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Beam-beam Compensation Activities at Fermilab. R&D Status.

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Abstract. The beam-beam interaction in the Tevatron produces the betatron tune spread in each bunch and a bunch-to-bunch tune spread. The tune spread sets limits on bunch intensity and luminosity. The beam-beam effects for antiprotons are usually more severe since the proton bunch population is higher.

The beam-beam effects for antiprotons can in principle be compensated with the use of an electron beam with a corresponding charge density. The status of studies of possibilities of the beam-beam compensation is reviewed in this paper.

INTRODUCTION

Investigation of the new frontiers of the elementary particle physics requires permanent increase of performance of the hadron colliders, which are one of the most powerful instruments for such investigations.

The Table 1 represents parameters of the two planned upgrades (Run II and TEV33) of the $p\bar{p}$ Tevatron collider [1,2]. The luminosity increase is achieved mostly due to increase of the bunch population and the number of bunches. Higher bunch population results in enhanced beam-beam effects, namely in increase of the so called betatron tune shift and tune spread (shown in the Table 1) produced by head-on collisions of the bunches in Interaction Points (IP) as well as due to parasitic collisions.

As a result the particles of the beam will cover larger area on the surface of ν_x and ν_y betatron frequencies and this area may cross the lines of higher order resonances that will lead to enhanced diffusion of the particles, decrease of lifetime, growth of emittance and decrease of the luminosity.

The betatron tune shift and tune spread, if it could be arbitrary controlled, is believed to provide a valuable knob for improving beam lifetime and eventually for the maximization of the collider performance.

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TABLE 1. Parameters of the Tevatron upgrades.

Parameter		Run II	TEV33
Beam energy	E_b, GeV	1000	1000
Luminosity	$\mathcal{L}$, $s^{-1}cm^{-2}$	$2.1{\cdot}10^{32}$	$1.2{\cdot}10^{33}$
No. of bunches (p,$\bar{p}$)	N_b	36,36	140,121
Min. bunch spacing	τ, ns	396	132
Protons/Bunch	$N_p/10^{11}$	2.7	2.7
Antiprotons/Bunch	$N_{\bar{p}}/10^{11}$	0.75	0.6
p-emittance rms	ε_{np}, $\pi\mu$m·rad	3.3	3.3
$\bar{p}$-emittance rms	$\varepsilon_{n\bar{p}}$, $\pi\mu$m·rad	2.5	2.5
Number of IPs	N_{IP}	2	2
Interaction focus	β^*, cm	37	37
Crossing half-angle	θ_{IP}, mrad	0	0.14
Bunch length	σ_s, cm	37	37→14
$\bar{p}$-tune shift	$\Delta\nu_{\bar{p}}$	~0.020	~0.015
p-tune shift	$\Delta\nu_p$	0.005	0.007
$\bar{p}$ bunch to bunch tune spread	$\delta\nu_{\bar{p}}$	0.007	0.010

The beam-beam compensation techniques based on the use of the intense electron beam have been proposed [3,4] and are under development now [5–8]. The present paper reviews the current status of these investigations.

NONLINEAR COMPENSATION: "ELECTRON COMPRESSOR".

Let us consider schematically the collision of proton and antiproton bunches at the interaction point (see Figure 1).

The proton bunch can effectively be considered as a lens acting on $\bar{p}$ bunch. This additional lens 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.

Since the charge density ρ of the proton bunch is Gaussian-like, the focusing force F (see Figure 1) of the equivalent lens is a nonlinear function of the transverse

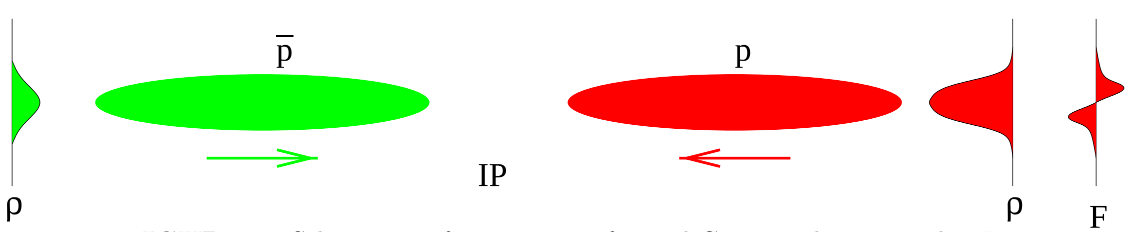

FIGURE 1. Schematics of interaction of round Gaussian beams at the IP.

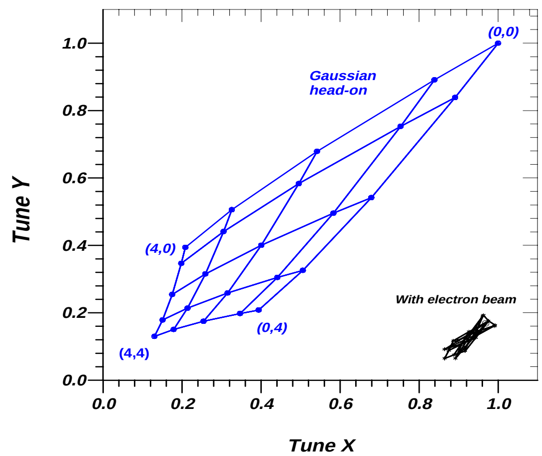

FIGURE 2. Betatron frequencies (tunes) in $\bar{p}$ bunch for particles with different betatron amplitudes (X, Y), head on collision case (large leaf) and the case with compensation by electron beam (small leaf, displaced for clarity) [3]. Tune shift is in units of ξ^p, betatron amplitude is in units of the bunch transverse size σ.

displacement.

Due to nonlinear focusing by p beam the betatron frequencies in $\bar{p}$ bunch are different for particles with different betatron amplitudes (X, Y) as shown on the Figure 2. For the RunII and TeV33 upgrades of Tevatron the spread of betatron frequencies (so called "footprint") of $\bar{p}$ beam is $\Delta\nu_{\bar{p}} \approx 0.02$ that is about the maximum experimentally achieved value for proton colliders. This tune spread $\Delta\nu_{\bar{p}}$ is big enough to cause an increase of particle losses due to higher order lattice resonances.

Compensation of beam-beam induced betatron tune spread within the $\bar{p}$ bunch can be made by an electron beam with equivalent charge distribution [3]. (One should note that usually $N_p \gg N_{\bar{p}}$, so the beam-beam effects for $\bar{p}$ are more severe, that is why we care only about compensation of beam-beam effects for antiprotons.) The scheme of the nonlinear compensation is shown on Figure 3.

The nonlinear focusing of $\bar{p}$ by the proton beam is compensated if a)the electron transverse charge distribution $\rho_e(r)$ is the same as in the proton beam $\rho_p(r)$ (but scaled on r); b) the $\bar{p}$ beam distribution at the "electron compressor" is the same as

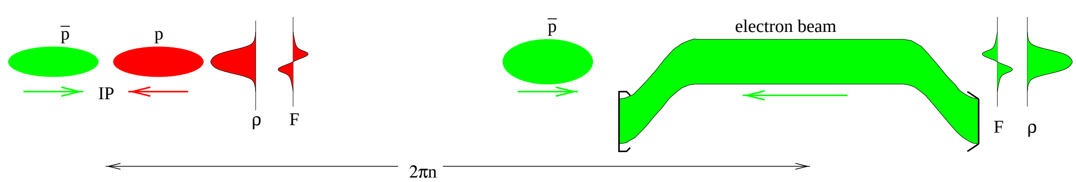

FIGURE 3. Scheme of compensation of the nonlinear beam-beam tune shift in the antiproton bunch by the electron beam with corresponded charge density.

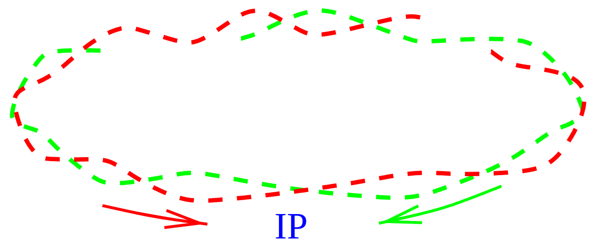

FIGURE 4. Parasitic interactions of proton and antiproton bunches.

at the IP (but scaled on r and with zero dispersion); c) the number of electrons on the path of $\bar{p}$ beam is $N_e = N_p/(1+\beta_e)$, for example $N_e \approx 4.5 \cdot 10^{11}$ or $J = 1.44$A with $\beta_e = 0.2$ and $L = 3$ m for TEV33.

The electron bunch should have Gaussian transverse distribution in ideal case, however, as it was shown in [3], more realistic and practically more easily achievable distributions can give as good result as the Gaussian one (see Figure 2), the electron beam density in this case was $\propto 1/(1+(r/\sigma)^8)$ ($\times$-marked line on the Figure 12).

The advanced studies of the nonlinear beam dynamics with the nonlinear focusing by the "electron compressor" have shown that the condition to cancel just the nonlinear tune shift may not be the only condition to satisfy for the antiproton dynamics to be improved. Status of these studies will be reported at the end of the paper.

LINEAR COMPENSATION: "ELECTRON LENS".

Beam beam interactions in colliders with a common vacuum chamber occur not only at the IP but also in hundreds places where the orbits are separated (see Figure 4). These parasitic interactions result in bunch to bunch tune spread. The effect is enhanced by the presence of injection and ejection gaps.

For TeV33 upgrade of the Tevatron the bunch to bunch tune spread is $\Delta\nu_{\bar{p}} \approx 0.01$. Such a tune spread is high enough to enhance dynamic diffusion of particles due to high order resonances, increase background in detectors and limit beam lifetime and luminosity.

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") with the current varying on special pattern [4]. The electron lens should be installed in a place where a) electron beam does not interact with proton beam; b) beta-functions $\beta_\perp$ are high enough so the electron current density n_e is reasonable; c) dispersion function is small enough; d) betatron phase advance to IP is close to $2\pi n$.

The possible candidates in Tevatron are the straight section F48 where $\beta_z = 110$m ($\bar{p}$ beam size is $\sigma_z \approx 0.51$mm) and the upstream end of C0 section. Two electron lenses installed in locations with different β_x/β_y are necessary to compensate the x and y bunch-to-bunch tune spread independently (see Figure 5).

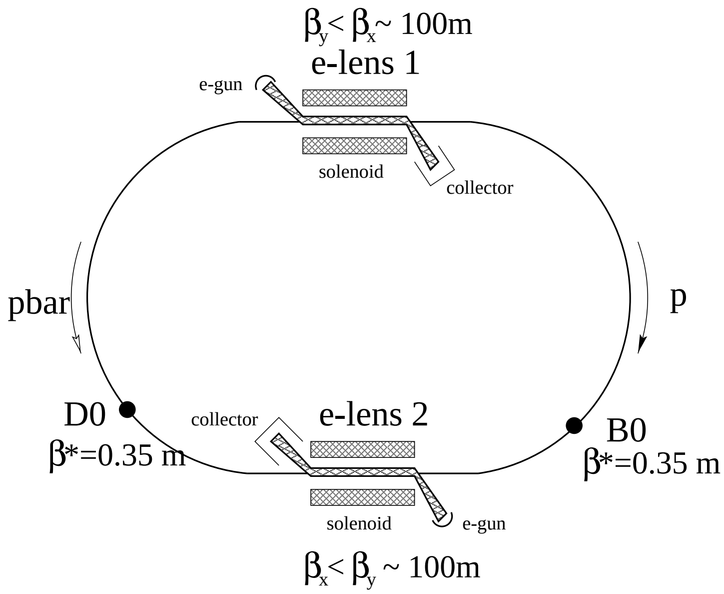

FIGURE 5. Schematics of the two electron lens location in the Tevatron.

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

$$\xi_{\perp}^{e} = -\frac{\beta_{\perp}}{2}\frac{(1+\beta_e)n_e L r_{\bar{p}}}{\gamma_{\bar{p}}} = -\frac{\beta_{\perp}}{2\pi}\frac{(1+\beta_e)JLr_{\bar{p}}}{e\beta_e c a^2 \gamma_{\bar{p}}},$$

For example the beam with $J \approx 1.65$ A, $L = 2$ m, $a = 1$ mm, energy 10 kV ($\beta_e = 0.2$) gives $\xi^e \approx -0.01$ in the Tevatron with $\gamma_p \approx 1066$ and beta function $\beta_{\perp}$=100m. The electron beam should allow 100% change of the current on 100 ns time scale (corresponds to the distance between bunches) to provide independent influence on different bunches.

Parameters of the electron beam.

The electron beam density n_e is defined from the required tune shift: $\xi^e = -\beta_{\perp}(1+\beta_e)n_e L r_{\bar{p}}/2\gamma_{\bar{p}}$. The length L is defined by the available at Tevatron space $L = 2$m. The electron beam radius a is defined by the $\bar{p}$ beam size. For the electron beam energy the lowest possible value should be chosen provided that a) the current is not limited by the gun itself; b) the electron beam renews faster than the $\bar{p}$-bunch spacing (132 ns).

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

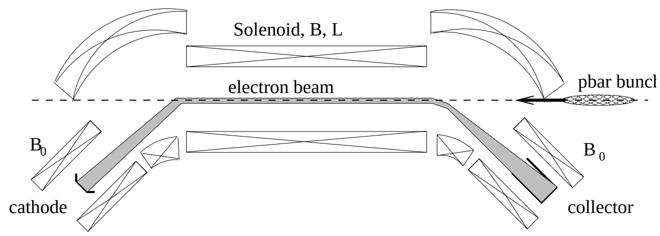

FIGURE 6. A possible layout of the "electron lens".

To decrease the current density to what is achievable for oxide cathode values, one need to use an 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 the electron lens with cathode current density $2\,A/cm^2$ and cathode radius $a_c = 5$ mm the ratio $B/B_c \equiv a_c^2/a^2$ is to be about 25.

A possible layout of the "electron lens" is shown on the Figure 6.

Experimental test facility at Fermilab.

An experimental installation that should demonstrate the feasibility of the electron lens is now under construction at Fermilab (see Figure 7). This set-up will serve as a prototype of the device that can later be inserted into the Tevatron ring. The test facility is being developed in close collaboration of several institutions worldwide, including the Budker Institute of Nuclear Physics (Novosibirsk, Russia) and the INFN LNL (Legnaro, Italy).

The parameters of the experimental installation are about the same as for the full scale device, except a lower magnetic field and current density. The goals of the set-up are a) to obtain 10 kV 2-meter long electron beam with total current up

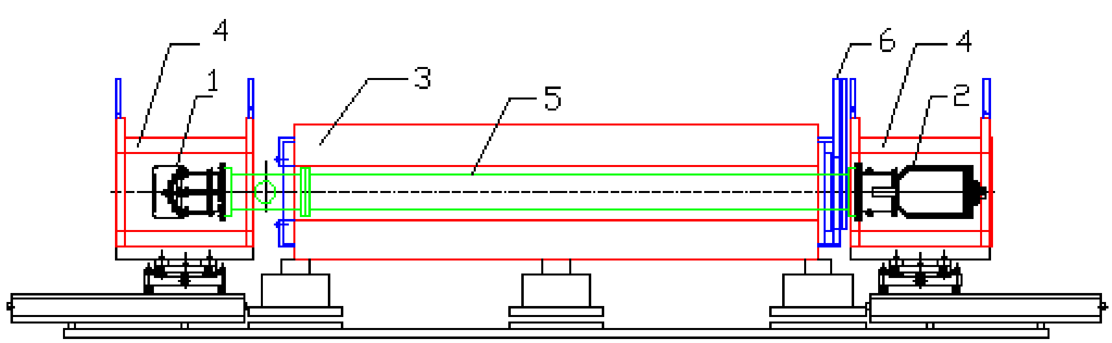

FIGURE 7. Layout of the experimental test facility at Fermilab. 1- electron gun, 10 kV, 2 A max, beam radius at the cathode 5mm, with special near cathode control electrode to change the beam profile; 2- electron collector with electrodes for current distribution analysis; 3- main solenoid, 2 meters long, 4 kG max; 4- additional solenoids, 3.5 kG max; 5- vacuum tube with beam diagnostics; 6- current input/output for solenoids.

to 2A propagating in a precise solenoid magnet; b) to test the current modulation in a few MHz bandwidth; c) to study the beam behavior and to develop necessary beam diagnostics; d) to find the physical and technical solutions needed to build the electron lens for beam-beam compensation in the Tevatron.

The status of the test facility at the end of 1998 is the following. The test facility is assembled, the measurements of the straightness of the magnetic field have been performed. The measured deviation of the magnetic field from the straight line is found to be about $1.6 \cdot 10^{-4}$ rad rms. The field deviation has been measured optically, using a magnetic arrow attached to the mirror which has two rotational degrees of freedom. The gun, collector and vacuum chamber have been installed and the total current of 2 A has been achieved. Investigations of the beam profile, tests of the beam current modulation, and other experiments are under way.

PARASITIC EFFECTS DUE TO ELECTRON BEAM.

The considered idea of the beam-beam compensation is not a first attempt in history of colliders. One of the first of such attempts was the idea of 4-beam neutralized collisions in e^+e^- e^+e^- colliding rings [10]. The experiment on the dedicated DCI rings has shown, however, that in spite of the significant charge compensation (5-10 times) and increase of the beam-beam parameter ξ from 0.018 to 0.024, no luminosity increase was achieved that was associated with coherent instabilities in the beams [11]. Another attempt was the idea to use neutralized 4-beam collisions in linear colliders, which, as it was shown in corresponded studies [12], also does not give significant benefits due to coherent charge separation instability if $\xi \gtrsim 1$.

Initial proposals of "electron compressor" for nonlinear compensation of the beam-beam induced betatron spread [3] and of the "electron lens" for linear compensation of bunch to bunch tune spread [4] have been exposed to intensive studies of the possible accompanying harmful effects [5–8]. In spite of several possibly harmful effects, which have been found, the idea of beam beam compensation by a single pass electron beam is very attractive. The magnitude of the harmful effects can be made sufficiently small by the proper choice of parameters of the compensating electron beam.

The results of investigations of the most important effects are reviewed briefly in the following sections.

Head tail in $\bar{p}$ beam due to electron beam [7].

Off center collision of the $\bar{p}$ bunch with electron beam results in drift of electrons in crossed magnetic and electrical fields $\vec{B} \times \vec{E}$ so that the head of the $\bar{p}$ sees E_y while the tail will also see E_x (see Figure 8). The resulting change of the betatron amplitude of the tail $\bar{p}$ particle is $\delta x_2 \propto y_1 \xi_x N_{\bar{p}} e/(Ba^2)$.

Taking into account that the head and the tail exchange their position with synchrotron frequency ν_s, one can see that as a result of such a skew interaction

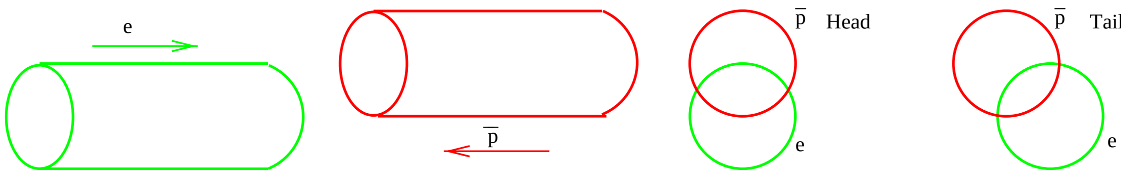

FIGURE 8. Off center collision of the $\bar{p}$ bunch with electron beam.

the horizontal betatron motion (ν_x), the vertical betatron motion (ν_y) and the synchrotron motion (ν_s) become coupled.

The skew coupling of X and Y betatron motion due to the electron beam changes the frequencies of unperturbed transverse motion. The effect is maximal for a pair of closest harmonics ($\nu_x + m\nu_s$) and ($\nu_y + n\nu_s$) (where m, n are integer). With increasing the electron beam current the real parts of their frequencies will become closer and finally collapse, at the same time the imaginary parts will appear, resulting in instability (see Figure 9).

The threshold of this Transverse Mode Coupling Instability (TMCI) in terms of magnetic field was found to be

$$B_{thr} \approx 1.3 \frac{eN_{\bar{p}}\sqrt{\xi_x^e \xi_y^e}}{a^2\sqrt{\Delta\nu\nu_s}}.$$

where $\Delta\nu = \nu_x - \nu_y$. This analytical result was confirmed by numerical simulations. Under the design parameters the minimum magnetic field that will keep the $\bar{p}$ beam stable is $B_{thr} = 17.5$ kG.

Electron beam distortion by elliptical $\bar{p}$ beam [6].

If the set-up will be located at the place where $\beta_x \neq \beta_y$ then axial symmetry is not conserved. The electron beam becomes a rotated ellipse to the moment when the tail of antiproton bunch passes it through, while the head of the bunch sees originally undisturbed round electron beam.

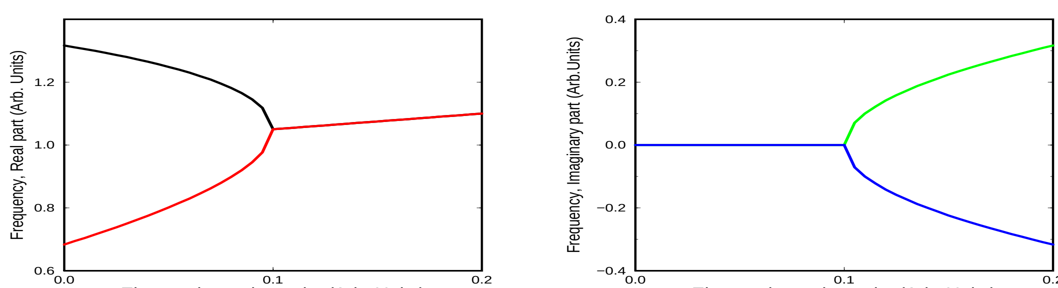

FIGURE 9. Illustration to the mode coupling instability. Frequencies of the antiproton bunch oscillation modes versus the electron beam intensity, Real part (left picture) and Imaginary part (right picture).

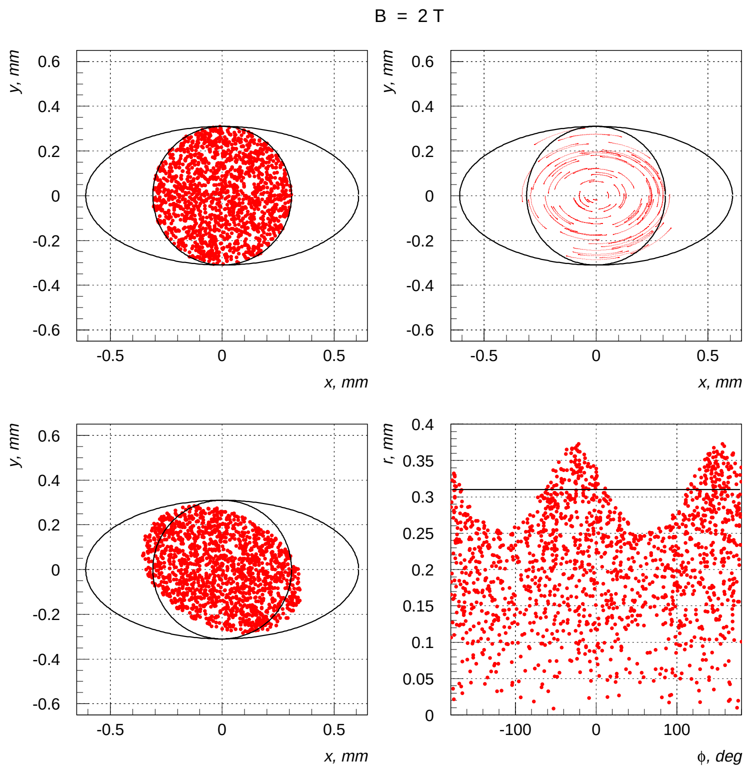

FIGURE 10. "Small" electron beam distortion due to $\bar{p}$ bunch. Round electron beam (radius $a_e = 0.31$mm) interacts with elliptical $\bar{p}$ beam in 2 Tesla solenoid field. Initial distribution (top left), electron velocities (top right), final transverse (bottom left) and azimuthal distributions [6].

The electric fields of the distorted electron beam produce $x{-}y$ coupling of vertical and horizontal betatron oscillations in the $\bar{p}$ beam. The distortion performs two variations over azimuth $\delta\rho \propto xy \sim sin(2\theta)$ and the maximum distortion scales as $\delta\rho^{max}/\rho_0^{max} \sim 0.2eN_{\bar{p}}/(a_e^2 B)$.

An example of the distorted electron beam is shown on the Figure 10. Note that distortion appears mostly at the edge of the beam that suggests (and was confirmed analytically and in simulations) that the coupling due to elliptically distorted electron beam can be additionally suppressed if the electron beam has a radius larger than the antiproton beam radius, $a \geq \sigma_{\bar{p}}$.

The field of the elliptic electron beam leads to $x - y$ coupling of betatron oscillations in the $\bar{p}$ beam. The average coupling can be corrected in the Tevatron, however the spread in coupling has to be small enough in order not to affect the $\bar{p}$ beam dynamics.

The high magnetic field can decrease coupling to an acceptable value. If $B = 2$T, the maximum coupling spread is $|\kappa| \simeq 4 \cdot 10^{-4}$ for thin electron beam , and $7 \cdot 10^{-5}$ for wider electron beam. These values are rather small with respect to the typical residual coupling in Tevatron (about 0.001).

$\bar{p}$ emittance growth due to variations of the electron beam [4].

Fluctuations of the electron current $\Delta J/J$ from turn to turn cause time variable quadrupole kicks which lead to a transverse emittance growth of the antiproton bunches. The emittance growth time is more than 10 hours if the peak-to-peak current fluctuations are smaller than $\Delta J/J \approx 1.8 \cdot 10^{-3}$.

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

Deviation of 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 forces. The effect is small if $\Delta B_{\perp}/B \lesssim 10^{-4}$.

All these conditions are believed to be achievable.

Nonlinear compensation. Advanced studies [5].

It was thought that the nonlinear compensation will compensate on average the nonlinear focusing of $\bar{p}$ by the proton beam resulting in decreasing the spread of the betatron frequencies (footprint), slowing the dynamic diffusion of particles due to high order resonances, improving radiation background in detectors, enhancing the beam lifetime and luminosity.

The nonlinear compensation, as it was just described, may not work as desired even assuming that the beam-beam interaction is the only source of nonlinearities.

The proton bunch length expressed in terms of the betatron phase advance is large $\Delta\psi_p \simeq \sigma_s/\beta^* \simeq 1$. In contrast, the electron beam length L is about 2-3 m that gives $\Delta\psi_e \simeq L/\beta \propto 0.01 - 0.02$ (see Figure 11).

Thus, the electron beam kick looks like a delta-function when transformed to the main IP. Consequently, such a short impact from the electrons contains a lot of resonance harmonics, although the average actions due to proton and electron beams are the same. One can reduce the betatron tune spread with a non-linear lens, but this alone does not assure that the motion is more stable than the one

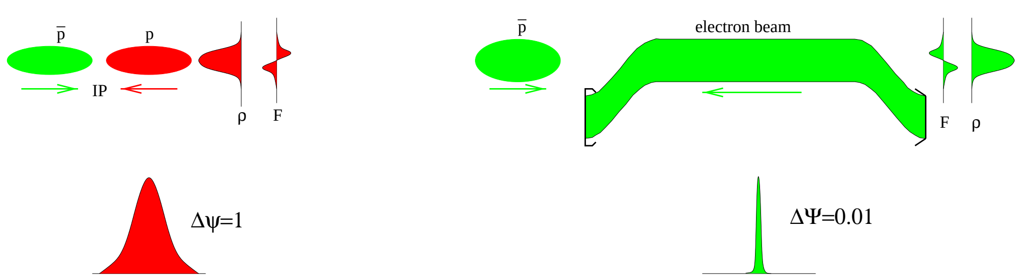

FIGURE 11. Illustration to the nonlinear compensation.

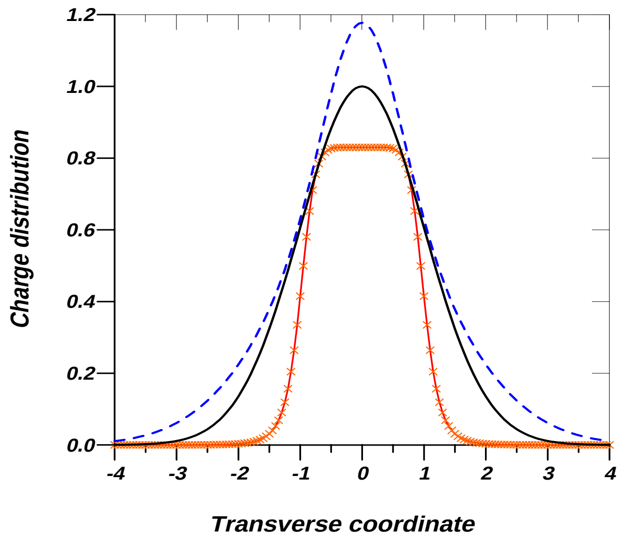

FIGURE 12. Gaussian charge distributions of the protons (solid line), of the electron beam in "electron compressor" (×-marked line) with $\rho_e(r) \propto 0.83/(1+(r/\sigma)^8)$ and of the optimized electron beam distribution (dashed line) [5].

with no compensation, because the resonance strengths can be more important than the tune spread.

The road to follow is to investigate the possibility to add 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.

In axially symmetrical system the existence of such a lens can theoretically be proven. In practical case a numerical method can be used, which consists of minimization of the sum of squared differences of coordinates and momenta at the beginning and at the end of N successive map transformations that will eliminate the Nth order resonance (the frequencies of all particles are equal to the particularly chosen value and the strength of the resonance is equal to zero). This procedure can be done for different N and an optimized electron beam distribution can be found (see an example on the Figure 12).

These investigations should be continued to prove that such a nonlinear insertion indeed improves the beam dynamics.

Stability of the electron beam. Drift instability.

"Drift instability" is the main reason that can limit the beam current in presence of ions.

Ionization of residual gas by electrons produces ions with the rate $dn_i/dt = n_e/\tau_n$ where "time of neutralization" $\tau_n = (\sigma_{\text{ioniz}} v_e n_0)^{-1}$. For our parameters $\tau_n \approx 0.25$ s if the vacuum pressure $P \approx 10^{-9}$ Torr.

Potential well of the electron beam prevents ions to get out of beam in transverse direction. The depth of the well is $U_e = \pi a^2 e n_e (1 + 2\ln b/a)$ where a, b – radius of electron beam and vacuum chamber, n_e – electron beam density. The ions may also be locked longitudinally if the electron beam is shrunk in the central part of the electron compressor.

Ions should be removed because they a) change charge density, i.e. spoil beam-beam compensation; b) may result in two beam drift instability.

Considering the motion of the charge density centers of the ion and electron beams in dipole approximation, one can find that there is an amplification of a small initial beam separation down along the beam [13–15]. The amplification coefficient is maximal at the resonance frequency

$$K_{\max} = \exp\left(-\frac{\Omega_d L}{v_e \varepsilon''}\right)$$

where $\Omega_d = 2\pi n_e ec/B$ – drift frequency, ε'' – imaginary part of the permeability, in our case approximately $\varepsilon'' \approx n_i/n_e$.

"Drift instability" of electron and ion beams appears when the feedback from the beam end to the beam beginning (e.g. by electrons reflected from the collector) is big enough $K_{\max}\eta > 1$, where η is the feedback coefficient (typically $\eta \approx 10^{-3} - 10^{-4}$).

This mechanism of the instability was confirmed by experiment and the stability condition was found to be

$$\frac{n_i}{n_e} j_e < \frac{v_e^2 B}{4Lc}$$

If $\beta_e = 0.2$, $B = 4$ T, $a = 1$ mm, $I_e = 2$ A, $L = 3$ m then the electron beam is stable if $n_i/n_e < 20$ % (much smaller fraction of ions is allowed from the point of view of beam-beam compensation).

The residual ions are therefore to be cleaned from the electron beam. Special cleaning electrodes will be used for this purpose. The vacuum should also be high enough to ensure that the neutralization time is sufficiently longer than the lifetime of ions in the electron beam. Estimations shows that proper cleaning electrodes together with vacuum better than $P < 3 \cdot 10^{-9}$ Torr will provide acceptable amount of residual ions in the electron beam $n_i/n_e < 0.5 \cdot 10^{-2}$.

CONCLUSION

The 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.

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