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COMPENSATION OF BEAM-BEAM EFFECTS IN THE TEVATRON COLLIDER WITH ELECTRON BEAMS

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Abstract

The beam-beam interaction in the Tevatron collider sets limits on bunch intensity and luminosity. These limits are caused by a tune spread in each bunch which is mostly due to head-on collisions, but there is also a bunch-to-bunch tune spread due to parasitic collisions in multibunch operation. We propose to compensate these effects with use of a countertraveling electron beam, and present general considerations and physics limitations of this technique.

1 INTRODUCTION

The two planned upgrades (Run II and TEV33) of the $p\bar{p}$ Tevatron collider [1] will give higher luminosity and will also have enhanced beam-beam effects. An increase of the betatron tune spread will come not only from head-on collisions of the bunches at the Interaction Points (IP), but also from parasitic long range beam-beam interactions resulting in bunch-to-bunch variation of betatron tunes, the latter being enhanced by the presence of injection gaps in the Tevatron bunch train (Pacman effect).

During Run II with 36 bunches in each beam the bunch-to-bunch spread is expected to be about $\Delta\nu \approx 0.007$, while the single bunch tune spread will be about $\Delta\nu \approx 0.018$. In the TEV33 upgrade the tune spread within each bunch and the bunch-to-bunch tune spread are both about 0.008. These values are about the maximum experimentally achieved value for proton colliders $\Delta\nu \approx 0.025$.

The betatron tune shift and tune spread, if they could be arbitrary controlled, are believed to provide valuable knobs for improving beam lifetime and ultimately for maximizing collider performance. Compensation of the beam-beam effects only for antiprotons is sufficient since the proton bunch population is significantly higher than the antiproton bunch population.

The beam-beam compensation techniques based on the use of intense electron beams have been proposed [2, 3] and are under development now [4, 5, 6, 7]. The present paper reviews the current status of these investigations.

2 LINEAR "ELECTRON LENS"

The tunes of individual bunches in the $\bar{p}$ beam can be corrected if an additional linear focusing is applied to each bunch individually. This focusing can be provided by the field of a wide electron beam ("electron lens", see Figure 1) with the current varying from bunch to bunch [3]. The electron beam must allow a 100% change of current in the 132 ns time between bunches in order to provide independent influence on different bunches.

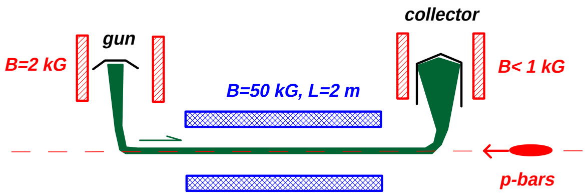

Figure 1: A possible layout of the "electron lens".

For a round, constant density electron beam with total current J_e, radius a, interacting with antiprotons over length L, the tune shifts are

$$\xi_\perp^e = -\frac{\beta_\perp}{2\pi}\frac{(1+\beta_e)Lr_p}{\gamma_{\bar{p}}\, e\, \beta_e\, c}\frac{J_e}{a^2}.$$

For example a beam with $J_e \approx 1.65$ A, $L = 2$ m, $a = 1$ mm, energy 10 kV ($\beta_e = 0.2$) gives $\xi_\perp^e \approx -0.01$ in the Tevatron with $\gamma_{\bar{p}} \approx 1066$ and beta function $\beta_\perp = 100$ m. The electron lens should be installed in a place where a) the electron beam does not interact with the proton beam; b) the beta-functions $\beta_\perp$ are high enough so the electron current density $j_e = J_e/(\pi a^2)$ is reasonable; and c) the dispersion function is small enough. Two electron lenses installed in locations with different β_x/β_y are needed to compensate the x and y bunch-to-bunch tune spreads independently (see Figure 2). An example of linear compensation is shown in Figure 3.

The required tune shift defines the electron beam density while the length L is defined by the space available in the Tevatron. The electron beam radius a is approximately

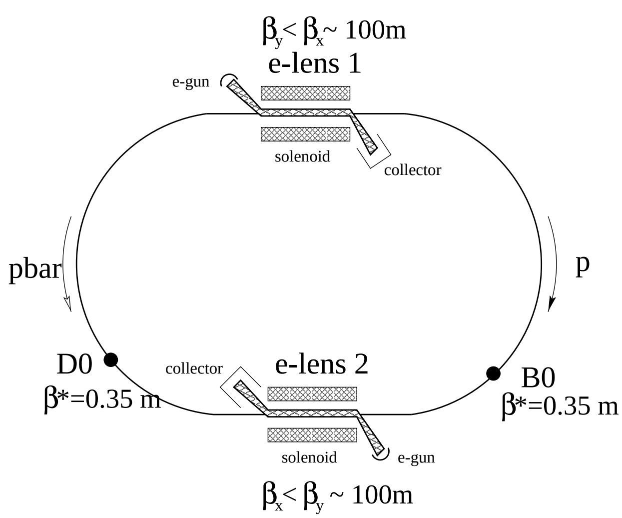

Figure 2: Tevatron layout with two "electron lenses".

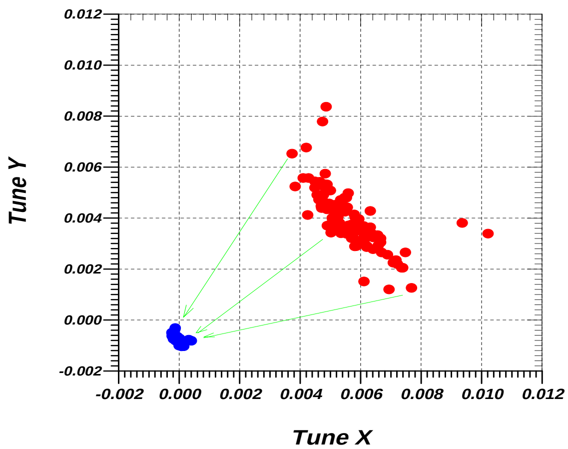

Figure 3: Initial (widely spread points) and resulting $\bar{p}$ bunch tune shifts (core particles only) with 10% error in the compensation.

2–3 times the $\bar{p}$ beam size. For the electron beam energy the lowest possible value should be chosen provided that a) the current production is not limited by a gun; and b) the electron beam can renew faster than the $\bar{p}$-bunch spacing (132 ns).

The gun current is $J_e = \mathcal{P} \cdot U_a^{3/2}$ where U_a is the anode voltage and $\mathcal{P}$ is the perveance that is typically $\approx 2 \cdot 10^{-6}$ A/V$^{3/2}$ for a diode gun. However, it can be made several times higher for a specially designed gun, such as a convex cathode immersed in a magnetic field [9]. Relying on a gun with perveance $(4-5) \cdot 10^{-6}$ A/V$^{3/2}$, the following optimized parameters of the electron beam can be deduced: the energy 10 kV ($\beta_e = 0.2$), $J_e \approx 1.65$ A, $L = 2$ m, radius $a = 1$ mm. Such a beam will achieve a maximum tune shift of $\xi_\perp^e \approx -0.01$ in the Tevatron.

To decrease the current density in the gun to what is achievable for an oxide cathode, one needs to use adiabatic magnetic compression, in which the beam is produced on the cathode with a larger radius a_c in a weak field B_c and then follows the magnetic lines to the region of stronger field B. For an electron lens with cathode current density 2 A/cm^2 and cathode radius $a_c = 5$ mm, one gets the ratio $B/B_c \equiv a_c^2/a^2$ to be about 25.

An experimental installation has demonstrated feasibility of the electron lens. The set-up will serve as a prototype of the device that can later be inserted into the Tevatron ring. The test facility and results of its commissioning are described in detail in [8].

3 NONLINEAR COMPENSATION: "ELECTRON COMPRESSOR"

The head-on collision of proton and antiproton bunches at the interaction point changes the betatron frequency of the on axis $\bar{p}$ by $\Delta\nu_z(0,0) = +\xi^p$ where $\xi^p \equiv N_p r_p/4\pi\varepsilon_n$ is the so called beam-beam parameter. N_p is the proton bunch population, r_p is the proton classical radius and ε_n is the normalized transverse emittance of the proton bunch. Assuming the charge density ρ of the proton bunch is Gaussian-like, the focusing force of the equivalent lens is a nonlinear function of the transverse displacement.

Due to the nonlinear focusing by the p beam the betatron frequencies in the $\bar{p}$ bunch are different for particles with different betatron amplitudes (X, Y) as shown in Figure 4. For the RunII and TEV33 upgrades of the Tevatron the spread of betatron frequencies (so called "footprint") of the $\bar{p}$ beam is $\Delta\nu_{\bar{p}} \approx 0.02$. This is big enough to cause an increase of particle losses due to higher order lattice resonances.

Compensation of this beam-beam induced betatron tune spread within the $\bar{p}$ bunch can be accomplished by an electron beam with an appropriate charge distribution [2]. The nonlinear focusing of antiprotons by the proton beam is compensated if a) the electron transverse charge distribution $\rho_e(r)$ is the same as the proton beam $\rho_p(r)$ (but scaled with r); b) the $\bar{p}$ beam distribution at the "electron compressor" is the same as at the IP (but scaled with r and with zero dispersion); and c) the number of electrons on the path of the $\bar{p}$ beam (for a single IP) is $N_e = N_p/(1+\beta_e)$. For example $N_e \approx 4.5 \cdot 10^{11}$ (or $J_e = 2.2$A) with $\beta_e = 0.2$ and $L = 2$ m for TEV33.

The electron bunch should have a Gaussian transverse distribution in the ideal case, in which the proton bunch has a Gaussian distribution. However, more realistic and practically more easily achievable distributions can give as good a result as the Gaussian case [2]. For example the electron beam density $\propto 1/(1+(r/\sigma)^8)$ was used for the footprint compression simulations presented in Figure 4.

The condition to cancel just the nonlinear tune shift is not the only condition to satisfy for the antiproton dynamics to be improved. An important issue to be considered is a difference of the proton bunch length and the electron beam length expressed in terms of betatron phase advance. Pursuing nonlinear compensation is based on the idea of adding a single thin nonlinear lens to an arbitrary nonlinear lattice in such a way that the particle motion in the modified structure would become resonance-free, though nonlinear, and at the same time the beam of particles would have a zero footprint [7].

Although theoretical studies of both nonlinear and linear compensation are under way, the first stage of experimental activities at Fermilab is devoted to linear compensation studies.

4 PARASITIC EFFECTS

Detailed studies of possible harmful effects produced by the electron lens have shown that all such effects can be made tolerable by a proper choice of the electron beam parameters. The most important issues are briefly described below.

Head tail in the $\bar{p}$ beam due to the electron beam [5]. An off center collision of the $\bar{p}$ bunch with the electron beam results in a drift of the electrons in crossed magnetic and electrical fields, such that, while the head of the $\bar{p}$ bunch sees a vertical field, the tail will also see a horizontal one.

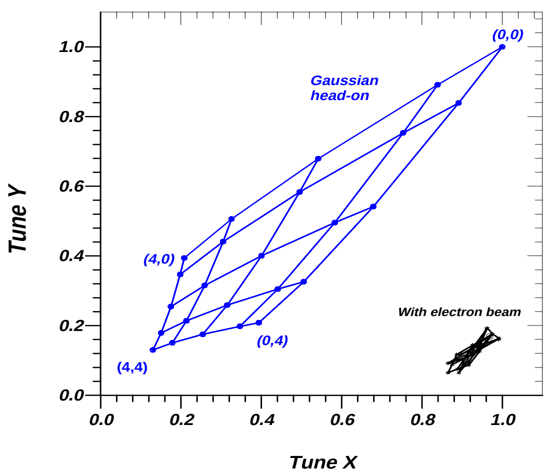

Figure 4: Betatron frequencies (tunes) in the $\bar{p}$ bunch for particles with different betatron amplitudes (X, Y). The head-on collision case (large leaf) and the case with compensation by the electron beam (small leaf, displaced for clarity) [2] are shown. Tune shift is in units of ξ^p, betatron amplitude is in units of the bunch transverse size σ.

Taking into account that the head and the tail exchange their position due to synchrotron motion, one can see that as a result of such a skew interaction the horizontal betatron motion, the vertical betatron motion and the synchrotron motion become coupled resulting in the so called Transverse Mode Coupling Instability (TMCI).

The threshold of this TMCI was found to be inversely proportional to the magnetic field B in the "electron lens". Under the design parameters the minimum magnetic field that will keep the $\bar{p}$ beam stable is $B \gtrsim 17.5$ kG. The instability is additionally suppressed if the electron beam radius is larger than the $\bar{p}$ beam size. The threshold magnetic field scales approximately as $\propto \xi^e_\perp / a^2$.

Electron beam distortion by elliptical $\bar{p}$ beam [4]. If the set-up is located at a place with unequal beta-functions $\beta_x \neq \beta_y$, then axial symmetry is not conserved. The electron beam becomes a rotated ellipse at the moment the tail of the antiproton bunch passes through it, while the head of the bunch sees the original undisturbed round electron beam. The electric fields of the distorted electron beam produce $x - y$ coupling of vertical and horizontal betatron oscillations in the $\bar{p}$ beam.

The choice of magnetic field can decrease the coupling to an acceptable value. If $B = 2$T, the maximum coupling spread is well below the typical residual coupling in the Tevatron (about 0.001). This effect is also additionally suppressed if the electron beam size is larger than the antiproton beam size.

$\bar{p}$ emittance growth due to variations of the electron beam [3]. Fluctuations of the electron current $\Delta J_e/J_e$ from turn to turn cause time variable quadrupole kicks which lead to a transverse emittance growth of the antiproton bunches. The emittance growth time τ (defined as $1/\tau = 1/\epsilon \cdot d\epsilon/dt$) is more than 10 hours (which is assumed to be tolerable) if the peak-to-peak current fluctuations are smaller than $\Delta J_e/J_e \approx 1.8 \cdot 10^{-3}$.

Transverse motion of the electron beam results in dipole kicks and coherent betatron oscillations of the antiprotons. After some decoherence time they will result in emittance growth of the antiprotons. The emittance growth time is more than 10 hours if $\delta X \leq 0.14\,\mu m$.

Deviations of the solenoidal magnetic field $\vec{B}$ from a straight line will cause off-center collisions of the antiproton and electron beams. In the case of the non-linear electron lens this may cause unwanted non-linear components of the space charge forces. The effect is small if $\Delta B_\perp / B \lesssim 10^{-4}$.

All these conditions are believed to be achievable.

Residual ions in the electron beam. Ionization of residual gas by electrons produces ions which could become trapped in the potential well of the electron beam. For typical parameters the "time of neutralization" is a fraction of a second. Nevertheless the ions should be removed because they a) change the charge density, i.e. spoil beam-beam compensation; and b) may result in a two beam drift instability.

The residual ions will be cleaned from the electron beam. Special cleaning electrodes together with a high vacuum (of the order of $3 \cdot 10^{-9}$ Torr), will ensure that the neutralization time is sufficiently longer than the lifetime of ions in the electron beam. An acceptable amount of residual ions in the electron beam is about half a percent.

5 CONCLUSION

Beam-beam compensation with an electron beam looks very promising. It provides additional powerful "knobs" to control beam dynamics in the Tevatron collider. No severe requirements on the electron beam were found for the suggested device. We believe that realization of the idea will give benefits for the Tevatron. Experimental studies of the electron lens prototype are under way.

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