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A. The technique

Beam-beam interaction between protons and antiprotons($\bar{p}$) in the Tevatron collider takes place at the two head-on interaction points (IPs) as well as at numerous parasitic crossings where the beam orbits are separated. The beam-beam effects are more severe for antiprotons because p beam intensity is several times the $\bar{p}$ one. Injection gaps in the Tevatron bunch trains result in bunch-to-bunch variation of the betatron tunes due to long-range beam-beam interactions (Pacman effect). During Run II with 36 bunches in each beam, the bunch-to-bunch (b.t.b.) 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 of about 0.008 [1]. These values are about the maximum experimentally achieved value for proton colliders $\Delta\nu \approx 0.025$.

It was proposed to compensate the beam-beam impact on $\bar{p}$s due to ps by space charge force of high current, low energy electron beam [2], [3]. The electron beam setup(s) is to be installed away from the $p\bar{p}$ interaction points at B0 and D0 - see Fig.1. The electron beam is to be born on an electron gun cathode, transported through an interaction region where it collides with $\bar{p}$s in a strong solenoidal magnetic field, and then absorbed in the collector.

Implementations of the proposal are: 1) an "electron lens" with modulated current to provide different linear defocusing forces for different $\bar{p}$ bunches in order to equalize their betatron frequencies; and 2) an "electron compressor", that is a nonlinear DC electron lens to compensate (on average) the nonlinear focusing due to the p beam.

a. Linear electron lens The tune shift of $\bar{p}$ bunch due to interaction with a round, constant density electron beam with total current J, radius a and interacting with $\bar{p}$s over length L, is equal to

$$\xi_z^e = -\frac{\beta_z}{2\pi}\frac{(1+\beta_e)JLr_{\bar{p}}}{e\beta_e ca^2\gamma_{\bar{p}}}, \qquad (1)$$

where $r_{\bar{p}} = 1.53\cdot 10^{-18}$m is the proton classical radius, and z is x or y. For example, one needs an electron beam with $J = 1.65$A of current along a $L = 2$m length, with $a = 1$ mm radius, and energy 10 kV ($\beta_e = 0.2$) in order to obtain $\xi^e \approx -0.01$ in the Tevatron collider with parameters $\gamma_p \approx 1066$, β_z=100m. If the electron beam radius a is several times the $\bar{p}$ rms beam size σ_z, then most of $\bar{p}$s are equal in the tune shift. To compensate the Pacman effect, the electron current has to be variable in time.

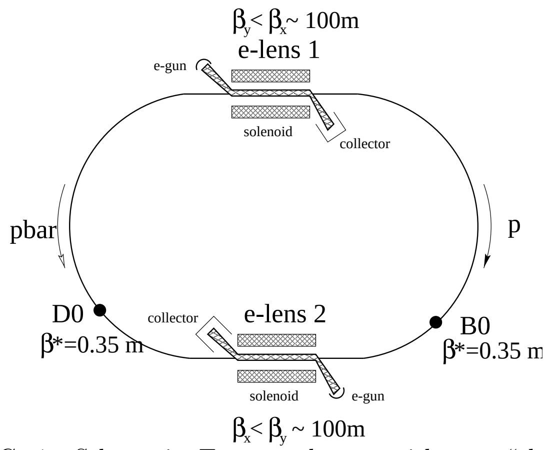

FIG. 1. Schematic Tevatron layout with two "electron lenses".

Two electron lenses - one at a location with the horizontal beta-function larger than vertical $\beta_x \gg \beta_y$ and another one at $\beta_x \ll \beta_y$ (see Fig.1) can compensate any given b.t.b. tune spread in both planes. Their net effect is $\xi_z^e(t) = \beta_{1,z}\cdot J_1(t)\cdot C1 + \beta_{2,z}\cdot J_2(t)\cdot C2$, where J_1, J_2 are currents in the two beams, $C_{1,2} \approx \frac{3.03\cdot 10^{-5}\cdot L[m]}{a^2[mm]}$.

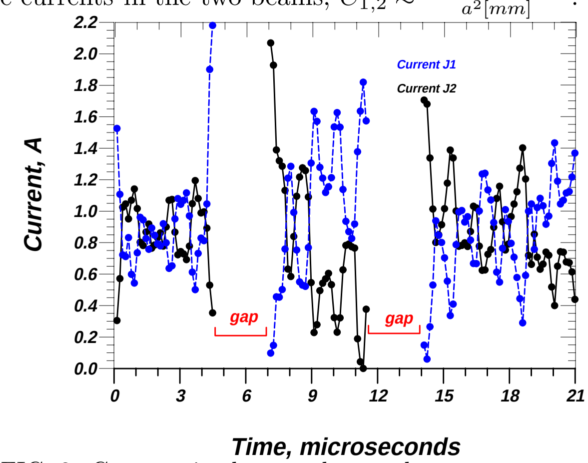

FIG. 2. Currents in the two electron lenses to compensate bunch-to-bunch tune spread in 140×121 bunches scenario.

Currents necessary for Pacman effect compensation in the TEV33 operation scenario with 140 p bunches and 121 $\bar{p}$ bunches are presented in Fig.2 (we used locations with different $\beta_{x,y} \simeq 100, 60$m, and $L = 2$m, $a = 1.2$mm) [2]. The pattern of these currents has to be repeated periodically with the Tevatron revolution period of about 21 μs. Positions of all $\bar{p}$ bunches are marked by circles. Minimum bunch spacing is $\tau = 132$ns. Maximum current is about 2.2 A. The result of implementing of these lenses would be that tunes of all the bunches would become identical - see Fig.3.

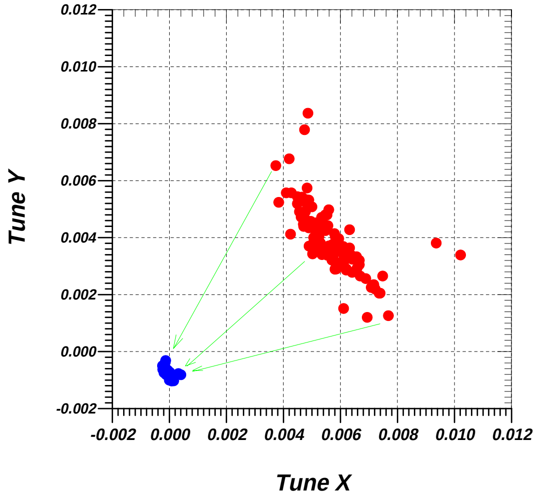

FIG. 3. Resulting $\bar{p}$ bunch tune shifts (core particles only) with 10% error of the compensation.

Separation of p and electron beams can sufficiently reduce the impact of electron space charge on ps. For example, a separation of $d \approx 10\sigma_p \simeq 7$mm will cause very little p beam tune shift of about $\xi_p^e(d) \approx 10^{-4}$.

b. Compensation of nonlinear beam-beam effects The interaction with other than a wide constant-density electron beam will not only shift the $\bar{p}$ beam tunes, but will also distort the $\bar{p}$ footprint in a way which depends on the transverse electron charge distribution, $e - \bar{p}$ separation, crossing angle in the set-up, etc. The electron beam can in principle shrink the $\bar{p}$ head-on footprint to a point if a) the electron transverse charge distribution $\rho_e(r)$ is the same as in the p beam $\rho_p(r)$; 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) the total electron beam charge $eN_e = JL/(\beta_e c)$ on the path of the $\bar{p}$ beam satisfies the equality condition of the beam-beam tune shifts $\xi^e \equiv -\frac{N_e r_p (1+\beta_e)}{4\pi\varepsilon_n} = -\xi^p = -\frac{N_{IP} N_p r_p}{4\pi\varepsilon_n}$. For simplicity, if we assume equal horizontal and vertical emittances and beta functions for $\bar{p}$s at the "electron compressor" device, then we get $N_e = N_{IP} N_p/(1+\beta_e)$. For TEV33 $N_e \approx 4.5 \cdot 10^{11}$ for $\beta_e = 0.2$, and for $L = 3$ m one needs $J = 1.44$A. The set-up can be set away of IPs, e.g., 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, c) betatron phase advances between the IP and the electron beam set-up to be multiple of 2π.

Rather effective footprint compression can be achieved even with non-Gaussian electron charge distributions. For example, Fig.4 demonstrates the $\bar{p}$ footprint due to head-on collision with Gaussian p beam $\rho_p(r) \propto exp(-\frac{r^2}{2\sigma^2})$ (larger leaf) and the beam footprint compressed with use of electron beam with charge density profile proportional to $\rho_e(r) \propto \frac{0.83}{1+(r/\sigma)^8}$ - see the smaller plot. For convenience of presentation we have separated the smaller footprint horizontally (in fact it would be around zero tune point $\nu_{(x,y)} = 0$). One can see a significant reduction (6 times) of the tune spread with use of the electron beam. The footprint compression is studied in more detail in [4].

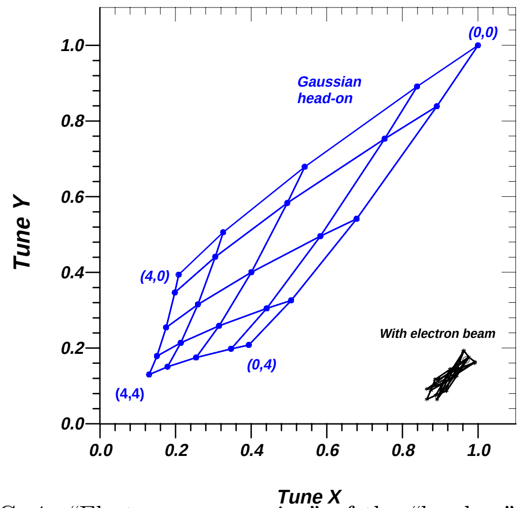

FIG. 4. "Electron compression" of the "head-on" $\bar{p}$ footprint.

The "electron compression" with 3-5 times more current (i.e., 4.5-7.5 A and proportional increase of the solenoid filed) can handle two or four near-IP "head-on" collision points, and, thus, to eliminate the crossing angle at the Tevatron IPs, that otherwise will half the luminosity [1].

B. Electron beam for beam-beam compensation

The necessary current of $a = 1$mm radius, 2-m long electron beam scales with electron velocity as $J = 9.9[A] \times \frac{\beta_e}{1+\beta_e}$. The maximum current of a space-charge limited diode electron gun is given by the Child-Langmuir law $J = [10^{-6}\,A/V^{3/2}] \cdot \mu\mathcal{P} \cdot U_a^{3/2}$, where a microperveance $\mu\mathcal{P}$ is a geometry dependable gun parameter, and U_a is the voltage difference between the cathode and the anode electrodes of the gun. In our case $U_e = U_a$ and we get a minimum electron energy of

$$U_e \approx \frac{1.2 J_0}{\mathcal{P}\sqrt{mc^2}} = \frac{16.3[kV]}{\mu\mathcal{P}}. \qquad (2)$$

The corresponding beam power current and power are $J \approx \frac{2.1[A]}{\sqrt{\mu\mathcal{P}}}$; $W = J \cdot U_e = \frac{34[kW]}{\mu\mathcal{P}^{3/2}}$. The electron lens requires modulation of the electron current with a characteristic time of $\tau \simeq 132$ ns. This can be done by varying the cathode-anode voltage U_a from zero to U_e. If the cathode-anode capacitance is approximately $C_a = 20$pF, then the reactive power in the modulator circuit is about $W_m = C_a U_e^2/(2\tau) \approx 20[kW]/\mu\mathcal{P}^2$. Thus, a higher gun perveance is beneficial for the beam power, beam current and the modulator power. There are two effects which do not allow to have the electron energy less than 2 kV: firstly, the electrons must be fast enough to provide the necessary current modulation for the bunch separation of about 132 ns; secondly, the electron beam kinetic energy must overcome the electron beam space charge potential with respect to the grounded vacuum chamber walls [2]. We rely on possibility to make the electron gun for the electron lens with $\mu\mathcal{P}$ between 1 and 3, and corresponding $U_e = 16 - 5.5$ kV, while for numerical estimates we use $U_e = 10$ kV and $\beta_e = 0.2$.

Because the required current density of about $50A/cm^2$ can not be obtained from oxide cathode, an adiabatic magnetic compression will be used. It means that the beam is born on the cathode with a larger radius $a_c = 5mm$ in a weak field $B_c = 2$kG and transported to the region of a stronger magnetic field $B = 50$kG, with conservation of the adiabatic invariant $B_c a_c^2 = Ba^2$. Thus, its radius will be $a = 1$mm. To prevent the $\bar{p}$ beam emittance growth, the electron current has to be very well stabilized $\frac{\delta J}{J} < 10^{-3}$, and its transverse motion has to be suppressed down to about 0.2 μm [3]. These are rather challenging tolerances in the e-lens regime.

High vacuum in the set-up (better than 10^{-8} Torr) and special cleaning electrodes should prevent concentration of residual ions inside the electron beam.

C. Strong magnetic field

c. Electron beam distortions. If the electron lens is set in the locations with unequal beta-functions $\beta_x \neq \beta_y$, then collision with non-round (elliptic) $\bar{p}$ beam will lead to appearance of elliptic distortion of the electron cross section with relative amplitude of about [5]:

$$\frac{\delta\rho^{max}}{\rho_0^{max}} \simeq \frac{0.2eN_{\bar{p}}}{a^2B} \approx \frac{0.6[N_{\bar{p}}/6\cdot 10^{10}]}{a^2[mm]B[kG]}. \tag{3}$$

It results in the space charge force distortion which must be minimized. For example, $B = 40$ kG solenoid field is needed to achieve about 1.5% distortion for the design electron lens parameters. Having the electron beam 2-3 times wider than the $\bar{p}$ beam size will reduce $\delta\rho$ 4-9 times [5] while providing much more linear electron lens. Ellipticity of the electron beam can lead to effective $x-y$ coupling of vertical and horizontal betatron oscillations in the $\bar{p}$ beam (mostly, in the bunch tail).That is of concern because Tevatron operates near the difference resonance $\nu_x = 20.585, \nu_y = 20.575$.

Having the solenoid field of $B = 40$kG, $\bar{p}$ beam size $\sigma_x = 0.61$mm, other parameters $N_{\bar{p}} = 6\cdot 10^{10}$, $\xi_x^e \simeq 0.01$, a maximum coupling spread is found to be equal to $|\kappa| \simeq 2\cdot 10^{-4}$ for the electron beam with the about same size as $\bar{p}$ beam size $a = \sigma_x$. $|\kappa| \approx 3.5\cdot 10^{-5}$ for wider electron beam $a = 2.5\cdot\sigma_x$. Both of these values are rather small with respect to the Tevatron global coupling correction goal of about 0.001. Note, that two 2 m long 40 kG solenoids for the electron lenses will contribute to the global Tevatron coupling of about $|\kappa| \simeq 0.001$.

d. Head-tail effect due to electron beam. Low energy electrons can create significant transverse impedance comparable with intrinsic impedance of the Tevatron ring, that can result in collective instability of the $\bar{p}$ bunch. The phenomenon is as follow: if the centroid of the $\bar{p}$ bunch head collides off the electron beam center, then the electron-$\bar{p}$ repulsion causes the electron motion. As the result, the electron beam acquires a displacement to the moment when it interacts with the tail of the bunch. The minimum magnetic field which can keep the $\bar{p}$ beam stable is given by formulae [6]:

$$B_{thr} \approx \frac{0.95eN_{\bar{p}}\xi^e}{\sigma_{\bar{p}}^2\sqrt{|\nu_x-\nu_y|\nu_s}} = \frac{17.5[kG]\frac{N_{\bar{p}}}{6\cdot 10^{10}}|\frac{\xi^e}{0.01}|}{(\frac{\sigma_{\bar{p}}[mm]}{0.7})^2\sqrt{\frac{\nu_s}{0.001}\frac{|\Delta\nu|}{0.01}}}, \tag{4}$$

Under the design beam parameters, B_{thr} is equal to 17.5 kG. The instability is additionally suppressed if the electron beam radius is larger than the $\bar{p}$ beam size, $a \geq \sigma_{\bar{p}}$,, as B_{thr} scales approximately as $\propto \xi^e/a^2$.

e. Field alignment. Electrons perform tiny and fast Larmor oscillations and follow magnetic field lines in a strong solenoid field B. Deviation of $\Delta\vec{B}$ from a straight line could cause off-center collisions of the pbar and electron beams. If one requires the solenoid field to be straight within 0.2 mm (that is about 25% of the $\bar{p}$ beam rms size), then the field homogeneity has to be $\frac{\Delta B_\perp}{B} \sim \frac{\Delta X}{L} \sim \frac{0.2mm}{2m} = 10^{-4}$. It is comparable with the field quality in numerous electron cooling devices.

D. Experimental test

The electron lens prototype is now under construction at Fermilab. The set-up consists of a diode electron gun and collector immersed in the magnetic field of 1-2.5 kG produced by 0.5 m long normal conducting solenoids, 2 meter long beam transport section inside 4 kG solenoid magnet. It will operate with about 2A 10kV electron beam modulated in few MHz bandwdth. The beam radius at the cathode is 5mm and it can be compressed to about 2.5mm in the main solenoid. The electron gun has special electrodes to controle the beam profile. The main solenoid of the installation is made precise enough so that the achievable angular field homogeneity is better than $5\cdot 10^{-5}$. The magnetic field straightness will be measured optically using a magnetic arrow attached to a mirror, and then improved if necessary by corrector coils.

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