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"Electron Compression" of Beam-Beam Footprint in the Tevatron

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Abstract

The beam-beam interaction in the Tevatron collider sets some 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 describe a counter-traveling electron beam which can be used to eliminate these effects, and present general considerations and physics limitations of such a device which provides “electron compression” of the beam-beam footprint in the Tevatron.

1 Introduction

Two major Tevatron upgrade projects are under realization and consideration now. One is based on the operation of the Main Injector and the Antiproton Recycler and is called Run II, and the second is called "TEV33" (see parameters of the collider in Table 1 [1, 2]).

Table 1: The Tevatron Upgrades

Parameter		Run II	TEV33
Beam Energy,	E, GeV	1000	1000
Luminosity	$L,\ s^{-1}cm^{-2}$	$2.1 \cdot 10^{32}$	$1.16 \cdot 10^{33}$
N of bunches (p, $\bar{p}$),	N_b	36	~100
Min. bunch spacing	τ, ns	396	132
Protons/Bunch	N_p	$3.3 \cdot 10^{11}$	$2.7 \cdot 10^{11}$
Antiprotons/Bunch	$N_{\bar{p}}$	$0.75 \cdot 10^{11}$	$\leq 2.7 \cdot 10^{11}$
p-Emittance rms,	ϵ_{np}, mm·mrad	3.3	3.3
$\bar{p}$-Emittance rms,	$\epsilon_{n\bar{p}}$, mm·mrad	2.5	3.3
Number of IPs	N_{IP}	2	2
Interaction focus	β^*, cm	35	35
Bunch length	σ_s, cm	~38	~35
$\bar{p}$-tune shift	$\Delta\nu_{\bar{p}}$	0.016	0.023
p-tune shift	$\Delta\nu_p$	0.003	0.007
$\bar{p}$-tune spread	$\delta\nu_{\bar{p}}$	0.003	0.01

There are several beam dynamics issues caused by beam-beam forces not only from the two head-on interaction points (IPs, at CDF and D0 experiments), but also from an additional $2 \times (N_b - 1) \sim$ hundred(s) of parasitic crossings of proton and antiproton bunches. It is to be noted that the design value of the total tune shift for antiprotons (pbars) is about the maximum experimentally achieved value for proton colliders $\Delta\nu \approx 0.025$ [3]. The "footprint area" of the $\bar{p}$ beam with such a tune shift is large enough to also cause an increase of particle losses due to higher order lattice resonances [4].

In order to achieve sufficient beam-beam separation away from the IPs, a crossing angle of about 200 microradian between proton and antiproton orbits at the main interaction points can be used. Besides the geometrical luminosity reduction, the crossing angle leads to synchrobetatron coupling, additional resonances, beam blow-up and luminosity degradation [5], although the maximum tune shift becomes smaller with the angle.

Other beam-beam induced effects include the variation of the betatron tunes along the bunch train and $x - y$ coupling due to skew component of the beam-beam kick

[2]. The maximum spread $\delta\nu_{max}$ of vertical and horizontal bunch tunes is estimated to be about 0.003 during Run II and about 0.01 in TEV33 as quoted in Table I. This spread and the estimated skew-kicks for TEV33 are expected to be a problem for collider operation if uncorrected.

Here we consider a device for elimination of the beam-beam effects mentioned above. It is an electron beam setup which is installed in the Tevatron ring (see Fig.1). Since the electron charge is opposite to the proton charge, the electromagnetic force on antiprotons due to the proton beam can be compensated by the electron beam.

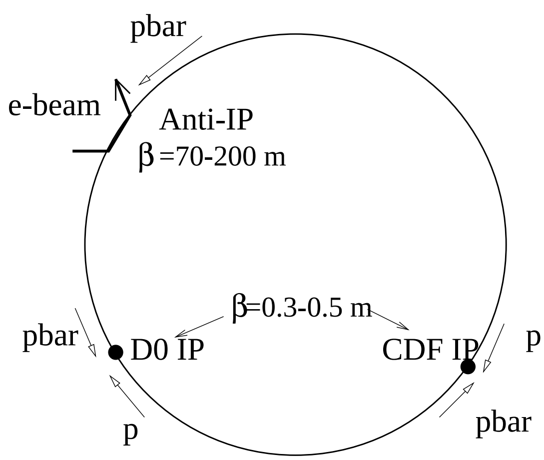

Figure 1: Tevatron with "electron compression" device.

2 "Electron compression" of tune space

Fig.2 presents a general view of the proposed "electron compression" device. Its electron beam travels in the direction opposite to the antiproton beam and interacts with an antiproton bunch via its electric and magnetic forces.

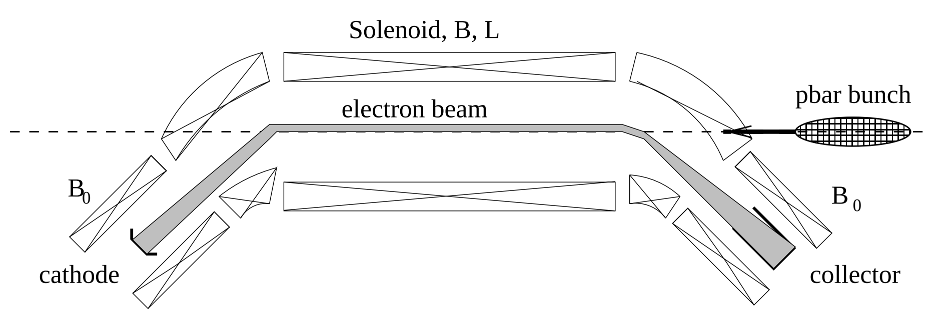

Figure 2: Layout of "electron compression" device.

This interaction shifts the antiproton beam tunes and distorts the tune footprint in a way which depends on the transverse electron charge distribution. For example, consider the footprint due to "head-on" collisions of round equal size proton and antiproton beams at the IPs. The "electron compression" can in principle shrink the $\bar{p}$ footprint to a point if a) the electron beam has the same transverse charge distribution as the proton beam; b) the $\bar{p}$ beam distribution at the "electron compressor" is the same as at the IPs (but scaled in size and with zero dispersion); and c) total electron beam charge eN_e on the path of the $\bar{p}$ beam (e.g. over the length L of the central solenoid in Fig.2) satisfies the equality condition of beam-beam shifts. This equality condition for protons and electrons is:

$$\frac{N_p r_p}{4\pi\varepsilon_n} N_{IP} \equiv \xi^p_{\bar{p}} = -\xi^e_{\bar{p}} \equiv \frac{N_e r_p (1+\beta_e)}{4\pi\varepsilon_n} \mathcal{F}, \tag{1}$$

here N_p is the number of protons per bunch, $N_{IP} = 2$ is the number of IPs, $r_p = e^2/m_p c^2 = 1.53 \cdot 10^{-18}$m is the classical proton radius, ε_n is the rms normalized proton bunch emittance, β_e is longitudinal velocity of the electron beam divided by speed of light v_e/c, and we assume that transverse sizes of all beams are the same $\sigma_e = \sigma_p = \sigma_{\bar{p}} = \sigma$. The numerical factor $\mathcal{F}$ depends on the relative length of the electron beam L and the pbar bunch σ_s. For example, $\mathcal{F} \approx 1$ if $L \gg \sigma_s$ and $\beta_e \ll 1$, and $\mathcal{F} \approx 1/2$ if $L \simeq \sigma_s$ and $\beta_e \approx 1$ [6]. For simplicity, we assume equal horizontal and vertical emittances and beta functions for antiprotons at the "compressor", and we consider a round electron beam with $L \gg \sigma_s$, which gives $\mathcal{F} \approx 1$. From Eq.(1) one gets

$$N_e = N_{IP} N_p / (1+\beta_e), \tag{2}$$

or $N_e \approx 2 \cdot N_p = 4.5 \cdot 10^{11}$ for $\beta_e = 0.2 << 1$ and $N_{IP} = 2$, $N_p = 2.7 \cdot 10^{11}$ in TEV33. The efficiency of the "electron compression" depends not only on how well the transverse electron current distribution matches the proton distribution, but also on factors that distort the antiproton beam footprint, such as multiple interactions at parasitic crossings and the crossing angle at the IPs. Note, that although the parasitic crossings can shift the tune significantly, the tune spread for most of the particles does not change too much. For example, for a single crossing with separation of $d \simeq (6-10)\sigma$ the tune shift is about $\Delta\nu \simeq 2\xi^p_{\bar{p}}/(d/\sigma)^2 \approx (0.02-0.05)\xi^p_{\bar{p}}$, while the tune *spread* for $\pm 1\sigma$ particles in the core is almost negligible $\delta\nu \sim \Delta\nu/(d/\sigma)^2 \approx (10^{-4}-10^{-3})\xi^p_{\bar{p}}$. The resulting footprint can have a rather complicated form, which, nevertheless, still can be compensated to some extent by the impact of the electron beam. The extent of compensation depends on the control of the electron current, the transverse distribution, the separation of the electron beam from the $\bar{p}$ orbit, the angular separation between the beams, and the choice of the horizontal/vertical antiproton beta-functions in the electron beam region.

Let us consider an example of the "electron compression" of the "head-on" footprint. Fig. 3a presents three transverse charge distribution functions (dimensionless) corresponding to:

$$\rho_G(r) = exp(-\frac{r^2}{2\sigma^2}), \tag{3}$$

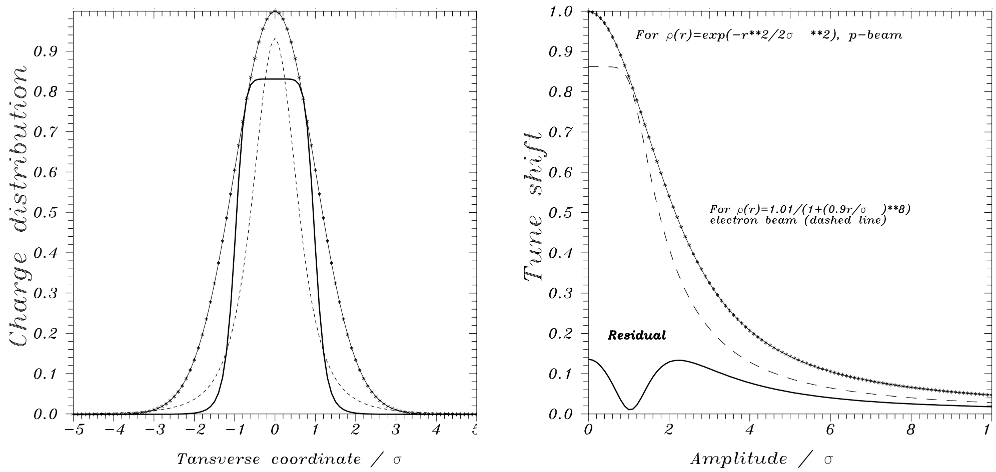

Figure 3: **a** – left figure – Three distribution functions $\rho_{G,1,2}(r)$ - see text, ; **b** – right figure – Tune vs. amplitude for two distributions and their difference (see text).

$$Compressor\,1 \quad \rho_1(r) = \frac{0.93}{(1+(\frac{r}{\sigma})^2)^2}, \tag{4}$$

and

$$Compressor\,2 \quad \rho_2(r) = \frac{0.83}{1+(r/\sigma)^8}. \tag{5}$$

The first one (solid line with markers in Fig. 3) represents an electron charge distribution which is the same as the Gaussian charge distribution in the proton beam at the IP, the second one is for a Lorenz distribution of electron charge in the "electron compressor" beam (we denote it as "compressor 1", dashed line in Fig. 3), the third one is for a more "step-like" or more uniform electron charge distribution ("compressor 2", solid line). Tune compensation with other than Gaussian distribution of the electron beam must be achieved by varying the beam charge distribution parameters. For example, the tune shift of large amplitude particles (pbars) depends mostly on the total electron charge $eN_e = \int_0^\infty 2\pi r\rho(r)dr$ rather than on details of $\rho(r)$, the current density at small $r << \sigma$ determines the tune shift of the core particles, etc. The more variables one has, the better the compensation one can get. For example, Fig. 3b shows the tune shift in units of the maximum tune shift ξ vs. the amplitude of the antiproton radial betatron oscillations a in units of σ. The Gaussian proton beam contribution is presented by the marked line and equal to

$$\frac{\Delta\nu(\alpha)}{\xi} = \frac{4}{\alpha}[1-\exp{(-\alpha/4)}]I_0(\alpha/4), \tag{6}$$

where $\alpha = (a/\sigma)^2$, and $I_0(x)$ is the modified Bessel function of order 0. The dashed line in Fig.3b is for the tune shift due to an electron beam with a distribution given by

$$\rho_3(r) = 1.01/(1 + (0.9r/\sigma)^8). \tag{7}$$

Finally, the solid curve is the difference of the two, i.e. the residual tune shift due to the combined effect of the "head-on" collisions with a Gaussian proton beam and the electron beam with $\rho_3(r)$. The resulting tune spread is about 7 times less than that due to protons only.

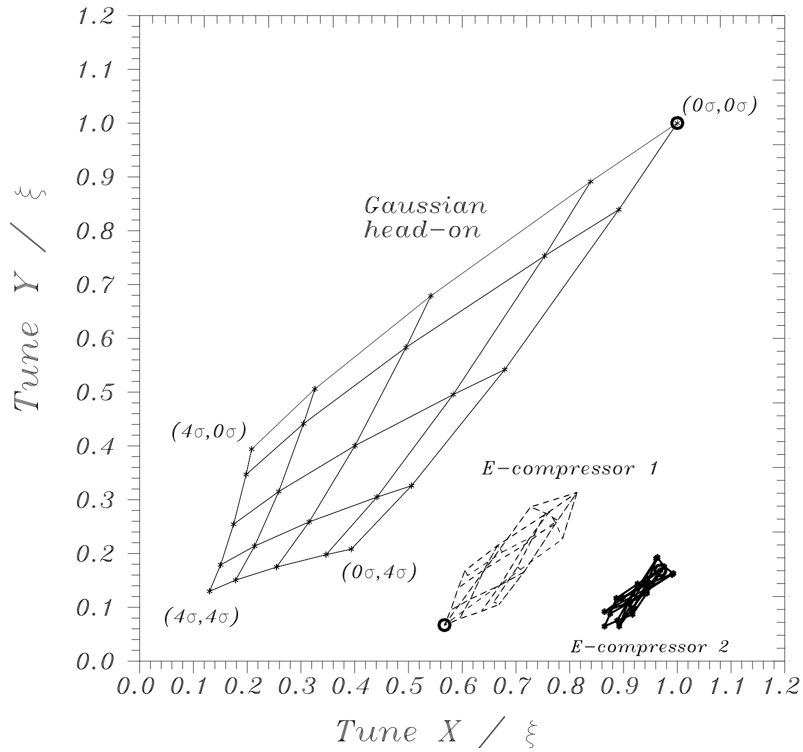

Figure 4: "Electron compression" of antiproton footprint.

Fig.4 demonstrates the effect of "electron compression" on the 2-D tune diagram. The largest "leaf" is the pbar footprint due to "head-on" collisions with protons, and the two smaller ones correspond to the addition of the "electron compressors" labeled 1 and 2. For convenience of presentation we have separated these three footprints horizontally, in fact they are concentrated around the zero tune point $\nu_{(x,y)} = 0$. Again, one can see a significant reduction (7-8 times) of the tune spread, especially for "compressor 2".

In the multibunch operation mode the proton and antiproton beams are separated around the ring except at the IPs. If the proton beam has gap(s) or significant bunch charge variations, then the beam-beam interaction at numerous parasitic crossings results in bunch-to-bunch variations of the tune shifts and coupling. The "electron compressor" allows, in principle, to avoid such detrimental effects and equalize tune shifts and coupling of different bunches by modulation of the electron current in time by providing different quadrupole kicks on different antiproton bunches. The long-range beam-beam interaction shifts horizontal and vertical tunes in opposite directions $\Delta\nu_x^{LR} \approx -\Delta\nu_y^{LR}$, while the head-on electron compressor shifts the tunes in the same direction $\Delta\nu_x^{EC} \approx \Delta\nu_y^{EC}$. Thus, in order to mimic the long-range interaction, one needs either to displace the electron beam or to install two "electron compressors" at appropriately disparate lattice functions (e.g. one at $\beta_x \gg \beta_y$ and another one at $\beta_x \ll \beta_y$).

Let us list the "knobs" of electron beam control which can be used for "electron compression":

1. electron beam charge, N_e
2. electron beam radius, a
3. transverse charge distribution function, $\rho(r)$
4. displacement w.r.t. the antiproton orbit, d
5. time variable current, $J_e(t)$.

Other "knobs" to play with could be the angle between the electron beam and the $\bar{p}$ orbit, a variable magnetic field along the "compressor" $B(z)$ (and, thus, the electron beam radius $a(z)$), ellipticity of the beam, its energy, etc. Their influence on the "compression" has not yet been studied in detail. Note, that there are also a few less flexible options like changing the electron current direction, variable and unequal antiproton beta functions $\beta_x \neq \beta_y$, as well as the installation of several electron beam devices. In any case, it seems that for any specific goal (e.g. "head-on" beam-beam interaction compensation) only a few of the "knobs" need to be implemented initially for the device to be useful.

The electron beam stability with respect to its own space charge force prefers a lower current density, or a larger beam size. Since the size is about the proton beam size, the electron beam is better installed at a large beta function location. Therefore, it definitely should not be set at the interaction point, where the sizes are the smallest, and vary over distances of about the bunch length $\beta^* \sim \sigma_s$. Good candidates can be some locations near the IP where the beta-functions can be as big as $\beta_p \simeq$1000 m, but at present there is no available space in the superconducting magnet lattice for the "compressor" at the locations where the the horizontal and vertical β_p are the same, and the dispersion function is equal to zero. Zero dispersion is desirable to avoid the possibility of synchro-betatron effects. Another possibility is to set the device at some other location, most probably in one of the Tevatron straight sections. The ideal straight section would provide a) equal horizontal and vertical beta-functions, and b) zero (or minimum) dispersion over the region of the interaction with electron beam.

3 Electron beam for "electron compression"

Let us consider the electron beam for the "compressor". It must be about the same size as the $\bar{p}$ beam which has an rms size of $\sigma_{\bar{p}} = \sqrt{\beta\varepsilon_n/\gamma_{\bar{p}}}$. In the ultimate case of the small emittance at TEV33 $\varepsilon_n = 3.3 \cdot 10^{-6}$m one gets $\sigma_{\bar{p}} = 0.6$mm with a beta function $\beta_{x,y} = 108$m (as at the A0 straight section of the Tevatron), or $\sigma_{\bar{p}} = 0.9$ mm at $\beta_{x,y} = 250$m (if one decides to modify the existing lattice and provide a high-beta, zero-dispersion region in the Tevatron). For simplicity, we will consider an electron beam with radius of $a_e = 1$mm and constant transverse distribution. From Eq. (2), one can estimate the electron beam current J_e necessary for the compression:

$$J_e \approx \frac{2\beta_e e N_p c}{L(1+\beta_e)}, \tag{8}$$

where L is the length of the beam-beam interaction. Taking $L = 3$m and $N_p = 2.7 \cdot 10^{11}$ we get $J_e[A] \approx 8.64\frac{\beta_e}{1+\beta_e}$. For example, for $U = m_e\beta_e^2c^2/2$=10 kV electron beam ($\beta_e = 0.2$) the required current is $J_e = 1.44$ A.

3.1 Space charge effects in the electron beam

The strength of the magnetic field at the interaction region is determined by the stability requirement of the high current electron beam. The equation for near axis electron oscillation amplitude r under the impact of a solenoidal field B, the space-charge force due to the electron beam, and the force due to incoming antiprotons is:

$$\frac{d^2r}{dz^2} + r(\frac{1}{4}K_B^2 - K_e^2 - K_{\bar{p}}^2) = 0, \tag{9}$$

where z is longitudinal coordinate. The effective focal length due to the magnetic field B is

$$2 \cdot K_B^{-1} = \frac{2\gamma_e\beta_e m_e c^2}{eB} \approx 3.3[cm]\frac{\gamma_e\beta_e}{B[kG]}. \tag{10}$$

The defocusing length due to electron space charge is

$$K_e^{-1} = \sqrt{\frac{J_0\gamma_e^3\beta_e^3a_e^2}{2J_e}} \approx 3.5[cm]\beta_e\gamma_e^{3/2}\sqrt{1+\beta_e}, \quad J_0 = mc^3/e = 17\ kA. \tag{11}$$

The minimum defocusing length due to the pbar beam is

$$K_{\bar{p}}^{-1} = \sqrt{\frac{\gamma_e\beta_e^2\sqrt{2\pi}\sigma_s\sigma_{\bar{p}}^2 m_e c^2}{e^2N_{\bar{p}}(1+\beta_e)}} \approx 6.6[cm]\beta_e\sqrt{\frac{\gamma_e}{1+\beta_e}}, \tag{12}$$

where we take $N_{\bar{p}} = 6 \cdot 10^{10}$, $\sigma_{\bar{p}} = 0.9$ mm and the rms length of the pbar bunch to be $\sigma_s = 35$cm. The beam is stable if the focusing term in Eq.(9) is stronger than the two defocusing terms. The magnetic field required for stability of the non-relativistic electron beam $\beta_e << 1$, $\gamma_e = 1/\sqrt{1-\beta_e^2} \approx 1$ is approximately equal to

$$B_{NR} \geq 1.02\, kG$$

and scales as:

$$B_{NR} \propto \frac{J_e^{1/2}}{\sigma_{\bar{p}}}. \tag{13}$$

For example, doubling the electron current requires only $\sqrt{2} \approx 1.41$ more magnetic field strength. Also, since the space charge term in (9) is about twice stronger than the one due to pbar beam forces, then there is an approximate scaling law of $B_{NR} \propto L^{-1/2}$.

In the opposite case of ultra-relativistic electrons, the third term is much stronger than the second one and one gets

$$B_{UR} \geq 1[kG] \cdot E[MeV],$$

with a scaling of

$$B_{UR} \propto \frac{N_{\bar{p}}^{1/2}}{\sigma_s^{1/2}\sigma_{\bar{p}}}. \tag{14}$$

Application of the last equation to $E_e = 10$ MeV electrons gives $B_{UR} \geq$ 3.3 kG.

Finally, we note that since the device uses the electron beam once over a passage, then one may use no magnetic field at all if the electron beam energy is high enough to have no (or minor) electron beam disruption over the length of the pbar bunch $K_{\bar{p}}^{-1} > \sigma_s$. For $\sigma_s = 35$cm this yields an energy of $E_e \geq 30$ MeV.

3.2 Choice of electron energy

A general conclusion of the above considerations is that a non-relativistic electron beam for the "electron compression" device is easier to provide and keep stable in a longitudinal magnetic field. The limit on the minimum voltage (kinetic energy) is set by the electron beam space charge potential U_{SC} with respect to the vacuum chamber wall:

$$U \geq U_{SC} = \frac{2eN_e}{L}\Big(ln(b/a_e) + 1/2\Big) \approx 510[V]\Big(ln(b/a) + 1/2\Big). \tag{15}$$

This gives $U > 2.3$ kV for a chamber radius of $b = 60$ mm and $a_e = 1$ mm beam radius.

If one needs to modulate the electron current in order to equalize the bunch-by-bunch tune shift, then the electrons have to be fast enough to provide different

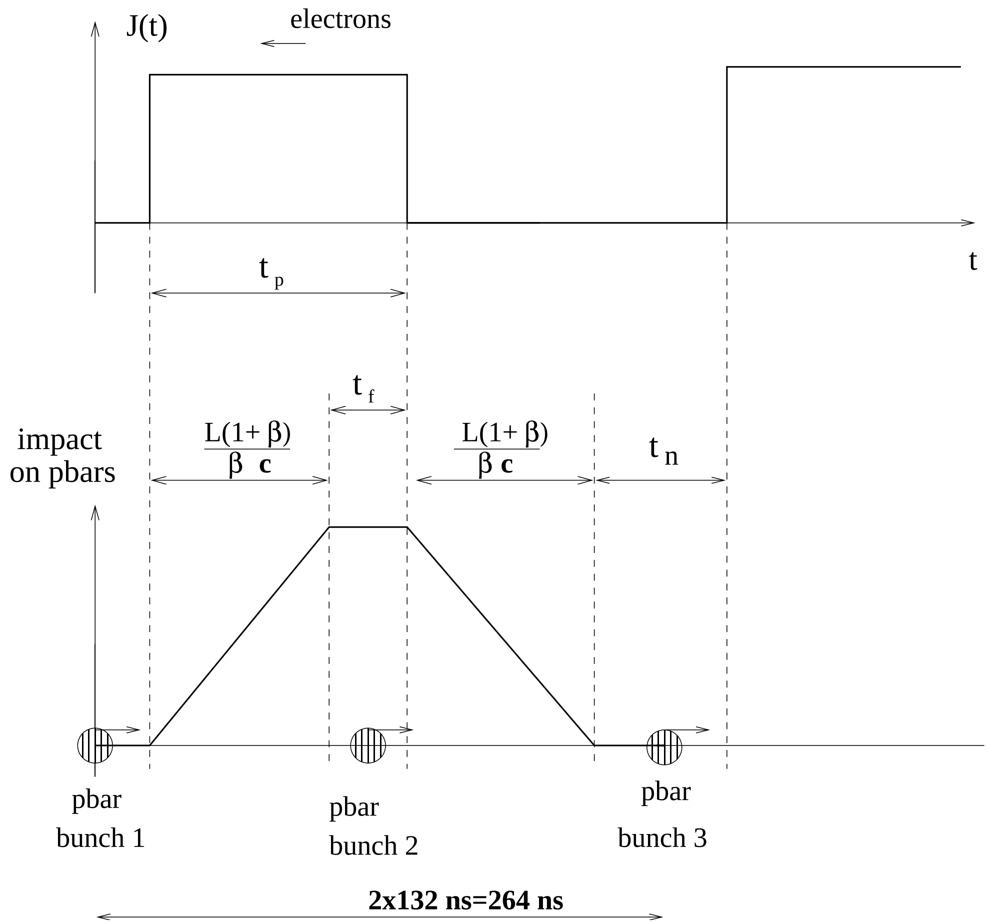

Figure 5: Electron current modulation scheme.

quadrupole kicks on different bunches. Fig.5 demonstrates how a step-like current modulation (upper plot) transforms into the impact on the antiprotons.

The characteristic "impact rise-time" for antiprotons is $\tau = L(1+\beta_e)/\beta_e c$. Let the required flat top of the pbar kick be about t_f =5 ns, and the required "no-impact time" to be the same $t_n = 5$ ns; then, summarizing all times in Fig.5, the condition of $264\,ns\ > t_f + 2L(1+\beta_e)/c\beta_e + t_n$ must be satisfied in order to have no impact on preceding and following bunches. That gives $\beta_e > 0.08$ or kinetic energy of the electrons $U > 1.6$kV.

The maximum current of a space-charge limited diode electron gun is given by the Child-Langmuir law

$$J_e = P \cdot U^{3/2},$$

where P (the perveance) is a gun-geometry dependable constant. Thus, high current requires higher $U = \beta_e^2 m_e c^2/2$. On the other hand, the electron beam power grows with energy.

Taking all the above into consideration we conclude that a current of $J_e = 1-2$A with U=10-20 kV electrons seems appropriate, although an exact optimum can only be found after more detailed studies.

3.3 Transverse size and emittance of the electron beam

The required current density for a 2 mm diameter beam is $j_e = \frac{J_e}{\pi a_e^2} \approx 280 \frac{\beta_e}{1+\beta_e}\ A/cm^2$, or about 46 A/cm^2 for a 10kV beam. This is somewhat larger than the $10 A/cm^2$ that oxide cathodes usually provide. To overcome the cathode current density limit, one can use adiabatic magnetic compression in which the beam is born on the cathode with a larger radius a_c in a weak field B_c and transported to the region of stronger magnetic field B, with conservation of the adiabatic invariant $B_c a_c^2 = B a_e^2$. If the maximum "shrinking" ratio $R \equiv a_c^2/a_e^2$ is determined by space charge repulsion compensated by magnetic field focusing in the transport section from the cathode to the solenoid, we can rewrite Eqs. (10) and (11), to get :

$$R_{max} \approx 1.1 \cdot B^2[kG]. \tag{16}$$

For example, we get $R = 10$ for $B = 3$ kG, $B_c = 0.3$ kG, and $a_c = 3.1 \cdot a_e$. Thus, one can obtain a significant increase of the electron current density with magnetic compression. In addition, electrostatic focusing by the electron gun electrodes can further increase the compaction factor and the current density in the solenoid.

Thermal emittance of electrons from the cathode, $\varepsilon_n \simeq \gamma_e \beta_e \varepsilon \approx 2 a_c \sqrt{T/mc^2}$, is approximately equal to 0.001a_c, where a_c is the cathode radius, if $T \approx 0.1$ eV is the thermal energy of emitted electrons. The corresponding thermal rms beam size at the solenoid (i.e. the minimum achievable beam rms size) is about

$$a_e^{th} = \left(2 \cdot K_B^{-1} \cdot \varepsilon\right)^{1/2} = 0.55[mm]\sqrt{\frac{a_c[cm]}{B[kG]}},$$

or about 0.18 mm with a_c=0.3 cm and $B = 3$ kG. This value does not limit the required beam size of about 0.6-2 mm.

3.4 Magnetic field configuration

One can note that the layout of the compressor presented in Fig.2 looks like existing designs for "electron cooling" installations. Nevertheless, the "electron compressor" is much more simple than classical "electron coolers" as there is no need for an extremely high collector efficiency and the required magnetic field uniformity is $B_\perp/B \sim a_e/L \simeq (2-6) \cdot 10^{-4}$ – an order of magnitude less stringent than what the coolers need [7]. One of the known disadvantages of the latter is the necessity of bending solenoids which produce an asymmetric impact for the pbar beam by a transverse component of the magnetic field. The scheme presented in Fig.6 does not have bending magnets at all [8]. One can imagine the electron gun emitting surface is a cylindrical band placed between two solenoids switched oppositely in a "cusp" configuration. Such a gun was fabricated and gave rather promising results with 1 A beam current [9]. Although there is not enough experience in beam quality and charge distribution tuning, the simplicity of the scheme is quite attractive.

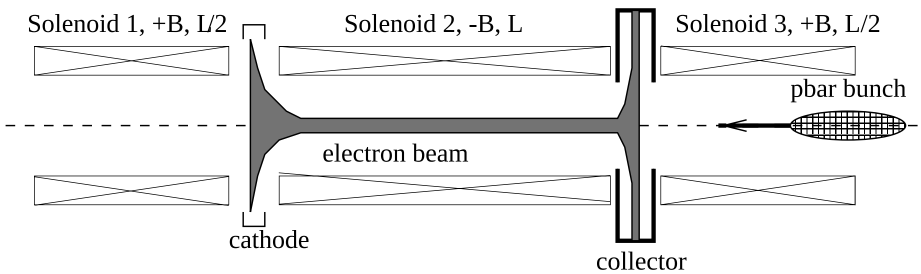

Figure 6: "Electron compressor" without bends.

3.5 Effect of ions

While passing through the vacuum chamber, the electron beam ionizes atoms of the residual gas. The charge of the resulting ions may lead to a transverse drift instability of the electron beam. Experimental investigation of the fully compensated electron beam [10] has shown that the instability threshold current density is about

$$j_{thr} \approx \frac{\beta_e^2 Bc}{3.8L}.$$

If the degree of charge compensation due to ions (i.e., the effectiveness of ion clearing) is equal to α =*(charge of ions)/(charge of electrons)*, then the equivalent threshold current of a 1 mm diameter beam is equal to:

$$\alpha J_e = 0.5[mA]\frac{U[kV]B[kG]}{L[m]}. \tag{17}$$

Therefore, a 10 kV electron beam with $J_e = 2$ A, L =3m requires $\alpha \simeq 0.002$ for $B = 3$kG. High vacuum inside the solenoid section and the use of ion clearing electrodes will be needed to achieve this goal.

Concluding this Section, we outline the main parameters of a possible "electron compressor":

- length $L = 3$ m;
- beam radius a_e=0.6-2 mm;

- electron current $J_e = 1 - 2$A;
- maximum voltage $U = 10 - 20$ kV;
- magnetic field $B = 1.5 - 4$ kG.

4 Effects on high-energy beams

When the Tevatron collider operates with many more protons per bunch than antiprotons per bunch, the pbar beam-beam tune shift is larger than the proton tune shift. Therefore, only one "electron compressor" – for antiprotons – will be necessary. The direction of the electrons' propagation is opposite to the pbars' velocity (i.e. they collide [1]). The proton beam moves in the opposite direction in the same vacuum chamber and it also may effectively interact with the electron current. If the proton and antiproton beam orbits are not separated, then an additional positive tune shift for protons results in

$$\xi_p^e \approx \frac{N_e r_p (1-\beta_e)}{4\pi\varepsilon_n} = \xi_{\bar{p}}^e \frac{1-\beta_e}{1+\beta_e}. \tag{18}$$

This does not differ too much from the pbars' maximum $\xi_{\bar{p}}^e \sim 0.024$ if $\beta_e \ll 1$. The latter is supposed to be too large to tolerate. One needs to avoid this impact on the proton beam due to electron charge. Separation of the proton and electron beams can help a lot: e.g. a separation of $d \approx 6\sigma_p \simeq 3$mm causes quite a minor proton beam tune shift of about

$$\xi_p^e(d) \approx \frac{2\xi_{\bar{p}}^e}{(d/\sigma_p)^2} \frac{1-\beta_e}{1+\beta_e} \sim 9 \cdot 10^{-4}, \tag{19}$$

with vertical and horizontal having opposite signs.

A very important issue is longer term control of the electron beam. The amount of required tune spread compensation varies in time, e.g. at injection proton and antiproton beams are everywhere separated and that yields one pattern of the footprint; after acceleration beams collide at two IPs, the separator strength goes down and they provide different separation at parasitic crossings, etc, and consequently, the tune footprint is changed; finally, after a few hours the intensity and emittances of the beams are significantly different. The "electron compressor" has to be adjusted in order to compress the tune area effectively. One way to reach the goal is to rely on a beam-beam model which predicts the footprint from measured data on bunch intensities, emittances and separation. Another choice is to continuously measure the beams' tune spectra and make necessary corrections in electron beam current,

[1] Due to the small inelastic cross section the pbar beam lifetime almost does not depend on electron current, i.e. "electron compressor" does not consume many antiprotons.

size and distribution (i.e. implement a kind of long-term feedback). Reliability of the set up during collider operation may probably require multiple cathodes or guns.

As the electron beam is used once upon antiproton passage, numerous high-energy beam instabilities will not appear (as the system has not even one-turn memory) and this is a significant difference from 4-beam compensation (see below). Nevertheless, since the electron beam takes some energy from the antiprotons' betatron oscillations, there is room for weaker dissipative-type instabilities. This issue needs further theoretical studies, as does the question of how minor variations of the electron beam density (estimated to be of the order of few percent) due to the impact of the antiproton charge at the head of the bunch will change the fields experienced by the particles at the tail of the antiproton bunch.

5 Discussion

5.1 "Electron compressor" for TEV33 with no crossing angle

In principle, the "electron compression" can allow us to eliminate the crossing angle at the interaction points. At present, a crossing angle is believed to be the best way to reduce the beam-beam tune shift and tune spread due to near-IP interactions. The electrostatic separators are not located close enough to the IP to avoid the first parasitic collision points. (Parasitic collision spacing is about 20 m = $\frac{1}{2}c \cdot 132$ ns). The crossing full angle at the IPs of about 0.2 mrad reduces the luminosity by about 50% [2].

Two or four near-IP "head-on" collision points will cause about three or five times larger tune shift and tune spread. Therefore, a proportional increase of the "electron compressor" current J_e from about 1.5 A to 4.5-7.5 A would be required to compensate these additional crossings. To keep the higher current beam stable, a stronger magnetic field is needed $B \simeq B_0\sqrt{3-5} \geq 1.5 - 2$ kG. Note from Eq. 13, that the magnetic field is proportional to the square root of the current. By eliminating the need for a crossing angle, this high-current "electron compression" can recover a factor of two in the luminosity, or provide the same luminosity with half the antiprotons.

Two or four additional interaction points at high beta-functions cost little in the rate of pbar consumption since the luminosity at these two additional "head-on" collision points is small $L \propto 1/\beta$, $\beta \gg \beta^*$.

5.2 Applications of the "electron compressor"

The implementation of the electron current modulation with about 7 MHz frequency will allow the variation of tune shifts of different pbar bunches and the compensation of the effect of numerous parasitic crossings in TEV33.

The most attractive feature of the "electron compression" is the shrinking of the tune area covered by pbar beam, but this requires a device which controls the beam intensity, radius, transverse charge distribution of the current, and separation of the antiproton and electron beams. By varying the cross section of the electron beam, one can also emphasize particular multipole terms in pbar dynamics, which can be useful for some applications.

The electron beam can be also used as an antiproton beam monitor because of the kick provided by the pbar beam. For example, a low current electron beam with radius much smaller than the pbar rms size can interact with details of the inner structure of the of pbar beam. By measuring the electron position at the entrance of the interaction region, one can obtain information on pbar charge and, probably, distribution.

5.3 Historical overview

The idea of the compensation of the beam-beam interaction was discussed previously for other collider facilities, mostly e^+e^- (probably one of the first publication is Ref.[11]). The theory of compensated electron-positron collisions in storage rings [12] predicts that collective instabilities in the circulating beams limit the performance and do not allow significant benefits with respect to the usual uncompensated case. Experiments with compensated e^+e^- beams were carried out at the DCI collider at Orsay at the end of 1970s. There were two intersecting rings with four equally populated beams (positrons and electrons in each ring) which collided at the same point. This arrangement yielded a space charge and a current compensation factor of about 5-10. It allowed an increase of the maximum beam-beam parameter ξ from 0.018 to 0.024. Nevertheless, there was no significant increase in luminosity, and it was demonstrated that the value of ξ rather than the residual compensated value of $\xi_r = \xi/(5-10)$ sets the limit. Stability regions, smaller in size than those observed in two-beam configuration, were found to decrease rapidly with current, probably because of collective modes.

In linear e^+e^- colliders, the beams collide once a shot, do not act on each other repeatedly, and therefore, there is no long-term memory through an opposing beam as in storage rings. Thus, collective phenomena are weaker and the charge separation in neutralized beams occurs only if the space charge parameter is very large $\xi \gg 1$ [15, 16]. Since the proposed "electron compressor" is a single-pass device and the electron beam carries no memory from turn to turn and from one $\bar{p}$ bunch to another, we believe that the electron beam related collective phenomena will play no role in the Tevatron beam dynamics.

It was pointed out in Ref.[14] that compensation of beam-beam effects with an electron beam leads to elongation of the transverse decoherence time due to the smaller tune spread. This also leads to less stringent requirements on the feedback system for emittance preservation in large colliders like the SSC and LHC, although the electron current densities considered in [14] are somewhat unrealistic.

6 Conclusion

We have described an electron beam to compensate beam-beam induced tune shift and tune spread of antiprotons in the proton-antiproton Tevatron collider. The impact of the electron beam space-charge forces on antiprotons is opposite to that due to protons. The “electron compressor” is best installed at some point in the ring with a high beta function (not necessarily near one of the interaction points).

Implementation of the “electron compression” scheme can lead to several advantages for the Tevatron, as it allows us:

1. to compress significantly the antiproton beam footprint due to head-on collisions and decrease the tune spread due to parasitic crossings; to give more freedom in the tune space available for machine operation; or to increase the proton beam intensity and, therefore, the Tevatron luminosity. Such a goal requires the “electron compressor” to have flexibility in forming the transverse current distribution, i.e. control the beam radius, intensity, separation with respect to the $\bar{p}$ beam orbit, etc.

2. to eliminate bunch-to-bunch antiproton tune spread due to parasitic beam-beam interactions.

3. to eliminate the crossing angle at the low-beta interaction points in the multi-bunch regime and, therefore, double the luminosity if the electron current is enough to compensate two (four) more proton-antiproton interaction points; or to get the same luminosity with smaller beam intensities.

The parameters of the suggested device for the goal #1 can be as follows: length of the electron beam equal to 3 m, a few Amperes of electron current, electron energy of 10-20 kV, about 1 mm beam radius, and a longitudinal magnetic field of 1-4 kG is required to maintain the beam stability.

For the goal # 2 one needs to have electron current modulation in the “compressor”. For goal # 3, the elimination of the crossing angle requires a larger electron current of 4-7 A and a stronger magnetic field of 2-7 kG.

To reduce the impact on the protons, the proton orbit in the “compressor” has to be separated from the electron beam by 6-10σ_p. The electron beam position at the exit of the “compressor” can also provide diagnostic information about the antiproton beam intensity and position.

The general conclusion is that the “electron compression” idea looks very promising as it provides additional powerful “knobs” to control beam dynamics in the Tevatron collider as well as serving as a beam monitor. We find no severe requirements on the electron beam for the suggested device, and believe that realization of the idea will give benefits for the Tevatron.

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