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SUPPRESSION OF BEAM-BEAM TUNE SPREAD USING HOLLOW ELECTRON BEAM *

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Abstract

Significant difference in transverse size of the proton and antiproton bunches at collision points is known to cause deterioration of the larger (proton) beam life time in the Tevatron. The reason is believed to be in the combination of large betatron tune spread induced by the high nonlinearity of the beam-beam force, and limited available tune space. We consider the prospects for application of hollow electron beam for beam-beam tune spread suppression.

INTRODUCTION

After the commissioning of electron cooling in Fermilab's recycler ring the intensity and brightness of antiprotons delivered to the collider was greatly increased. At the present time, antiproton bunches that are injected into the Tevatron have intensity up to $1 \cdot 10^{11}$ and a typical transverse 95% normalized emittance of 5 π mm mrad. At the same time, parameters of the proton beam remained mostly stable with $3 \cdot 10^{11}$ particles per bunch and transverse emittance of 15-16 π mm mrad. The total head-on beam-beam tune shifts for the two beams became essentially equal and reached 0.03. However, due to the significant difference of the transverse beam sizes that at times reached a factor of two, protons experience much stronger beam-beam effects being affected by strong nonlinearity of the smaller antiproton beam. To alleviate this effect, a system of controlled antiproton emittance blow up was commissioned [1]. Still, the large tune spread induced on the protons by head-on beam-beam effects makes it harder to accommodate the proton beam within the available tune space, and requires precise (to 0.001) control of the betatron tunes thus complicating collider operations. It was proposed to suppress the tune spread by a specially shaped hollow electron beam lens that would "augment" the antiproton beam and create an effectively uniform distribution of the negative charge seen by the protons. The combination of the antiproton beam and the hollow electron beam then represents a linear focusing element for protons. It is obvious that due to the proton-antiproton interactions and proton-electron interactions taking place at different azimuthal positions in the ring some adverse effects in the proton beam dynamics could arise.

In this report the feasibility of beam-beam compensation with a hollow electron beam is studied numerically using a macroparticle tracking code. Possible design of an electron gun for generation of the hollow beam beam is presented.

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GENERATION OF HOLLOW BEAM

A pure hollow beam created by the electron gun may be obtained using a ring cathode [2, 3], whereas "soft" hollow beams always require a solid cathode. Different distributions of radial densities may be obtained either by varying the electrode voltages or by changing the whole gun setting (by moving or re-shaping the electrodes). The first option gives the easiest (and the cheapest) way but often is limited e.g. by virtual cathode phenomenon, etc.

In Fig. 1 the calculation of an electron gun with 84% central density drop is shown. The effect was due to appropriate choice of the control electrode.

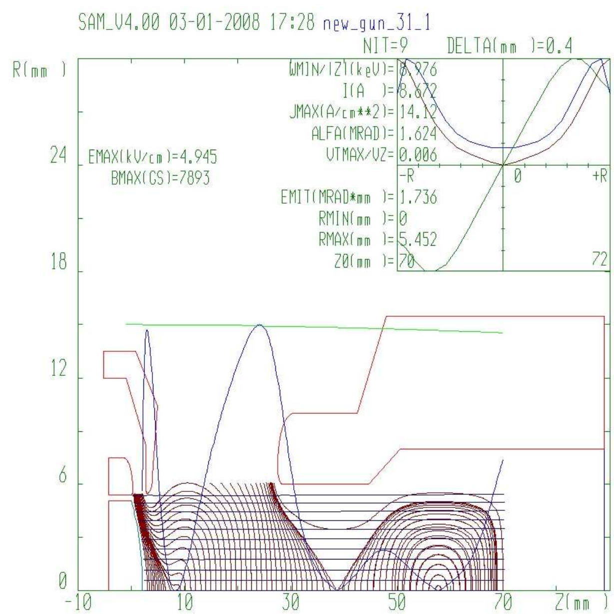

Figure 1: Electron gun configuration for generating soft hollow beam with a central d ensity drop of 84%. Voltages are -10 kV cathode, -4 kV control electrode, 0 kV anode.

The further progress could hardly be obtained only by re-powering the electrode. Moving the electrodes and/or re-shaping them may be more flexible, although more expensive. In Fig. 2 one can see a nearly hollow beam with a "soft" inner profile.

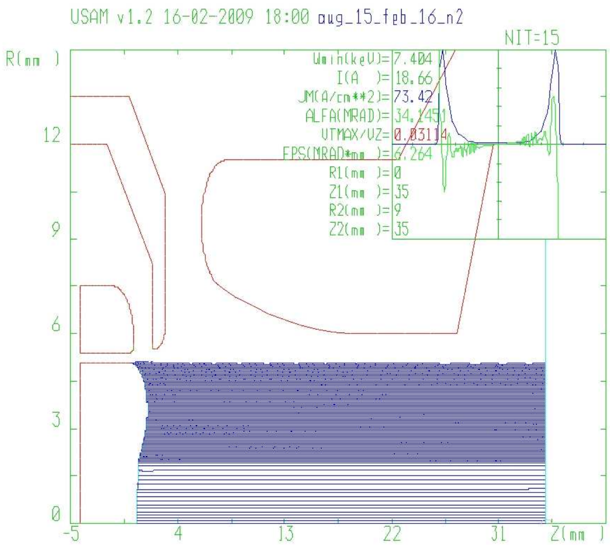

Figure 2: Electron gun configuration for generating soft hollow beam with a central density drop of 100%. Cathode profile is NOT spherical, anode is reshaped to suppress current on the axis,, voltages are -10 kV cathode, -4 kV control electrode, 0 kV anode.

SIMULATION MODEL

The simulations were performed using a simplified optics model. The test machine consisted of a single head-on IP, an accelerator arc with linear tune chromaticity, and a single beam-beam compensator element.

The machine and beam parameters resemble those of the Tevatron: the proton and antiproton transverse emittance of 18 and 5 π mm mrad, bunch length of 52 and 44 cm, momentum spread of 1.4 and $1.2{\cdot}10^{-4}$, respectively. $\beta^* = 28$ cm, and betatron tunes $Q_x = 0.583$, $Q_y = 0.587$. The electron lens was placed at a model location where the horizontal and vertical beta-functions are equal to 175 m and the phase advance from the main IP in horizontal and vertical plabe are 0.25.

The head-on beam-beam tune shift ξ for protons at the main IP was 0.03.

For simplicity, the electron beam was assumed to have the density distribution

$$\rho(r) = \begin{cases} \frac{N_e e}{2\pi\sigma^2 l_e}\left(1 - e^{-r^2/2\sigma^2}\right), & r < a \\ 0, & r > a \end{cases} \qquad (1)$$

where N_e is the number of electrons in the beam, σ is the size of the "hole" in the electron beam, l_e is the interaction length, a is the external size that is larger than the proton beam size. The σ of the electron beam was matched to the size of the antiproton beam at the location of the compensation element.

In units of beam-beam tune shift ξ_e induced by the electron beam the kick is

$$\Delta r' = \frac{4\pi\xi_e}{\beta}\left(r - \frac{2\sigma^2}{r}\left(1 - e^{-r^2/2\sigma^2}\right)\right) \qquad (2)$$

Simulations were performed with the weak-strong macroparticle tracking code LIFETRAC [4]. A new thin element was defined which changes the transverse momenta of particles according to eqn. 2. No provision was made for effect from the fields at the edges of the proton-electron interaction region.

RESULTS

Footprint Suppression

Figure 3 shows the proton tune footprints with the electron lens turned off, at full compensation with no tune correction, and with lens on and tune corrected to bring the footprint to the original position. It is clear that the tune footprint is reduced with the electron lens on. Positive shift of the peak is consistent with expectations: the unperturbed vertical tune was 0.587, hence the linearized force with $\xi = 0.03$ moves it to ~0.617.

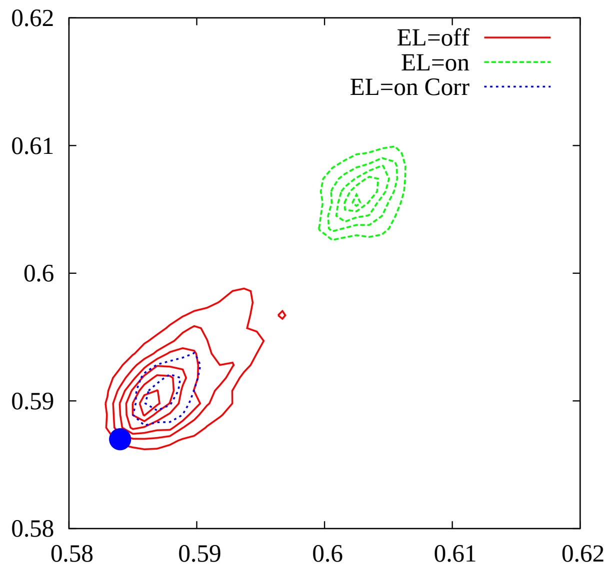

Figure 3: Proton tune footprints. Red - e-lens off, green - e-lens on, blue - e-lens on and corrected lattice tune, blue point - location of the unperturbed lattice tune.

Life Time Issues

The test simulation runs lasted for 10,000 turns. Even for such small number of turns some particle losses were observed in the case of electron lens turned on. There are no losses with e-lens off. The losses are clearly tune-dependent as demonstrated by a tune scan in Fig. 4. Where the largest losses are observed the particles are lost mostly in the transverse y-direction. The most probable cause is the 1/5 resonance.

Effect of Dispersion and Chromaticity

It were mostly off momentum particles that were found to be lost with the electron lens turned on. Hence, the de-

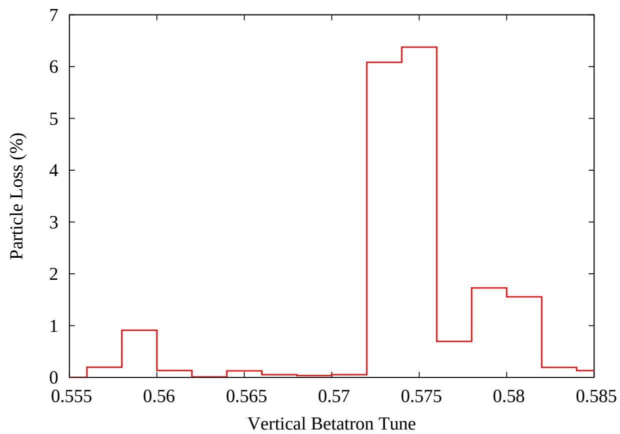

Figure 4: Beam loss in % vs. bare lattice vertical betatron tune. Electron lens at 100% compensation (corresponding $\xi_e = 0.03$).

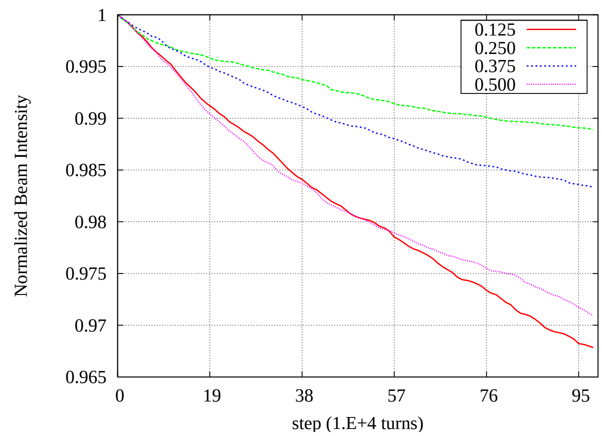

Figure 6: Beam intensity vs. number of simulation turns. Electron lens at 100% compensation (corresponding $\xi_e = 0.03$), different values of phase advance between IP and e-lens in units of 2π.

pendence of losses on the chromatic lattice parameters was studied. In Fig. 5 the beam intensity evolution for two values of chromaticity is shown. Clearly in the case of zero chromaticity the particle losses are almost completely eliminated. Similar dependence was observed on the value of dispersion at the location of e-lens.

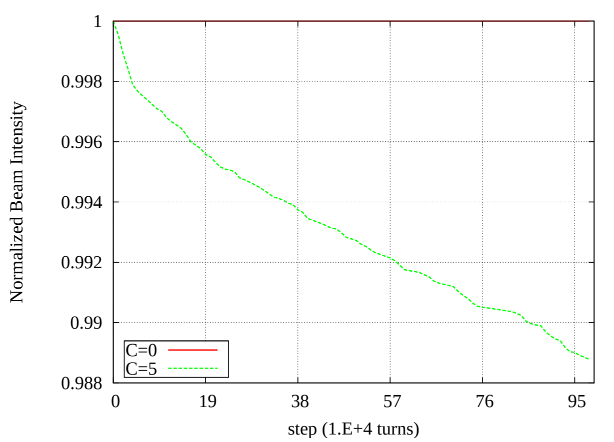

Figure 5: Beam intensity vs. number of simulation turns. Electron lens at 100% compensation (corresponding $\xi_e = 0.03$), red line - zero chromaticity, green line - chromaticity of 5 units.

Effect of Phase Advance and Hole Size

Simulations with different values of phase advance between the main IP and the compensation element revealed that the phase advance of 1/2 π is optimal for the model configuration (Fig. 6).

The effect of the σ value was also studied. Losses increase drastically if σ is less that the antiproton beam size at the location of e-lens. For σ greater than the antiproton beam size only a small change of losses is observed until the ratio of 1.5

SUMMARY

Calculations show that a smooth hollow profile beam can be generated by a gun with properly shaped electrodes. Mactoparticle simulation in a simplified model demonstrated the expected reduction of the tune footprint of the proton beam. Compensation of the head-on beam-beam effect expressed in improvement of the beam life time was observed in a long-term simulation for the case of zero chromaticity and well aligned proton and electron beams. However, particle losses are increased when the chromaticity and dispersion at the electron lens are not cancelled, or if the proton and electron beams are not properly aligned which makes the application of such compensation device at the Tevatron impractical.

ACKNOWLEDGMENTS

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