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Beam-Beam Effect Compensation at the LHC

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Abstract

Computer simulations were done to study the decoherence of beam oscillations in the LHC collider due to the tune spread generated by the head-on beam-beam interactions. The tune spread generated in colliders by head-on beam-beam interactions usually causes fast decoherence of the betatron oscillations and, therefore, imposes more stringent requirements on a feedback system. The beam-beam force excites high order betatron resonances, this places a strong limit on the collider luminosity. According to our computer simulations, beam-beam tune spread might be reduced by collisions of the beam with a space charge of a low energy electron beam. The low energy beam could be kept stable during collisions using a solenoidal magnetic field. It was shown that for reasonable tolerances of the low energy beam parameters quite good beam-beam effect compensation could be obtained and beam-beam tune spread could be reduced by a factor up to about 100.

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1. INTRODUCTION

The head-on beam-beam effect is the major source of nonlinearities in high energy colliders. Such a nonlinearity imposes certain limits on the collider luminosity due to the beam instability. The long range beam-beam interaction could be avoided in some crossing schemes, but the head-on beam-beam tune spread and related beam instability remains as the most fundamental luminosity limitation for proton-proton colliders. The strongly non linear beam-beam force excites high order betatron resonances, so particles diffuse into the tails of the transverse distributions and get lost. For the LHC collider the beam-beam interaction luminosity limit is about 2.5×10^{34} cm^{-2}s^{-1}, i.e., still above the design luminosity of 1.0×10^{34} cm^{-2}s^{-1}. However, the tune spread generated by head-on beam-beam interactions causes fast decoherence of the betatron oscillations and, therefore, imposes more stringent requirements on any feedback system. For the LHC collider a solution leading to a reduced beam-beam tune spread would be very important.

2. DECOHERENCE OF BEAM OSCILLATIONS DUE TO BEAM-BEAM EFFECT

In the LHC collider, there exist many external circumstances in which the centroid of a circulating beam is displaced from the design orbit. If particle motions are linear, the displaced beam will undergo betatron oscillations as a whole (coherently) because all particles in the beam have the same tune, defined by the number of betatron oscillations in one revolution. However, nonlinearities in the machine can cause different particles to have different tunes, i.e., can generate a tune spread in the beam. When this is the case, the betatron motions of particles in a displaced beam will not be coherent, and the so-called phase mixing or decoherence results. Eventually, the phase space distribution of the beam will approach an equilibrium with the beam centroid returning to the design orbit, and the beam size (emittance) enlarged. For the LHC collider, the tune spread is primarily generated by the nonlinear Coulomb force experienced by the two counter-rotating beams when they collide at the interaction points, i.e., the so-called head-on beam-beam interaction.

The reasonable approach to the calculation of the head-on beam-beam effect in the

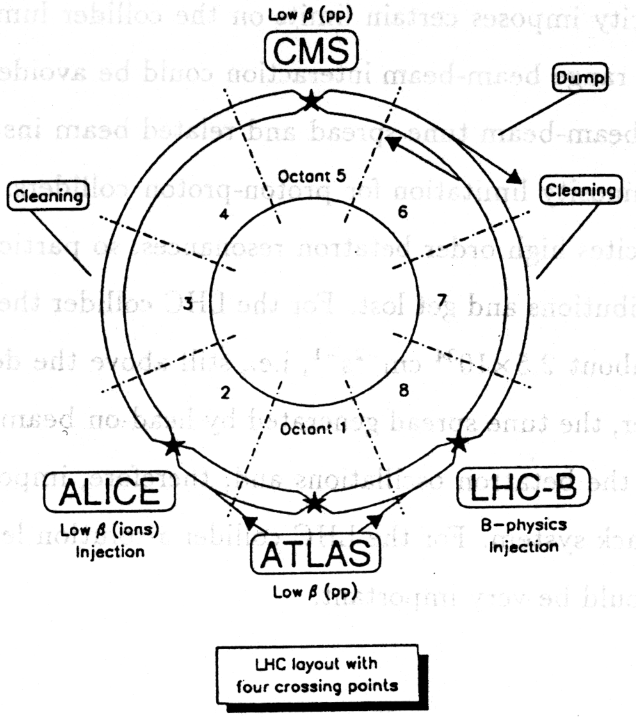


Figure 1: LHC schematic lay-out.

collider mode is the so-called weak-strong model. In this model one beam is regarded as "weak" and the counter-rotating beam, unperturbed by the weak beam, is considered as "strong". If the particle distribution of the counter-rotating ("strong") beam is a round Gaussian, the kicks given to the protons of the "weak" beam by the space charge of the "strong" beam are [1]:

$$\begin{bmatrix} \Delta X' \\ \Delta Y' \end{bmatrix} = \frac{2N_b r_p}{\gamma_p} \frac{1}{X^2+Y^2} \left(1 - exp(-\frac{X^2+Y^2}{2\sigma^2}) \right) \begin{bmatrix} X \\ Y \end{bmatrix},$$

where N_b is the number of particles in a bunch of the strong beam, r_p the classical proton radius, γ_p the Lorentz relativistic factor of a 7 TeV proton, and σ the r.m.s. beam size at the low-β IPs (IP1 and IP5 in Fig. 1). We have used $N_b=10^{11}$ and $\sigma=15.9$ μm in accordance with the LHC design.

To illustrate the decoherent process due to the beam-beam interactions, we show in

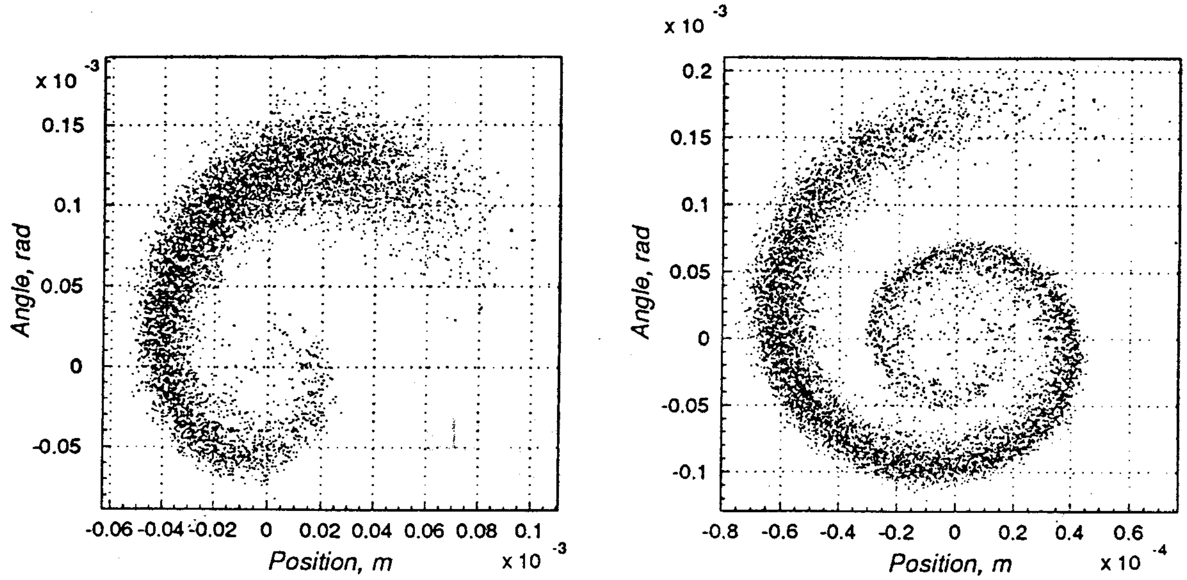


Figure 2: Distributions of the beam in phase space after a horizontal displacement of 3 sigma. Left) after 200 turns, right) after 400 turns.

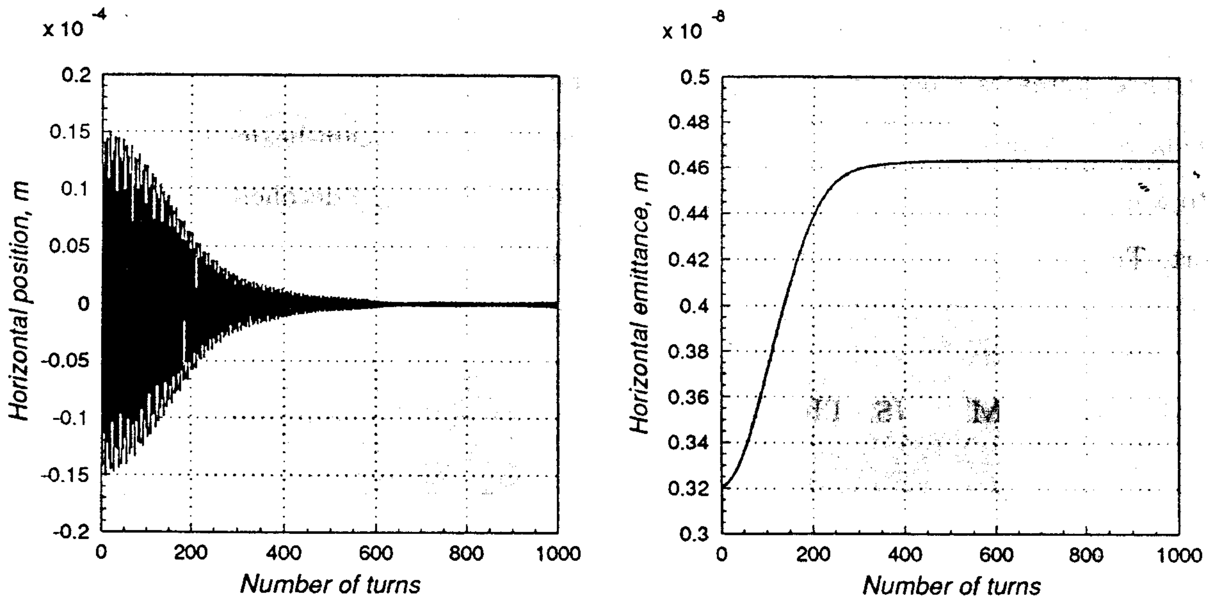


Figure 3: Left) oscillations of the beam centroid after an initial beam displacement of 1 sigma, right) growth of the relative-to-centroid beam emittance after an initial beam displacement of 1 sigma. No compensation.

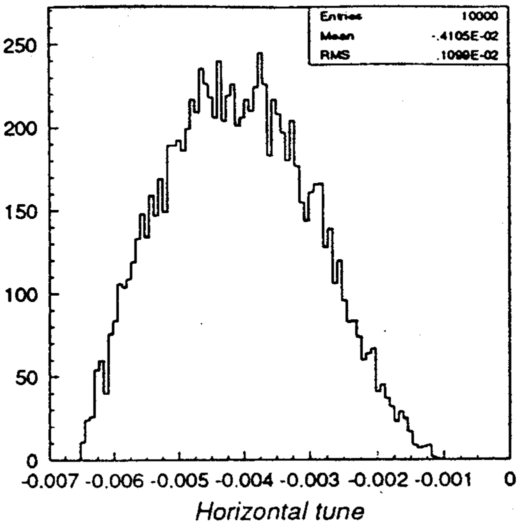


Figure 4: Horizontal tune distribution of beam particles. No compensation.

Fig. 2 the phase space distributions of the beam at 200 and 400 turns after a horizontal displacement of 3σ. One can see that the beam distribution in phase space is being homogenized. Fig. 3 demonstrates that, as beam decoheres, the position of its centroid oscillates with decreasing amplitude and eventually settles around zero (the design orbit) and that the beam emittance increases monotonously and finally approaches a steady-state value. The phase mixing of particles due to the tune spread generated by the beam-beam interaction has lead to a new equilibrium in the beam. One can see also that the decoherence time is rather short. The corresponding beam tune distribution is shown in Fig. 4.

3. SCHEME OF COMPENSATION

An ideal solution for compensation of the beam-beam effect in proton-proton machines is an instantaneous collision of a proton bunch with a counter-rotating beam of negatively charged particles having the same parameters as a counter-rotating proton bunch. We assume that we are still far away from the conditions of one-pass collective instabilities [2]. In this case the angular kick delivered to a primary proton by the space charge of the counter-rotating proton bunch would be exactly canceled by the kick delivered by the negative space charge of the compensating beam. We show that a low energy electron beam could be used as the compensating beam. This idea was initially proposed in [3]. It is important that the compensating beam be formed with the same two-dimensional transverse coordinate distribution as the proton bunch.

The longitudinal profile of the compensating beam is not really important, because the angular kick delivered to the primary proton by the compensating beam could be accumulated along the length of the available collision region (about 2 meters for the LHC case), which is still short in comparison with a betatron wave length.

Instead of a compensating collision point placed immediately after the proton-proton collision, one can place the collision point in a more accessible location with a betatron phase advance relative to the proton-proton collision point of $n\pi$, where n is integer, the same in the X-plane and in the Y-plane. Here the image of the proton beam in the X-Y plane is similar to the image in the proton-proton interaction point, being different only in scale. By using a place in the lattice with high beta values one could relax the requirement to form a beam of a very small size, as in the low-β IPs. In the LHC case, a beam with sigma of 0.2 mm could be used, close enough to the interaction points. Two separate compensating devices in each ring should be used to compensate full head-on beam-beam interaction in the two low-β IPs.

The current in the relativistic electron beam which is necessary for compensation of the beam-beam effect of the counter-rotating beam should be about equal to the current of the proton beam. Electron guns with comparable parameters are available now from the industry. Deviation of the intensity of the individual proton bunches from the average value, if large, could be compensated by strobing the electron beam in time, using available bunch-by-bunch intensity information.

Figs. 5-7 show the behavior of the beam emittance and tune distributions for different displacements of the compensating electron beam with respect to the proton bunch and for deviations of the electron beam charge from that of the proton bunch. The results are summarized in Figs. 8-9 where the decoherence time (defined as the time at which the relative-to-centroid emittance crosses the midpoint between the initial and final values) and r.m.s. of the beam tune distribution are plotted versus the electron beam displacement or its relative charge. Fig.10 shows how the variations of the electron bunch shape affect the

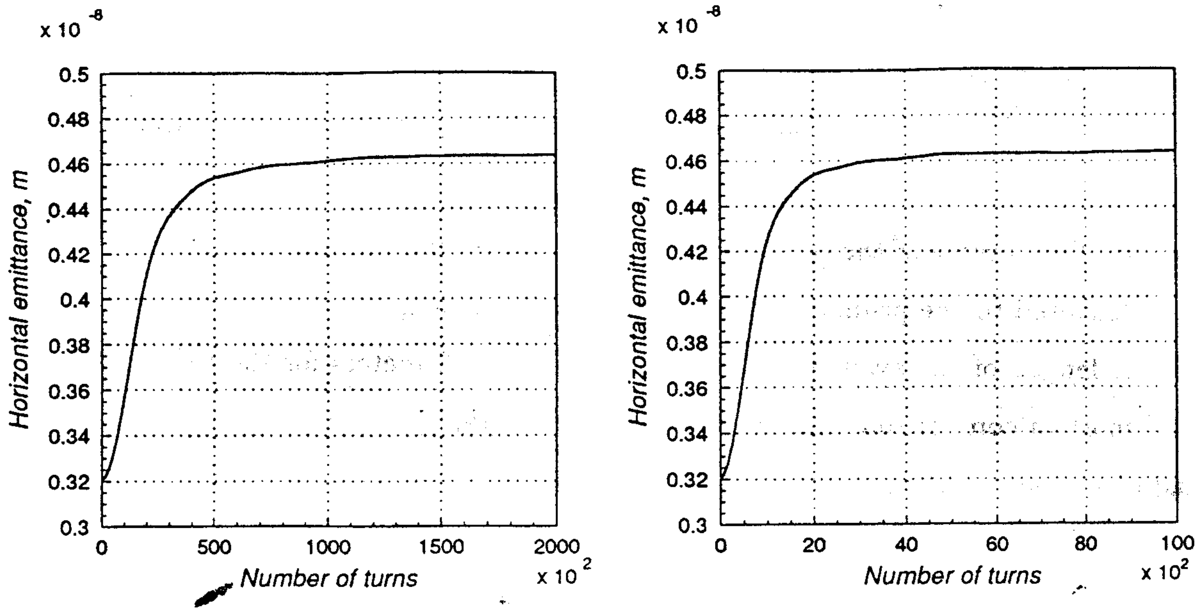


Figure 5: Growth of the relative-to-centroid beam emittance after an initial beam displacement of 1 sigma. Left) displacement of the compensating electron beam of 0.1 σ, right) displacement of the compensating electron beam of 0.5 σ.

r.m.s. of the beam tune ditsribution.

4. BEHAVIOR OF LOW ENERGY ELECTRONS INSIDE THE PROTON BUNCH

One of the problems with using a low electron beam for beam-beam effect compensation is electron oscillations during passage through the proton bunch. Even passing once and then being dumped, electrons experience some oscillations inside the proton bunch, which makes it difficult to distribute proper kicks among all the protons in the bunch. Fig. 11 presents a trajectory of a 10 keV electron with an impact parameter of 160 μm colliding with a bunch of 10^{11} protons. The space distribution of protons is three dimensional Gaussian with $\sigma_x = \sigma_y = 160$ μm, $\sigma_z = 77$ mm, which represent the typical parameters of the LHC beam. The ZBEAM tracing code used is described elsewhere [4]. To simplify the calculations, only transverse components of the electrical field of the bunch were taken into account. This is a good approximation for a long bunch with small transverse dimensions. Because of the low energy of the electrons we neglect possible radiation effects.

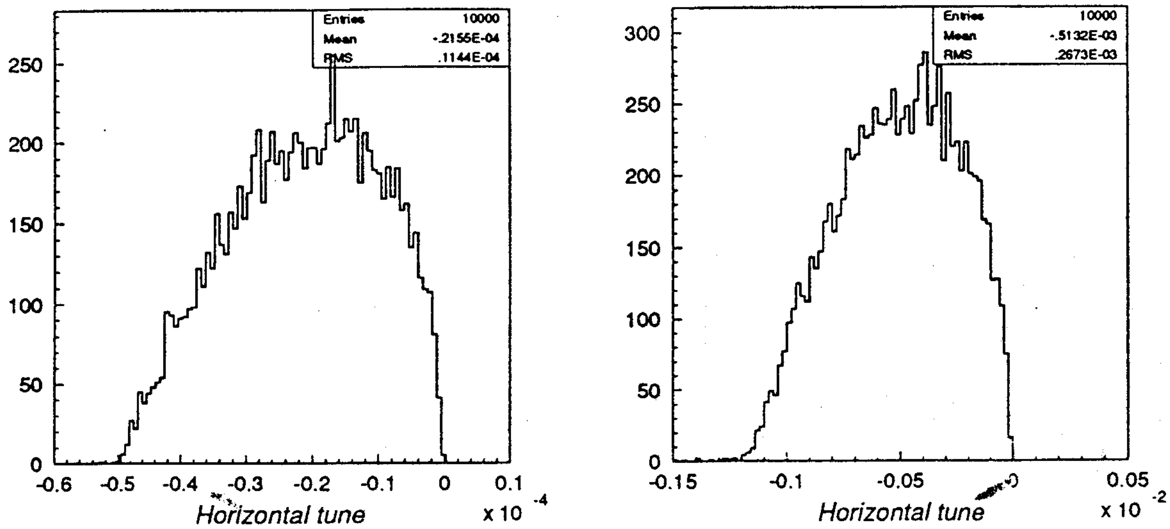


Figure 6: Horizontal tune distribution of beam particles. Left) displacement of the compensating electron beam of 0.1 σ, right) displacement of the compensating electron beam of 0.5 σ.

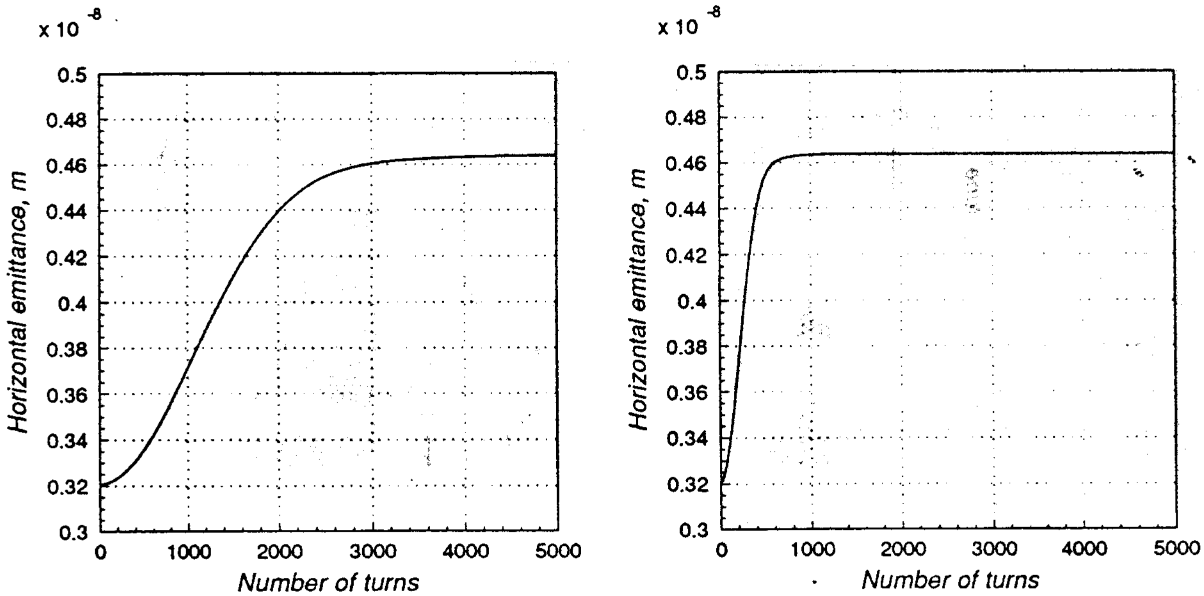


Figure 7: Growth of the relative-to-centroid beam emittance after an initial beam displacement of 1 sigma. Left) cumulative charge of the compensating electron beam is 90% of the proton bunch charge, right) 50% of the proton bunch charge.

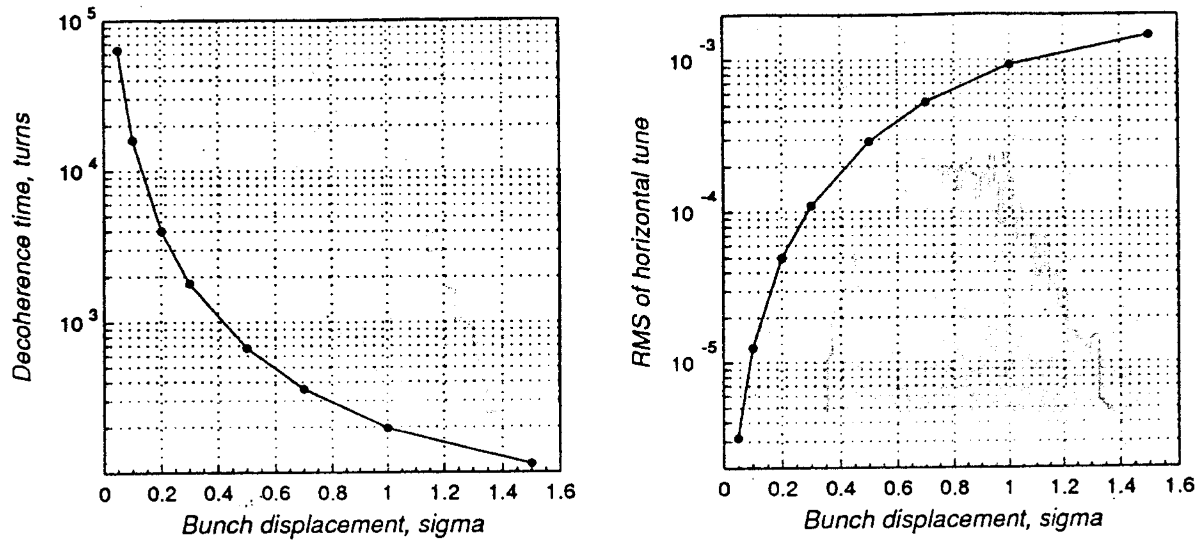


Figure 8: Decoherence time expressed in number of turns (left) and RMS of the horizontal tune distribution of the beam particles (right) versus electron beam displacement. The curve is drawn to guide the eye.

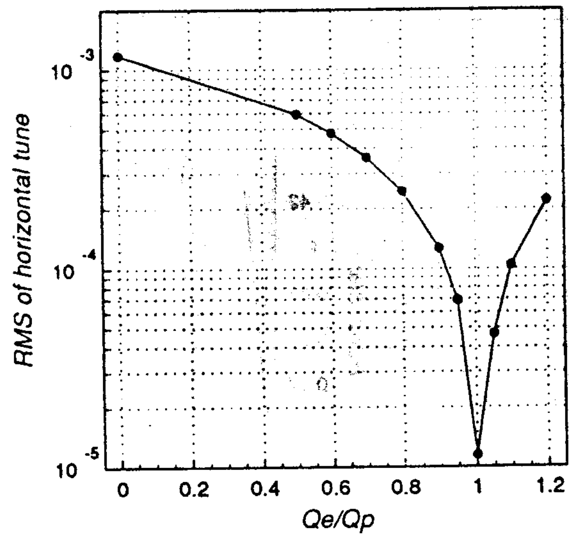


Figure 9: RMS of horizontal tune distribution of the beam particles versus the ratio of the electron to proton bunch charges. Displacement of the electron bunch is 0.1 σ. The leftmost point corresponds to the case without compensation. The curve is drawn to guide the eye.

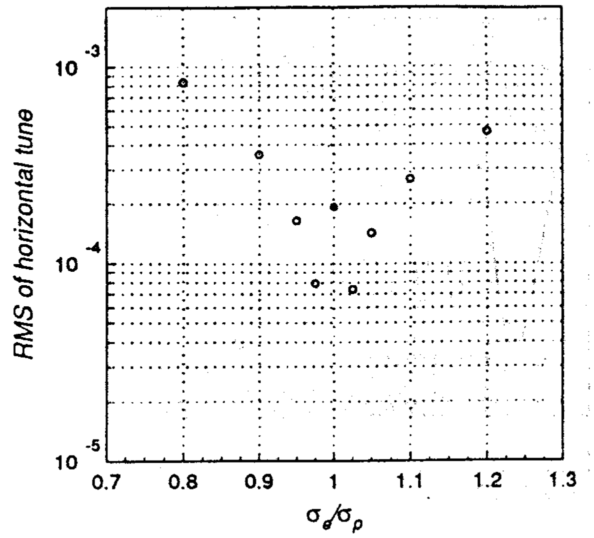


Figure 10: RMS of horizontal tune distribution of the beam particles versus the ratio of the electron to proton bunch sigmas (white circles). Black circle presents the best result for a cylindrical electron bunch (with r_e=$1.3\sigma_p$ and Q_e=$0.6Q_p$.

As seen in Fig. 11, a 10 keV electron makes several oscillations before it leaves the proton bunch. This immediately imposes difficulties in delivering the proper kick to all the protons in the bunch, because the distribution of electron density in the bunch will vary along the bunch length.

We considered using a solenoidal magnetic field as a method to prevent electron oscillations (see Figs. 12-13). One can see from the figures, that in the case of B=2 Tesla the radial position of a 10 keV electron with zero incoming angle remains constant with an accuracy of about two micrometers. Even after introducing an angular spread of one degree the radial positions of the electron remain practically constant.

5. CONCLUSIONS

The presented results show that for reasonable tolerances on the electron beam parameters it is possible to achieve a good beam-beam effect compensation with the resulting reduction of the beam tune spread by a factor of up to about 100.

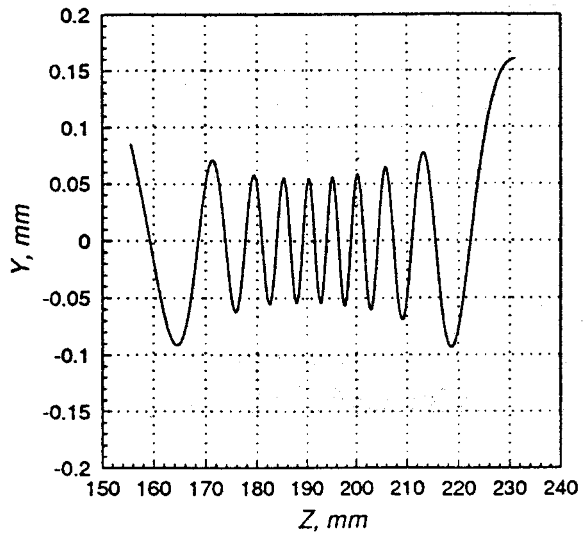


Figure 11: The trajectory of a 10 keV electron with an impact parameter of 160 μm colliding with a proton bunch, Z-Y view. The proton bunch is moving to the right, and the electron is moving to the left. Plus/minus 3σ of the proton bunch charge distribution in Z-direction is treated by the tracing code.

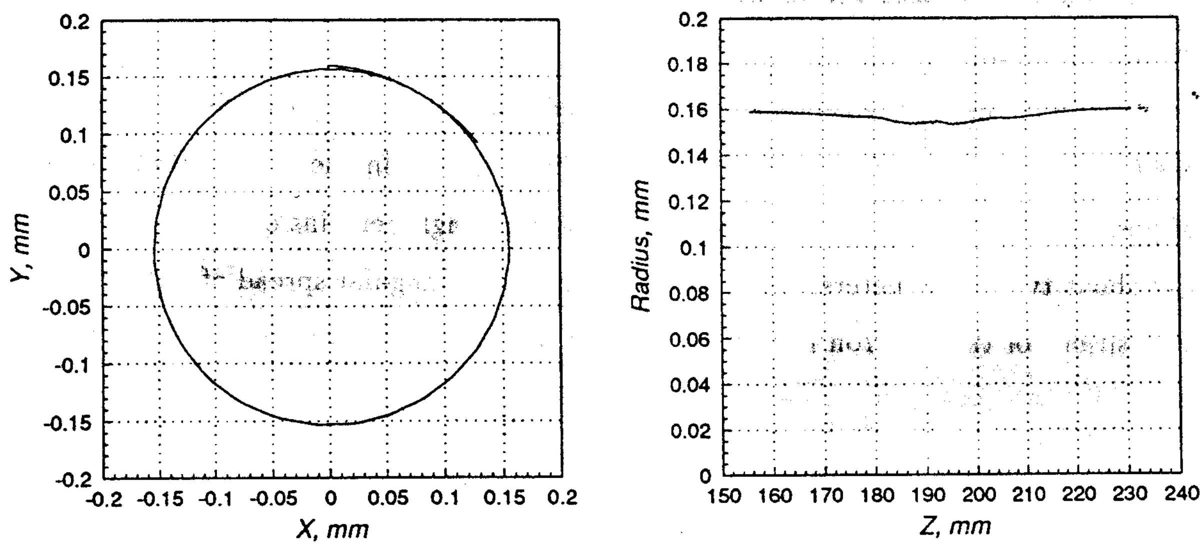
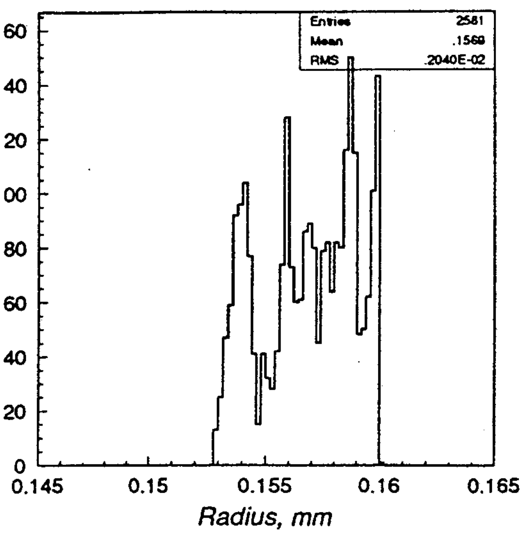


Figure 12: The trajectory of a 10 keV electron with an impact parameter of 160 μm inside a proton bunch when a solenoidal magnetic field of 2 T is applied: left) X-Y view, right) Z-R view (R is a distance of an electron from the center of a proton bunch in X-Y plane).



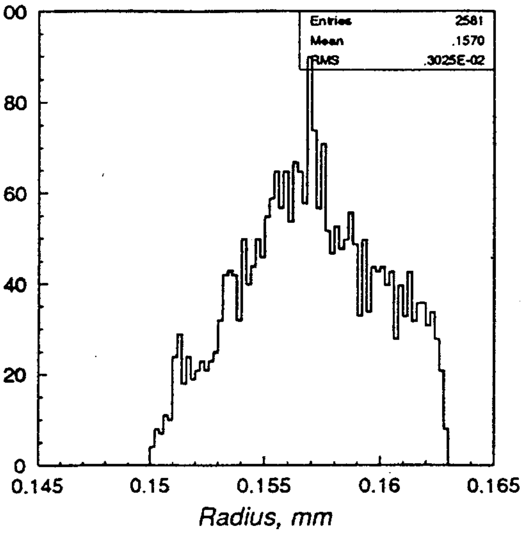


Figure 13: Distribution of R with incoming electron angle of 0° (left) and 1° (right).

6. ACKNOWLEDGMENTS

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