WEAK-STRONG SIMULATION OF HEAD-ON BEAM-BEAM COMPENSATION IN THE RHIC*

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Abstract

In the Relativistic Heavy Ion Collider (RHIC) beams collide in the two interaction points IP6 and IP8. To further increase the bunch intensity above 2×10^{11} or further reduce the transverse emittance in polarized proton operation, there will not be enough tune space between the current working area [2/3, 7/10] to hold the beam-beam generated tune spread. We proposed a low energy DC electron beam (e-lens) with similar Gaussian transverse profiles to collide with the proton beam at IP10. Early studies have shown that e-lens does reduce the proton-proton beam-beam tune spread. In this article, we carried out numerical simulation to investigate the effects of the head-on beam-beam effect on the proton's colliding beam lifetime and emittance growth. The preliminary results including scans of compensation strength, phase advances between IP8 and IP10, electron beam transverse sizes are presented. In these studies, the particle loss in the multi-particle simulation is used for the comparison between different conditions.

INTRODUCTION

To further increase the luminosity in the RHIC polarized proton (pp) run, we can decrease the β^* at IPs, increase the bunch intensity and decrease the beam transverse emittance. In the 2009 pp run, the β^* has reached 0.7m at both 250 GeV and 100GeV. In the 2008 pp run, the bunch intensity has reached 1.7×10^{11} in the Blue ring. And an upgrade to the polarized proton source to reduce the beam transverse emittance is under way.

The store lifetime of the proton beam in the RHIC is determined by the beam-beam dynamic aperture and the proton polarization. Currently the working points for the proton beams are constrained between [2/3, 7/10]. It has been been shown that the store lifetime and polarization are negatively affected when the working point is close to 7/10. Therefore, to further increase the bunch intensity above 2×10^{11} and decrease beam transverse emittance below 15πmm.mrad, there will not be enough tune space between [2/3, 7/10] to hold the beam-beam generated tune spread.

We proposed a DC low energy electron beam (e-lens) to head-on collide with the proton beam to compensate the proton-proton beam-beam tune spread in the RHIC polarized proton run [1, 2]. The electron beam has the similar Gaussian transverse distribution as that of the proton beam at the compensation point IP10. The proton-proton collisions take place at IP6 and IP8.

In this article, we carried out multi-particle simulation based on the weak-strong beam-beam interaction model to investigate the head-on beam-beam compensation's effect on the proton beam's lifetime in the 250 GeV RHIC pp run [3]. We modified the element-by-element tracking code SixTrack [4] to track about 10^4 macro-particles up to 10^7 turns. The particle loss is used for the measure to compare the different compensation schemes. The preliminary simulation results presented.

BEAM PARAMETERS

The two RHIC proton beams collide at IP6 and IP8. In the current design, the e-lenses are to be installed close to IP10. Table 1 lists the proton beam parameters for this study [1]. The β^* at the IP6 and IP8 are 0.5m. The β_{elens} at IP10 is 10m. The default betatron phase advances between IP6 and IP8 are $(10.61\pi, 8.60\pi)$, and the phase advances between IP8 and IP10 are $(8.43\pi, 10.90\pi)$.

The nonlinear magnetic field errors in the interaction regions are included in the simulation. Limited by power supplies, only sextupole, skew sextupole and octupole errors are locally corrected. The working point without beam-beam is (28.685, 29.695). The linear chromaticities are corrected to +1.

In the following we first have the electron beams have the same transverse Gaussian profiles as that of the proton beam at IP10. For simplicity, we define full and half head-on beam-beam compensation to compensate full and half of the proton-proton beam-beam parameter. Therefore, with bunch intensity $N_p = 2.0 \times 10^{11}$, for the full head-on beam-beam compensation, the electron particle density is $N_e = 4.0 \times 10^{11}$. For the half head-on beam-beam compensation, $N_e = 2.0 \times 10^{11}$. Figure 1 shows the tune footprints without and with head-on beam-beam compensation with bunch intensity $N_p = 2.0 \times 10^{11}$.

SIMULATION MODEL

SixTrack is a symplectic 6-D element-by-element tracking code. It has been widely used for the calculations of long-term dynamic apertures for hadron colliders. In our simulation, all non-linear elements are modeled as thin-lens kicks and linear elements are represented by 6×6 matrices. Currently 4-D weak-strong beam-beam interaction

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Table 1: Beam Parameters Used in the Simulation

normalized transverse rms emittance	2.5 nm
transverse rms beam size at IP6 and IP8	0.068 mm
transverse rms beam size at e-lens	0.40 mm
harmonic number	360
rf cavity voltage	300 kV
rms longitudinal bunch area	0.17 eV.s
rms momentum spread	0.14×10^{-3}
rms bunch length	0.44 m

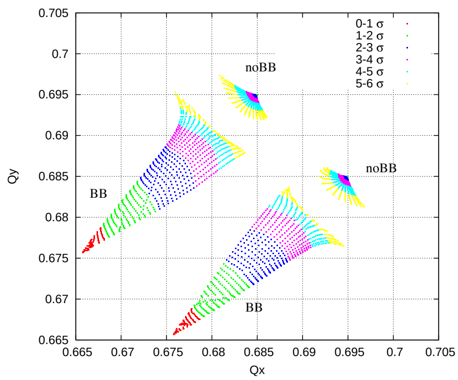

Figure 1: Tune footprint with $N_p = 2 \times 10^{11}$.

model is used in our simulation. The proton-electron beam interaction in the e-lens is modeled as another beam-beam interaction.

For our purpose, we modified SixTrack to be able to track up to 64*357 particles per job. The initial coordinates of the particles are generated outside of SixTrack. Turn-by-turn coordinates of particles can be written to an output file. But most of the time, we save only $< x^2 >$ and $< y^2 >$ of all particles to avoid heavy data writing. We also modified SixTrack to allow the changes of beam-beam interaction parameters on turn-by-turn basis. These parameters includes the intensity, the offsets and the beam sizes of the rigid beam.

Normally we track 6400 or 12800 macro-particles up to 5×10^6 or 10×10^6 turns. The initial coordinates of macro-particles are generated to represent the required 3-D Gaussian distributions. To save the computation time, we normally track a hollow Gaussian bunch. The particle loss in the tracking turns and the beam decay per hour are used as the measures to compare different simulation cases.

SIMULATION RESULTS

Bunch Intensity $N_p = 2.0 \times 10^{11}$

Figure 2 shows the particle losses without and with head-on beam-beam compensation. The proton bunch intensity $N_p = 2.0 \times 10^{11}$ is adopted. The electron intensity in the interaction region varies from 1.0×10^{11} to 4.0×10^{11}. From Fig. 2, the proton beam without beam-beam compensation has the best beam lifetime. This can be explained that with bunch intensity $N_p = 2.0 \times 10^{11}$, the beam-

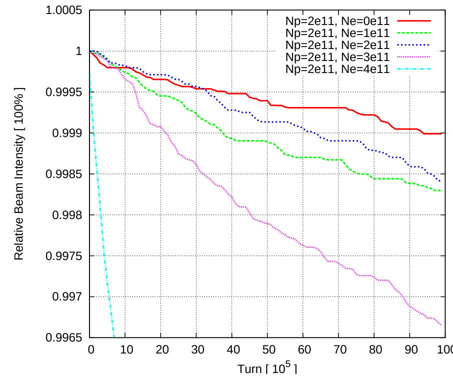

Figure 2: Beam-beam compensation with $N_p = 2 \times 10^{11}$.

beam tune shift has not reached to 2/3 resonance yet. The proton-proton beam-beam parameter with $N_p = 2.0 \times 10^{11}$ is about -0.02. When bunch intensity is above 2.0×10^{11}, head-on beam-beam compensation is needed.

From Fig. 2, the full head-on beam-beam compensation with electron intensity $N_e = 4 \times 10^{11}$ gives the worst proton lifetime. The proton beam decay with half beam-beam compensation with $N_e = 2.0 \times 10^{11}$ and the quarter beam-beam compensation with $N_e = 1.0 \times 10^{11}$ are comparable and are about 4.5%/hr. In our simulation, the emittance growth is noisy due to limited tracking turns and the number of macro-particles.

The study of stability of single proton particle motion [5, 6] shows that the head-on beam-beam compensation will help stabilize the particles in the bunch core by pulling them away from the 2/3 resonance. However, the head-on beam-beam compensation also introduces nonlinearity into the dynamics of particles, especially to the particles with large amplitude. Therefore, only partial head-on beam-beam compensation is recommended.

Phase Advance Adjustment Between IP8 and IP10

Here we artificially introduce phase shifts before and after IP10 to adjust the betatron phase advances between IP8 and IP10 where the e-lens is located. During this exercise, the local Twiss parameters and the global tunes are not changed. The phase shift is achieved by a 6 *6 simplectic matrix. The tiny residual dispersion at IP10 is considered.

In the following we always adjust the horizontal and vertical betatron phases at the same time. For phase advances of exact multipoles of π, the phase advances between IP8 and IP10 are $(7\pi, 9\pi)$. In the simulation, the proton bunch intensity $N_p = 2.0 \times 10^{11}$ is used.

Figure 3 shows the particle loss with phase advance adjustment between IP8 and IP10. From Fig. 3, the default (no adjustment) phase advances and phase advances with exact multipoles of π give almost same proton beam lifetime. The default phase advances are about 19π in the horizontal plane between IP6 and IP10 and about 11π in the vertical plane between IP8 and IP10. Also from Fig. 3,

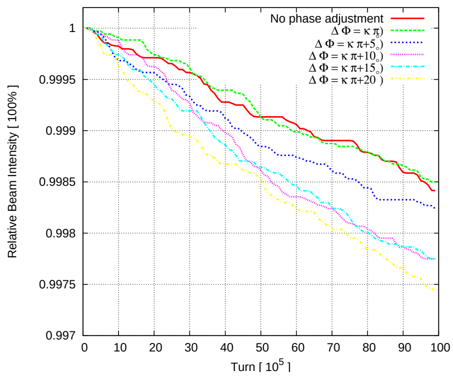

Figure 3: Phase adjustment between IP8 and IP10.

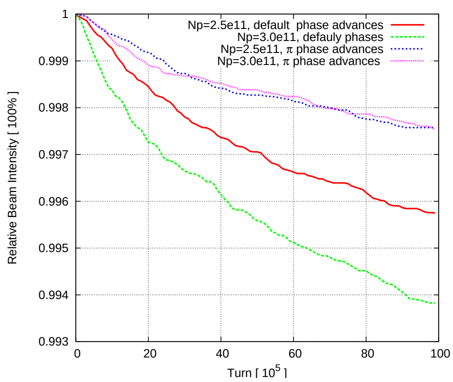

Figure 4: Particle loss with $N_p = 2.5\times10^{11}$ and 3.0×10^{11}.

when the phase advances between IP8 and IP10 are drifting away from the exact multipoles of π, the proton beam lifetime gets slight worse.

Bunch Intensity $N_p = 2.5 \times 10^{11}$ *and* 3.0×10^{11}

The original goal of adopting head-on beam-beam compensation in the RHIC pp run is to reduce the proton-proton beam-beam tune spread when the proton bunch intensity increases above 2.0×10^{11}. With $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}, the tune footprints of proton beam cross the 2/3 resonance line. The proton beam loss during the 2/3 resonance crossing due to proton-proton beam-beam interaction is not simulated in our current study.

Figure 3 shows the particle loss with the proton bunch intensity $N_p = 2.5 \times 10^{11}$ and $N_p = 3.0 \times 10^{11}$. With half beam-beam compensation, the beam decay of proton beam are about 12%/hr and 18%/hr for the cases with $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}. With the exact phase advances of multipoles of π between IP8 and IP10, the proton beam decay drops to about 7.5%/hr. for both $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}. The exactly phase advances of multipoles of π between IP8 and IP10 help the beam lifetime for bunch intensity larger than 2.0×10^{11}.

Unmatched Electron Beam Size

In the above simulation, the electron transverse beam sizes are exactly the same as that of the proton bunches

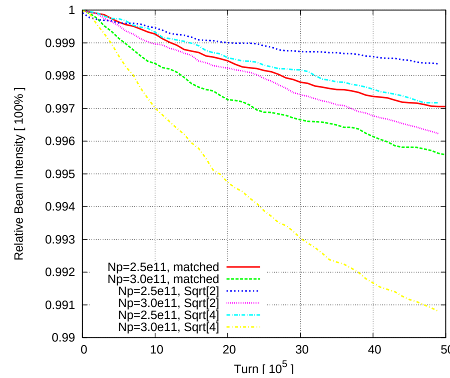

Figure 5: Particle loss with unmatched electron beam size.

at IP10. Here we calculate the proton particle loss with enlarged electron beam sizes. In our simulation, the electron beam size is scaled by a factor k. To keep the same beam-beam tune shift from the head-on beam-beam compensation, the electron intensity is scaled by factor of k^2 at the same time. Figure 4 shows the particle loss with enlarged electron beam size in the case of half head-on beam-beam compensation with $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}.

From Fig. 3, with the electron beam size slightly enlarged by factor of $\sqrt{2}$, the proton beam lifetime gets better for bunch intensities $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}, comparing to the cases with matched electron beam size. With doubled electron beam size, the proton beam lifetime get worse for bunch intensity $N_p = 3.0 \times 10^{11}$. From this simulation, a slightly larger electron beam size is recommended.

CONCLUSION

In the article we reported the preliminary simulation results of the head-on beam-beam compensation's effect on the proton beam lifetime with the lattice for the 250 GeV RHIC polarized proton run. We found that only partial head-on beam-beam compensation can be considered for the practical use in order to avoid the nonlinearities introduced by the compensation. The phase advances of multipoles of π between IP8 and IP10 and slightly larger electron beam transverse size than the proton beam size at IP10 improve the proton lifetime in the half beam-beam compensation with proton bunch intensities $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11}.

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