Compensation of Beam-Beam Effects in the Tevatron Collider, Status of R&D Activities at Fermilab.

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Abstract

Compensation of beam-beam effects in the Tevatron with electron beams has been recently suggested to improve the collider performance [1, 2]. The method implies that an antiproton beam propagates through a countertraveling low-energy high-current electron beam ("electron lens"). An impact of the negative electron space charge can reduce betatron tune spread within antiproton bunch and a bunch-to-bunch tune spread – the effects due to collision with intensive proton beam responsible for reduction of the beam lifetime and luminosity. A prototype device for the beam-beam compensation in the Tevatron has been commissioned at Fermilab. We describe basic principles of the beam-beam compensation, represent the experimental set-up and report results of the first tests of the electron beam.

1 INTRODUCTION

The two planned upgrades (Run II and TEV33) of the $p\bar{p}$ Tevatron collider [3] will give higher luminosity and will also have enhanced beam-beam effects (see Table I). 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). For example, the larger circles in Fig.1 from [3] shows the spread in vertical and horizontal tunes for small betatron amplitude particles (core) in all $\bar{p}$ bunches for TEV33 with 140 proton and 121 antiproton colliding bunches. In the same Figure, the smaller circles represent the tunes of non-zero amplitude particles in three of the $\bar{p}$ bunches. One can see that the tune spread within each bunch and the bunch-to-bunch tune spread are both about 0.008.

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 in the Tevatron.

The beam-beam compensation techniques based on the use of intense electron beams have been proposed [1, 2] and are under development now [4]–[11]. Realization of the beam-beam compensation technique can not only give additional flexibility in choosing the collider parameters and improving its luminosity and lifetime, but it also can be used as a tool to study the beam-beam effects (e.g. Pacman) in order to gain a new knowledge applicable to the LHC or other future colliders.

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 2) with the current varying from bunch to bunch [2]. The electron beam must allow a 100% change of current in the 132 ns time between bunches in order to provide indepen-

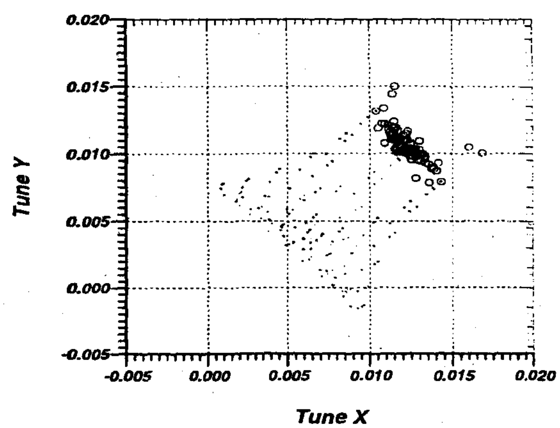

Figure 1: Tune spread in the $\bar{p}$ beam for the TEV33 Tevatron upgrade [3]. Large circles are for tunes of core particles in 121 antiproton bunches. Small circles are tunes of non-zero betatron amplitude particles in some bunches.

Table 1: Parameters of the planned Tevatron upgrades

Parameter		Run Ib (1993-95)	Run II	TEV33
Beam energy	E_b, GeV	900	1000	1000
Luminosity	$\mathcal{L}, s^{-1}cm^{-2}$	$1.6 \cdot 10^{31}$	$2.1 \cdot 10^{32}$	$1.2 \cdot 10^{33}$
No. of bunches (p,$\bar{p}$)	N_b	6,6	36,36	140,121
Min. bunch spacing	τ, ns	~3500	396	132
Protons/Bunch	$N_p/10^{11}$	2.3	2.7	2.7
Antiprotons/Bunch	$N_{\bar{p}}/10^{11}$	0.55	0.75	0.6
p-emittance rms	ε_{np}, $\pi\mu$m·rad	3.8	3.3	3.3
$\bar{p}$-emittance rms	$\varepsilon_{n\bar{p}}$, $\pi\mu$m·rad	2.2	2.5	2.5
Number of IPs	N_{IP}	2	2	2
Interaction focus	β^*, cm	35	37	37
Crossing half-angle	θ_{IP}, mrad	0	0	0.14
Bunch length	σ_s, cm	60	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**

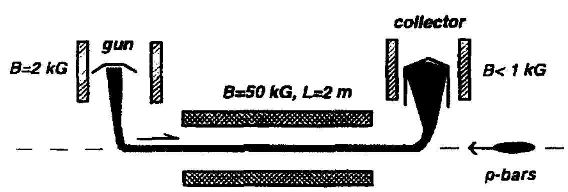

Figure 2: A possible layout of the "electron lens".

dent influence on different bunches.

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

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

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 3).

The currents of two electron lenses versus time t for the TEV33 operation scenario with 140 p bunches and 121 $\bar{p}$ bunches are shown in Fig.4. The patterns of these currents have to be repeated periodically with the Tevatron revolution period (about 21 μs). Fig.5 shows the initial 121 bunch tunes and the resulting bunch tunes assuming a 10% compensation error (see circles in the lower left corner). Such an error may be due to current mismatch, inadequate beam-beam model or imprecision of the single bunch tune diagnostics. Without errors the result of compensation would look like a point in Fig.5.

The electron beam parameters are determined by the following constraints. 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 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 $\approx 2 \cdot$

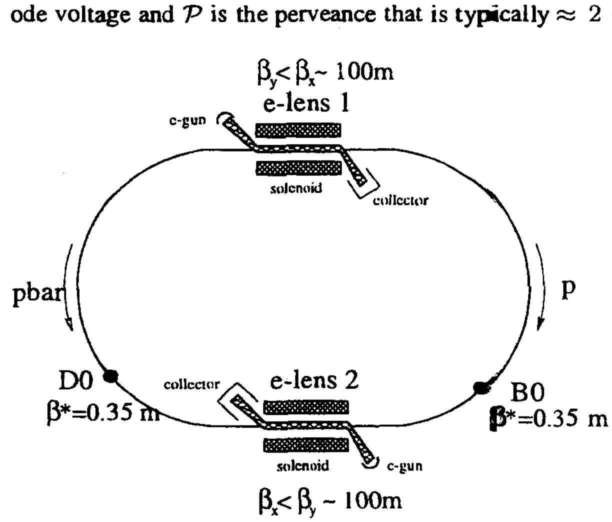

Figure 3: Tevatron layout with two "electron lenses".

$10^{-6}\,A/V^{3/2}$ 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 [12]. 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 $\xi^e_\perp \approx -0.01$ 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 which should demonstrate feasibility of the electron lens has been commissioned at Fermilab. 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 outlined below in this paper and are also described in detail in [8]–[10].

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 6. For the RunII and TEV33 upgrades of the Tevatron

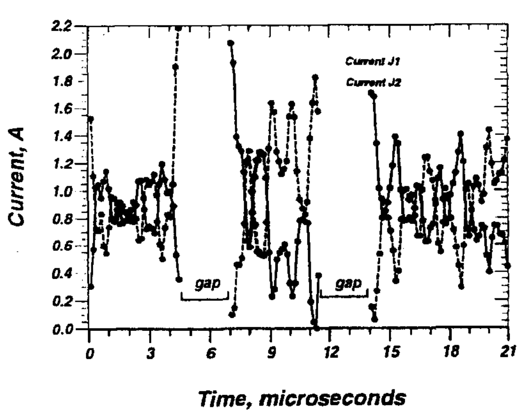

Figure 4: Currents in the two electron lenses to compensate the bunch-to-bunch tune spread in the 140×121 bunches scenario.

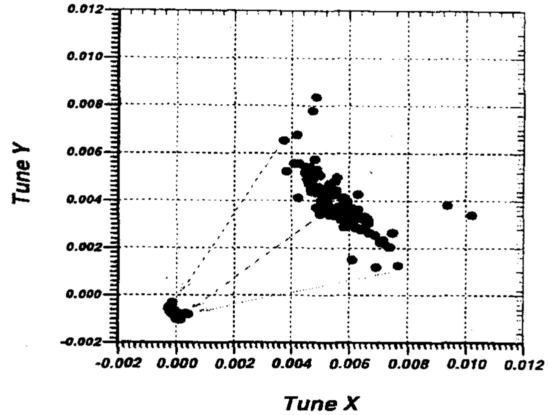

Figure 5: Initial (widely spread points) and resulting $\bar{p}$ bunch tune shifts (core particles only) with 10% error in the compensation.

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 [1]. 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

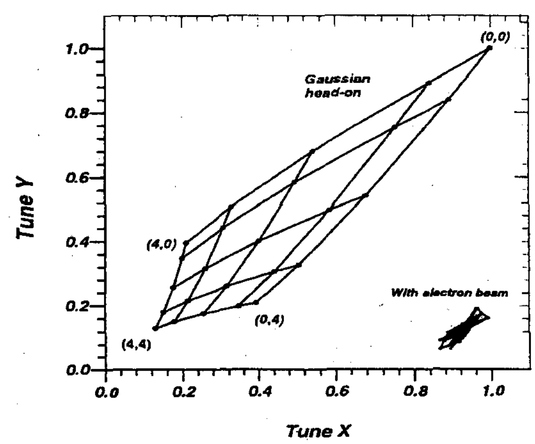

Figure 6: Betatron frequencies (tunes) in the $\bar{p}$ bunch for particles with different betatron amplitudes (X, Y). The head-on collision case (large leaf) and the case with compensation by the electron beam (small leaf, displaced for clarity) [1] are shown. Tune shift is in units of ξ^p, betatron amplitude is in units of the bunch transverse size σ.

$L = 2$ m for TEV33.

The electron bunch should have a Gaussian transverse distributionin 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 [1]. For example the electron beam density $\propto 1/(1+(r/\sigma)^8)$ was used for the footprint compression simulations presented in Figure 6.

Cancelation of just the nonlinear tune shift is not the only condition to improve the antiproton dynamics. 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 electric fields, such that, while the head of the $\bar{p}$ bunch sees a vertical field, the tail will also see a horizontal one. 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 $\propto \xi_{\perp}^{e}/a^2$.

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 [2]. 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 $\Delta B_{\perp}/B \lesssim 10^{-4}$.

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 "ELECTRON LENS" PROTOTYPE

An experimental R&D program on beam-beam compensation was started at FNAL Beams Division early in 1998. The "electron lens" prototype has been designed, fabricated, assembled in the Linac Lab and commissioned in December 1998. The goal of the set-up is to study feasibility and properties of the electron beam required for the beam-beam compensation. Currently, these studies are under way. The scheme of the set-up (in present configuration) is shown in Fig.7 and Fig.8. Table 2 shows the Tevatron "electron lens" (TEL) design parameters and parameters of the prototype set-up operation to date.

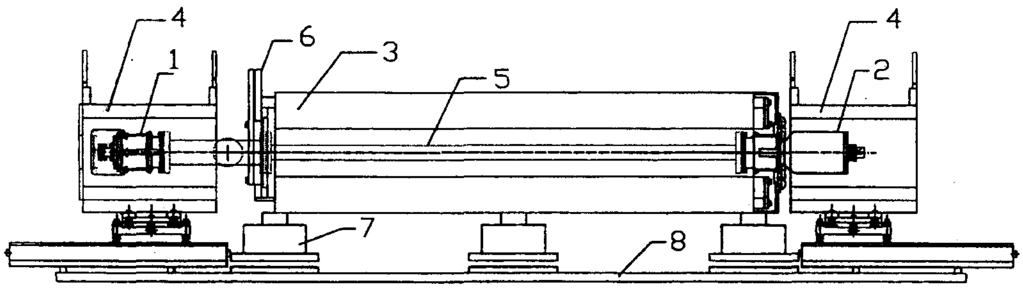

Figure 7: Scheme of the prototype of the beam-beam compensation device. 1– electron gun, 2– collector, 3– 4kG solenoid with 16 pairs of dipole corrector coils, 4– gun and collector solenoids, 5– vacuum pipe, 6– current input/output for main solenoid, 7– adjustable supports, 8– assembly table.

Figure 8: Prototype of the Tevatron beam-beam compensation device ("electron lens"). From left to right: modulator(not seen), short solenoid with electron gun inside, vacuum pump connection, long 4 kG solenoid, short solenoid with collector.

Table 2: Parameters of the "Tevatron Electron Lens" and of its prototype.

Parameter	units	TEL	Prototype
Effective length,	m	2.0	1.96
Electron current,max,	A	2.2	3.05
Electron energy, max	kV	5-10	6.4
CW modulation time,	μs	0.4(0.13)	0.5
Solenoid field,	kG	50	4
Electron current density,max,	A/mm^2	0.65	0.18
Beam deviation,rms	mm	0.1	0.07
Configuration		2 bends	straight
Beam shape control		yes	yes

Major components and systems of the "electron lens" prototype are: electron gun, electron collector, modulator, power supplies, magnetic system, vacuum system, control system. Electrons are thermally emitted from a cathode of the gun and extracted toward the positive potential of an anode U_a (see scheme in Fig.9). Then they propagate through some 2 m long beam pipe which is under potential U_p (usually, $U_p \approx U_a$). Finally, electron beam is absorbed in a collector at a smaller potential $U_c \leq U_a$. Focusing of the electron beam is provided by the strong longitudinal magnetic fields (of the order of few kG all along the set-up).

The high perveance electron gun is made in accordance with a novel approach proposed in [12] based on use of a convex cathode (see Fig.10). A 10 mm diameter 45° convex cathode of the gun is immersed in 0.7-2 kG longitudinal magnetic field. Special shape of the cathode and of the control electrode provides a uniform current density profile, low transverse beam temperature and high perveance (these conditions can not be met in a standard Pierce geometry with a planar cathode). Fig.11 shows the maximum electron current J_e vs voltage between the anode and the cathode of the gun U_a. Numerical simulations of the gun yielded the perveance $\mathcal{P} = 4.9 \cdot 10^{-6}\ A/V^{3/2}$, while measurements give a somewhat larger value of $\mathcal{P} = 5.85 \cdot 10^{-6}\ A/V^{3/2}$. The excessive perveance is probably explained by imperfect alignment of the cathode.

The electron collector (Fig.13) is able to absorb about 5-10 kW of electron beam power on its water cooled walls. In contrast with typical designs, this collector has no additional electrodes for repelling secondary electrons. These

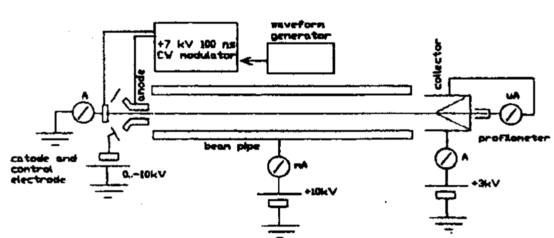

Figure 9: Electrical scheme of the "electron lens" prototype.

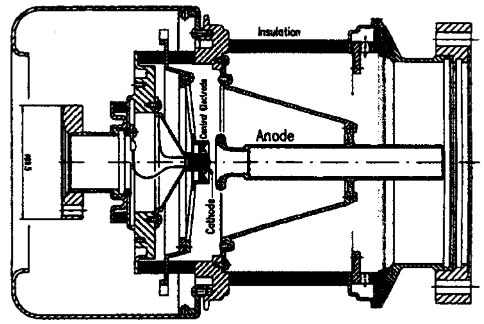

Figure 10: Electron gun.

electrons are captured due to rapid decrease of the magnetic field in the collector entrance. Typical relative losses of electrons are about $5 \cdot 10^{-4}$, minimum 10^{-4}.

The electron beam current profile measurements are possible by using a profile analyzer (see Fig.14) installed in the collector. The backplate of the collector has a tiny hole 0.2 mm in diameter and an additional Faraday cup behind it to measure the current which goes through the hole. This current is a measure of the electron beam current density. Dipole correctors allow movement of the electron beam across the hole and a measurement of the current profile. This analyzer can also be used to measure the temperature of the beam.

The control electrode of the gun can be used to vary the current density distribution. Fig.12 demonstrates an example of "bell-like" shape of the current density distribution obtained by applying a negative voltage to the control electrode. In this case the total current is reduced by about 30% from 0.22 A to 0.16 A when the control electrode is under negative HV.

The magnetic system of the "electron lens" prototype

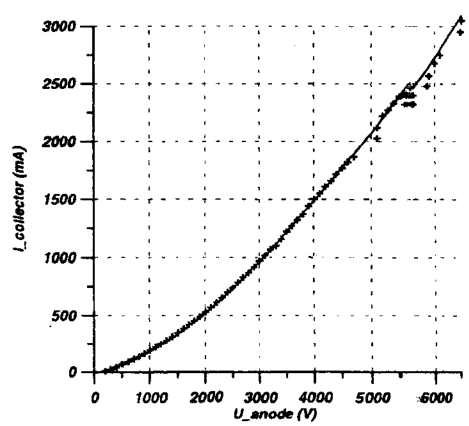

Figure 11: Current in the collector vs anode voltage. Smooth line represents a fit accordingly to Child's law with microperveance of $\mu\mathcal{P} = 5.85$.

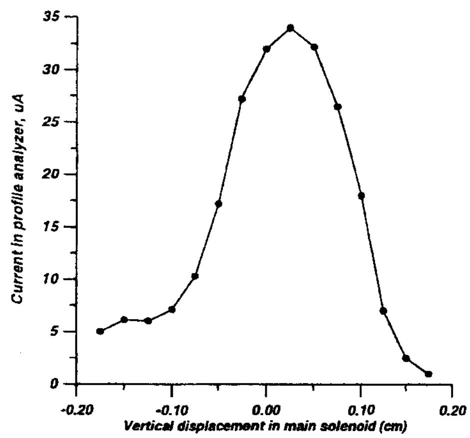

Figure 12: Vertical beam scan: analyzer current vs beam deflection in main solenoid.

consists of the main solenoid (1.96 m long, 4 kG maximum field) and of two solenoids (50 cm long, 4 kG maximum field) that produce longitudinal magnetic fields in the gun and collector. Since low energy electrons in a strong magnetic field just follow the magnetic field lines, the straightness of magnetic field is essential for the beam-beam compensation to work properly. One of the goals of the prototype is to get a straight electron beam in the main solenoid with a deviation less than 0.1 mm rms. Precise coil fabrication and winding together with field correction by 4 pairs of 50 cm long and 12 pairs of 12 cm long dipole corrector coils installed atop the main solenoid in both planes allowed to acheive the necessary field quality.

A calculation of the electron beam trajectory corresponding to the measured magnetic field is shown in Figure 15. The rms trajectory displacement over 80% of the length of the main solenoid was found to be $\sigma_x = 0.05$ mm and $\sigma_y = 0.04$ mm, which satisfies the requirements for the "electron lens". Use of corrector coils allows about 10 times field

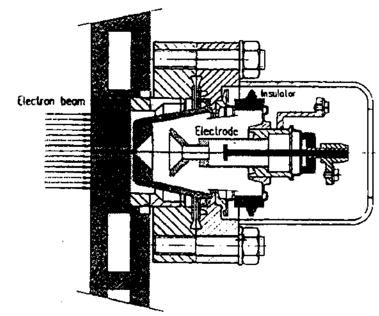

Figure 14: Beam profile and temperature analyzer.

quality improvement. These results suggest that the same field quality in the full scale beam-beam compensation device can be achieved with a few dipole correctors at the ends of the main 5 T solenoid.

A linear "electron lens" will be used to compensate the bunch-to-bunch tune spread in the Tevatron antiproton beam. The minimum bunch spacing in the Tevatron is 396 ns in Run II and 132 ns in the TEV33 upgrade of the collider. A straightforward way to get needed CW modulation of the current is to vary the anode voltage $U_a(t)$.

The anode is modulated using a grid driven, 25 kW tetrode. Fig.16 shows 1 MHz modulation of the anode voltage (1.5 kV peak-to-peak, 3 kV maximum)- see lower line, and the total electron current (0.43 A peak-to-peak, 0.7 A maximum) - see upper line. Future upgrades to the modulator will allow a greater degree of anode modulation at higher frequencies. A new all solid-state modulator, utilizing MOSFET technology, is also under development [10].

Our future plans at the "electron lens" prototype include studies of the collector efficiency vs the set-up parameters, electron beam profile measurements with a thin wire in

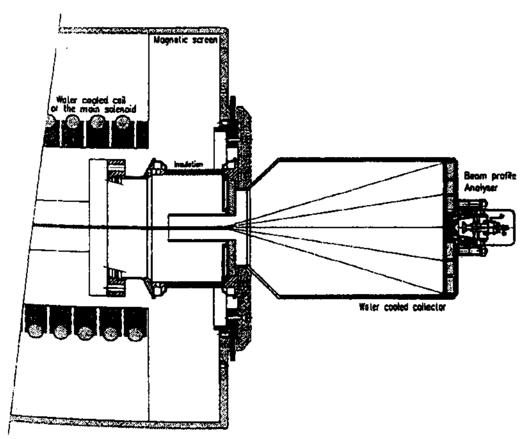

Figure 13: Electron collector.

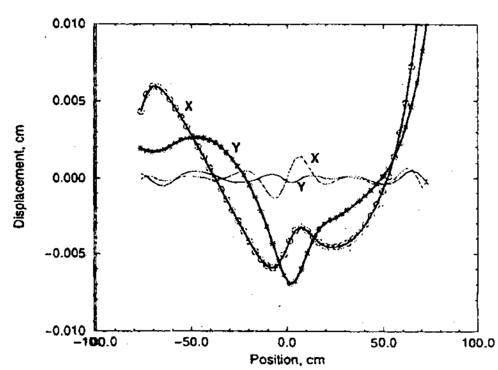

Figure 15: Simulation of the electron beam displacement without (stars and circles) and with correction by dipole coils in the measured solenoid field.

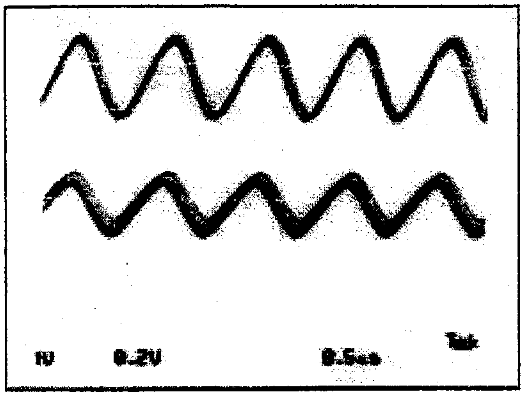

Figure 16: Current modulation in the "electron lens" prototype with frequency 1 MHz. Upper line - current in the collector 0.2 A/div (0.43 A peak-to-peak), lower line - anode voltage 1 kV/div (1.5 kV peak-to-peak).

main solenoid, and installation of diagnostic tools to control the amount of ions and secondary electrons in the system. A new (smaller size) electron gun and collector are under consideration.

Design of the full scale "electron lens" is going in parallel with studies of the prototype. Fabrication of the full scale device will start in the second half of this year and first tests under beam in the Tevatron are expected to happen to the end of 2000.

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7 CONCLUSION

Beam-beam compensation with an electron beam provides additional useful "knobs" to control beam dynamics in the Tevatron collider. It can also be used to study beam-beam effects relevant for the LHC and other future colliders. Experimental studies at the electron lens prototype and design of the first full scale "Tevatron electron lens" are under way.

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