ELECTRON LENS IN RHIC

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Abstract

Increasing the luminosity requires higher beam intensity and often focusing the beam to smaller sizes at the interaction points. The effects of head-on interactions become even more significant. The head-on interaction introduces a tune spread due to a difference of tune shifts between small and large amplitude particles. A low energy electron beam so called electron lens is expected to improve intensity lifetime and luminosity of the colliding beams by reducing the betatron tune shift and spread. In this paper we discuss the results of beam simulations with the electron lens in RHIC.

INTRODUCTION

In high energy storage-ring colliders, the beam-beam interactions are known to cause the emittance growth and the reduction of beam life time, and to limit the collider luminosity. The long-range beam-beam effects can be mitigated by separating the beams to the extent possible. However, in order to increase the luminosity, it needs to increase the beam intensity and often to focus the beam to smaller sizes at the interaction points. The effects of head-on interactions become even more significant. A tune spread is introduced by the head-on interactions due to a difference of tune shifts between small and large amplitude particles. In the proton-proton run of RHIC [1], the maximum beam-beam parameter reached so far is about $\xi = 0.008$. The combination of beam-beam and machine nonlinearities excite betatron resonances which diffuse particles into the tail of beam distribution and even beyond the stability boundary. It is therefore important to mitigate the head-on beam-beam effect. The compensation of the beam-beam effect with use of low energy electron beam, so called electron lens, has been proposed in particular for a reduction of the large tune spread of proton beam and emittance growth in RHIC [2]. In this paper, we will discuss the effects of an electron lens on the beam loss for different betatron tunes.

MODEL

To investigate the effects of an electron lens on tune change and beam loss, a weak-strong tracking code BB-SIMC [3] is applied. In the code, the weak beam is represented by macroparticles with the same charge to mass ratio as the beam particles. The transverse and longitudinal motion of particles is calculated by linear transfer maps between nonlinear elements at which nonlinear forces are exerted on the particles. We adopt the weak-strong model to treat the beam-beam interactions. The strong bunch is

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Table 1: RHIC parameters at proton-proton collision.

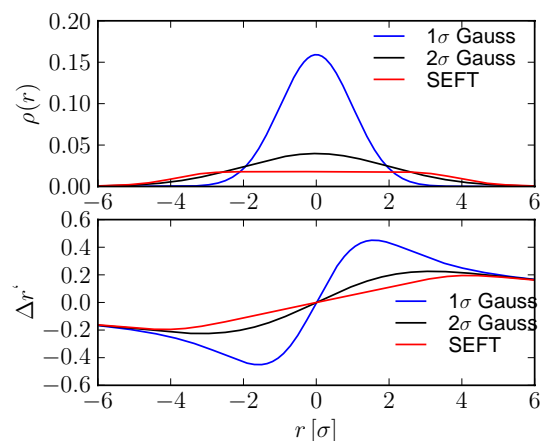| quantity	unit	Blue ring
beam		proton
energy, γ	Gev/n	250
bunch intensity	10^{11}	2
$\epsilon_{x,y}(95\%)$	mm mrad	15
(β_x^*, β_y^*)	m	$(0.52, 0.52)$
$(\beta_x, \beta_y)^\dagger$	m	$(10.4, 9.7)$
(ν_x, ν_y)		$(28.685, 29.695)$
(ξ_x, ξ_y)		$(1, 1)$
$\mathcal{A}_B$	eV·s	0.17
$\sigma_{\Delta p/p}$		1.43×10^{-4}
σ_z	m	0.44

† beta function at electron lens location.

Figure 1: (top) Transverse electron beam distributions: (black) $1\sigma_P$ Gaussian distribution, (blue) $2\sigma_p$ Gaussian distribution, and (red) constant distribution with smooth edge; $\rho(r) \sim \frac{1}{1+(r/4\sigma_p)^8}$. (bottom) Kicks from the electron beam distribution. Note that the number of particles of three distribution is the same.

divided into slices in a longitudinal direction to consider the finite bunch length effect of the beam-beam interaction. Since the beta function at the electron lens location is much greater than the bunch length, as shown in Table 1, the electron lens is considered as a thin element because the betatron phase advance is negligible over the bunch length.

In order to see the effects of different electron beam distributions, we choose three electron profiles as shown in Fig. 1: (a) $1\sigma_p$ Gaussian distribution with the same rms beam size as that of the proton beam σ_p at the electron lens location (IP10), (b) $2\sigma_p$ Gaussian distribution with rms size twice that of the proton beam, and (c) Smooth-edge-flat-
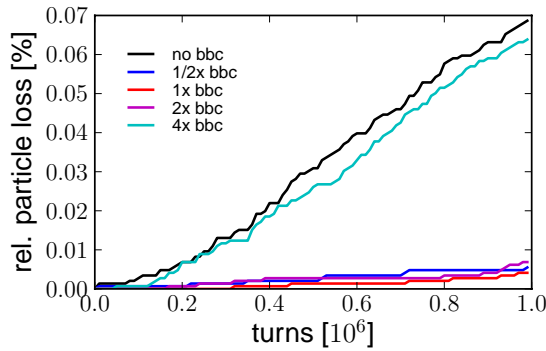
Figure 2: Plot of particle loss according to electron beam intensity for a $2\sigma_p$ Gaussian electron beam profile.
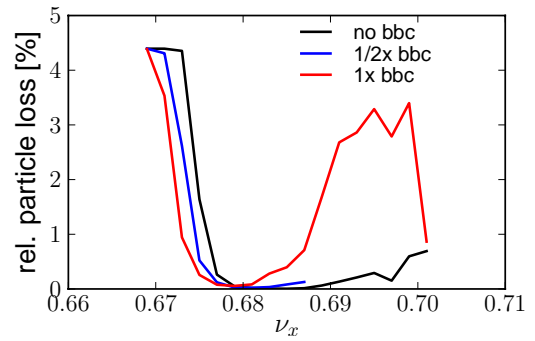

Figure 3: Plot of beam loss versus betatron tunes for different electron beam intensities for $1\sigma_p$ Gaussian electron elens. Vertical tune is $\nu_y = \nu_x + 0.01$.

top (SEFT) distribution with an edge around at $4\,\sigma_p$. The transverse kick on the proton beam from the electron beam is given by

$$\Delta \vec{r'} = \frac{2\tilde{n} r_0}{\gamma} \frac{\vec{r}_\perp}{r_\perp^2} \zeta\left(r_\perp : \bar{\sigma}\right),$$

where $\tilde{n}$ is the number of electrons of the electron beam adjusted by the electron speed, r_0 is the classic proton radius, and γ is the Lorentz factor. The function ζ is given by

- for Gaussian distribution

$$\zeta\left(r_\perp : \bar{\sigma}\right) = \left[1 - \exp\left(-\frac{r_\perp^2}{2\bar{\sigma}^2}\right)\right],$$

- for SEFT distribution

$$\zeta = \frac{\sqrt{2}\tilde{\rho}_0}{8}\left[\frac{1}{2}\log\left(\frac{\theta_+^2 + 1}{\theta_-^2 + 1}\right) + \tan^{-1}\theta_+ + \tan^{-1}\theta_-\right],$$

where $\tilde{\rho}$ is a constant, and $\theta_\pm = \sqrt{2}\left(\frac{r}{\sigma}\right)^2 \pm 1$.

SIMULATION RESULTS

When the electron beam profile matches the proton beam, the full compression of the tune spread requires the electron beam intensity $N_e = N_{ip} \cdot N_p$, where N_{ip} is the number of IPs, and N_p the proton beam intensity. In this study, the electron beam intensity is given by $N_e = 4 \times 10^{11}$ which is defined as the electron beam intensity required for full compensation or 1x bbc. Figure 2 shows the results of particle loss in 1×10^6 turns for different intensities with the $2\sigma_p$ Gaussian electron beam profile. At the simulation, the largest electron beam intensity 4x bbc, or 1.6×10^{12} is chosen to match the peak of $2\sigma_p$ Gaussian distribution to that of the full compensation at $1\sigma_p$ Gaussian. The beam life time with the largest electron beam intensity is comparable with that without beam-beam compensation. However, as the electron beam intensity is decreased, the particle loss decreases significantly. The kicks from three different electron beam distributions are shown in Fig. 1 (bottom). The electron lens kicks are calculated using the same electron intensity, 4×10^{11}, for the three
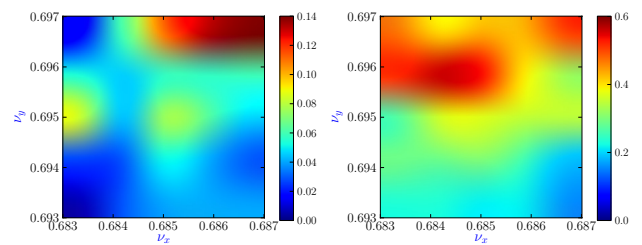

Figure 4: Contour plot of beam loss relative to the loss of no wire case for $1\sigma_p$ Gaussian electron elens: (left) $\frac{1}{2}$x bbc and (right) 1x bbc.

distributions. Since the proton beam profile is assumed a Gaussian with $1\sigma_p$, the kicks from the $2\sigma_p$ Gaussian electron beam are quite different from those from the proton beam for small amplitude particles. At amplitudes larger than $4\sigma_p$, the electron lens kicks are approaching to the proton beam's. The tune shift due to the head-on beam-beam interaction is quite large at small amplitude particles, but small at large amplitude. The betatron tune compensation itself, therefore, may not help to increase the beam life time.

In order to see the effects of the betatron tune on the beam loss, the tune scan is performed with increment $\Delta \nu_x = \Delta \nu_y = 0.002$, as shown Fig. 3. The horizontal scan range is $0.669 \leq \nu_x \leq 0.701$. The vertical tune is $\nu_y = \nu_x + 0.01$. Initially we have performed beam tracking simulations without beam compensation to see the beam dynamics due to the machine nonlinearities and head-on collisions. In particular, the beam loss scan shows that there are no dangerous resonances near the present working point and the loss is reasonably small. Below 0.68 of horizontal tune, the beam loss is significant while a finite particle loss is observed above $\nu_x = 0.69$. However, by including the beam compensation with the $1\sigma_p$ Gaussian electron lens in the simulations, we see that no increase of beam life time is indicated by the simulations for the case of the electron beam intensity $\geq 2 \times 10^{11}$ over the tune scan range. Figure 4 shows the contour plots of beam
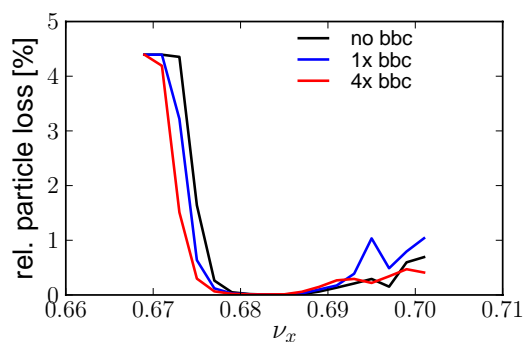
05 Beam Dynamics and Electromagnetic Fields

Figure 5: Plot of beam loss versus betatron tunes for different electron beam intensities for $2\sigma_p$ Gaussian electron elens. Vertical tune is $\nu_y = \nu_x + 0.01$.
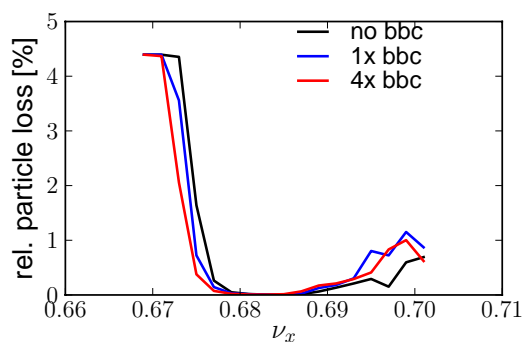

Figure 6: Contour plot of beam loss relative to the loss of no wire case for $2\sigma_p$ Gaussian electron elens: (left) `1x bbc` and (right) `4x bbc`.

loss for $1\sigma_p$ Gaussian electron elens in the vicinity of the working point. Since the particle loss is relative to the loss without beam-beam compensation, the positive value represents the increase of the beam loss. The maximum beam loss reached in the case of electron intensity 4×10^{11} is of the order of 0.6 % while the maximum loss for the electron intensity 2×10^{11} is of the order of 0.14 %. As can be seen, the relative loss remains positive all over the tune scan range.

For the $2\sigma_p$ Gaussian and SEFT electron beam profiles, we calculated the particle beam losses for different betatron tunes, i.e., diagonal scan $0.669 \leq \nu_x \leq 0.701$ and $\nu_y = \nu_x + 0.01$, and rectangular scan $0.669 \leq \nu_x \leq 0.701$ and $0.679 \leq \nu_y \leq 0.711$. The results of the $2\sigma_p$ Gaussian electron lens are shown in Figs. 5 and 6. It is clearly seen in Fig. 6 that the electron lens reduces the particle loss over the wide range of betatron tunes for both 4×10^{11} and 1.6×10^{12} electron beam intensities. Only at the upper and right corner of betatron tune space, the effect of beam-beam compensation on the beam loss is not beneficial for both electron beam intensities. The maximum reduction of the beam loss is about 0.05 % and 0.02 % for 4×10^{11} and 1.6×10^{12} electron beam intensities respectively. The particle losses of proton beam with SEFT electron lens are plotted in Figs 7 and 8. The beam-beam force of the SEFT electron profile is close to that of the wide Gaussian distribution, as shown in Fig. 1. The results of the SEFT electron lens is

Figure 7: Plot of beam loss versus betatron tunes for different electron beam intensities for SEFT electron elens. Vertical tune is $\nu_y = \nu_x + 0.01$.
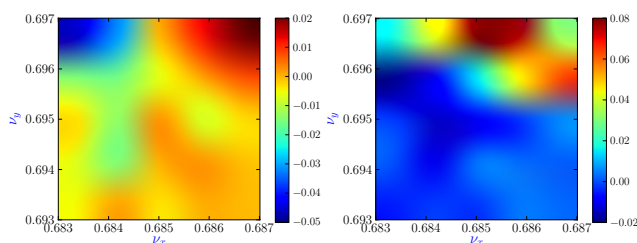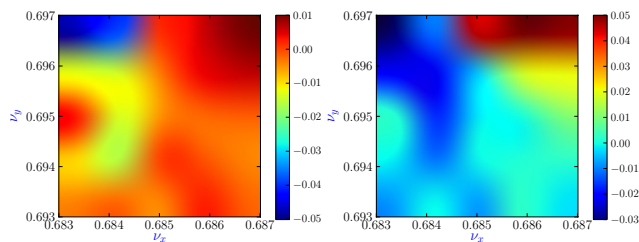

Figure 8: Contour plot of beam loss relative to the loss of no wire case for SEFT electron elens: (left) `1x bbc` and (right) `4x bbc`.

quite similar to those of the $2\sigma_p$ Gaussian electron lens.

SUMMARY

In this paper, we investigated the effect of the low energy electron lens on proton-proton beams at collision energy in RHIC using weak-strong simulations. The result shows that full tune-spread compression does not help to reduce the particle loss. Wider electron beam profile than proton at electron lens location is found to increase beam life time. Electron beam intensity less than proton beam intensity is beneficial to proton beam life time. At high proton bunch intensity ($N_p \geq 2.5 \times 10^{11}$), significant beam-beam effects are expected. It needs to verify the advantage of electron lens at high intensity.

ACKNOWLEDGMENTS

REFERENCES

[1] C. Montag et al., Proceedings of EPAC08, p2566 (2008).

[2] Y. Luo and W. Fischer, BNL-CAD/AP/286 (2007).

[3] H.J. Kim et al., PRST-AB **12**, 031001 (2009).