off}(t)$. The uncaptured beam intensity measured by the Abort Gap Monitor (AGM) plotted in red. The DCCT excess grows for about 30 minutes before reaching saturation at intensity of about 16×10^9 protons.

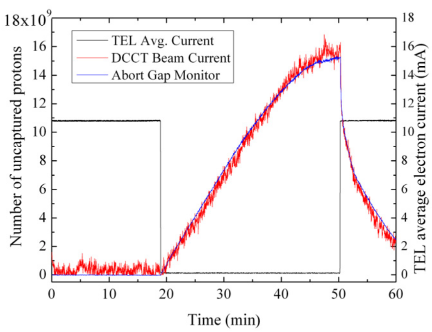

Figure 8: Uncaptured beam accumulation and removal by the TEL. The black line represents the average electron current of the TEL; the red line is the uncaptured beam estimated from the DCCT measurement; the blue line is uncaptured beam in the abort gap measured by the AGM.

Electron Columns

The space charge effect is one of the main factors to limit intensity of proton beam in proposed high current proton storage rings. It could be compensated by sufficient number of devices which are capable of trapping electrons, generated from the ionization of residual gas by proton beam, to form "electron columns" [9]. The longitudinal magnetic field of a solenoid which is supposed to be strong enough to keep electrons from escaping from the transverse position they are born at and suppress the e-p instability, but at the same time weak enough to allow ions escape and not affect the process of charge compensation. The ring electrodes at both ends of the solenoid supply electric field to trap the electrons longitudinally.

The preliminary studies with the Tevatron Electron Lens configured to work as "electron column" had shown significant accumulation of electrons inside an electrostatic trap in 3T longitudinal magnetic field with intentionally increased vacuum pressure. These negatively charged electrons moved vertical tune of 150 GeV proton beam upward by as much as +0.005.

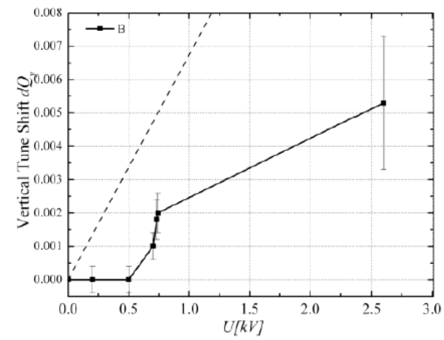

Figure 9: Summary of tuneshift vs. U[kV] measurements. The theoretical estimation is shown by the dashed line.

However, at the nominal vacuum pressure in the TEL of about 3×10^{-9} Torr no tuneshift is observed with any voltage on the electrodes up to -2.6 kV. And the significant vacuum instability was observed accompanied by the proton beam instability, which led either to the emittance growth or even to a proton beam loss, presumably, due to beam scraping. Further theoretical and bench studies are needed to understand the dynamic processes inside the ionized and magnetized "electron column".

SUMMARY

The successful demonstrations of the BBC prompted the BBC project for RHIC and R&D studies on LHC [11]. And the collimation effect also lead to the proposal of using hollow electron beam to do the collimation for LHC [10]. Once the new Gaussian electron gun is installed in the TEL2, its nonlinear beam-beam compensation abilities will be studied further in detail.

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