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

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Abstract

To compensate the large tune spread generated by the beam-beam interactions in the polarized proton (pp) run in the Relativistic Heavy Ion Collider (RHIC), a low energy round Gaussian electron beam or electron lens is proposed to collide head-on with the proton beam. Using a weak-strong beam-beam interaction model, we carry out multi-particle simulations to investigate the effects of head-on beam-beam compensation on the proton beam's lifetime and emittance growth. The simplectic 6-D element-by-element tracking code SixTrack is adopted and modified for this study. The code benchmarking and preliminary simulation results are presented.

INTRODUCTION

To compensate the large tune shift and tune spread generated by the proton-proton (p-p) head-on beam-beam interactions, a low energy round Gaussian electron beam, or electron lens (e-lens), is proposed to collide head-on with the proton beam [1, 2]. In a previous study of single partice stability of motion in the presence of head-on beam-beam compensation, we found that the e-lens stabilizes particles below 3 σ and destabilize the particles above 4 σ, and reduces the long-term dynamic apertures in the current design [3, 4].

In this article, we investigate the head-on beam-beam compensation's effect on the proton beam's lifetime and emittance growth in RHIC. To do that, numeric simulation tracking of multi-particles are carried out. The 6-D simplectic element-by-element tracking code SixTrack [5] is adopted and modified for our purposes. Benchmarking of the code against the RHIC operation is under way.

Table 1 lists the proton beam parameters for this study. Two RHIC proton beams collide at IP6 and IP8. One for the Blue ring and another one for the Yellow ring. They are tentatively put in the interaction region of IR10. For simplicity, in our simulation the interactions between the protons and the electron beams are assumed to take place exactly at IP10. The chromatic sextupoles and multipole field errors in the IRs are included in the study.

For the best head-on beam-beam compensation, the electron beams are assumed to have the same transverse Gaussian profiles as that of the proton beam at IP10. 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, $N_e = 2.0 \times 10^{11}$. Full and half head-on beam-beam compensations compensate full and half linear beam-beam tune spread.

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Table 1: RHIC parameters used in the simulations.

lattice	
RHIC ring circumference	3833.845 m
proton beam energy	250 GeV
relativistic γ	266
$\beta^*_{x,y}$ at IP6 and IP8 (p-p BB)	0.5 m
$\beta^e_{x,y}$ at IP10(e-lens)	10 m
$\beta_{x,y}$ at all other IPs	10 m
proton beam	
particles per bunch N_p	2×10^{11}
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

SIMULATION CODE

SixTrack Modifications

SixTrack is a simplectic 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.

For speed, the 4-D weak-strong beam-beam interaction model is used in our simulation. The proton-electron beam interaction in the e-lens is modeled as another beam-beam interaction. Proton particles receive beam-beam kicks from the opposite proton bunches at IP6 and IP8 and from the electron beam of the e-lens at IP10.

SixTrack can track up to 64 particles in each job. For our purpose, we modified it 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. The change can be a simple white noise or an oscillation with a certain frequency. This modification makes it possible to determine tolerances of parameters in the beam-beam compensation.

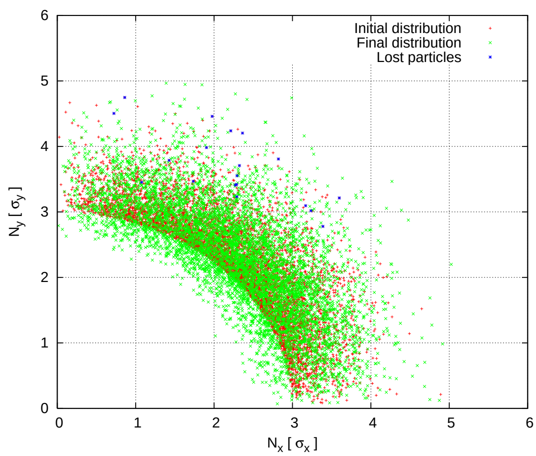

Figure 1: Particle distributions in 'hollow bunch' tracking

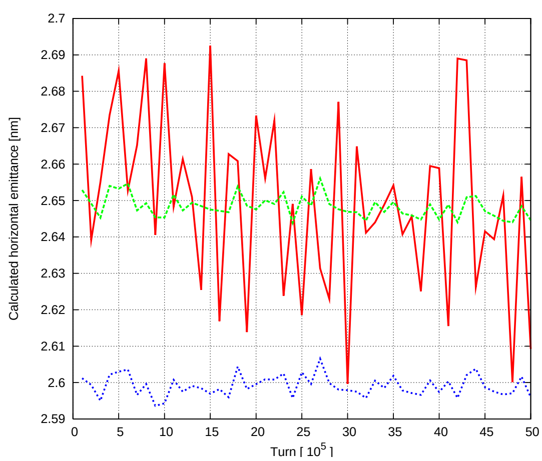

Figure 2: Calculated horizontal emittances in the example.

Beam Decay Calculation

Particle loss is well defined in the tracking. The physical aperture is set to 1 m in SixTrack if there is no collimator in the lattice. Normally the particles with large amplitudes in the bunch tail are likely to be lost earlier. However, limited by the total number of macro-particles in the simulation, there are few particles with large amplitudes in a Gaussian particle distribution. Therefore, to extrapolate the simulated particle loss to the real beam decay correctly, a big enough number of total macro-particles and a good Gaussian distribution generator are needed. In our simulation, we use the Gaussian distribution generator supplied by the Numerical Recipes [6].

As an example, we track 12800 particles of a 6-D Gaussian proton bunch up to 2×10^6 turns. Only the proton-proton beam-beam interactions at IP6 and IP8 are turned on. The non-collisional tunes are (28.685, 29.695). Other beam parameters are given in Table 1. It turns out that there is only one of the 12800 macro-particles lost in 2×10^6 turns. To overcome the statistical error in the calculation of particle loss, one solution is to increase the total number of macro-particles in the simulation. However, this will significantly increase the simulation time. Another approach is to track particles in the bunch tail only, while assuming all particles in the bunch core will survive until the end of tracking. This method will not increase simulation time but there are more partilces in the bunch tail.

As a comparison, with the same simulation parameters as above, we track 6400 particles whose initial transverse amplitudes are sampled from $3-5\sigma$s. These 6400 particles represent a total of 105634 particles of a 6-D Gaussian proton bunch. Fig. 2 shows the initial and final distributions of these particles, together with the initial coordinates of lost particles. Tracking such a hollow bunch over 2×10^6 turns, there are a total of 19 out of 6400 macro-particles lost. To use this method, the boundary needs to be determined below which particles will not be lost. For maximum efficiency, this boudary should be as large as possible.

Emittance Calculation

The emittance can be calculated through the determinant of beam size matrix or simply from σ^2/β. Since the real emittance growth of the proton beam in 10^7 turns is very small, a very high resolution in the emittance calculation is required. Increasing the total number of macro-particles in simulation and a good algorithm of emittance calculation are helpful. We have noticed that particle loss and large amplitude particles affect the value of calculated emittance. In the following, we calculate the emittance only with particles below 5 σ. With the same simulation parameters as above, we track 12800 particles of a 6-D Gaussian proton bunch up to 5×10^6 turns. The red curve in Fig. 2 shows the calculated horizontal emittances at $10^5 \times k$ turns, $k = 1, 2, ..50$.

To reduce the fluctuation in the calculation of the emittance, the straight-forward way is to increase the total number of particles in the simulation. However, limited by the CPU time, this is not easily possible. Another approach is to calculate the averaged emittance with the coordinates of all the particles in all turns in each step of 10^5 turns. In Fig. 2, the green and blue lines show the calculated emittances using this method. The difference is that the green and the blue curves only count macro-particles below 5 σ and 4 σ respectively. One can see in Fig. 2 that this approach does reduce the fluctuation in the calculated emittance. However, it is still difficult to see that there is a clear trend of the emittance change.

PRELIMINARY SIMULATION RESULTS

In this section, we present the preliminary simulation results of the head-on beam-beam compensation in the RHIC. The tunes without beam-beam interaction are (28.685, 29.695). The beam-beam tune shift with the proton-proton interactions at IP6 and IP8 is about -0.02. The beam-beam interaction will slightly change Twiss parameters at IPs. In the following example, we show the results with the initial particle distribution generated with Twiss parameters without beam-beam modification.

Fig. 3 shows the simulated beam decay in 2×10^6 turns under different beam-beam conditions. The vertical axis is the relative beam intensity. From Fig. 3, the beam lifetime with half head-on beam-beam compensation is comparable with that without beam-beam compensation. The beam decay is below 8%/hour. Full beam-beam compensation results in a visibly reduced beam lifetime.

The early particle loss in the simulation tracking is mainly due to the beam-beam dynamic aperture. The study of stability of single particle motion has shown that full head-on beam-beam compensation will destabilize the particles above 4 σ and reduce the long-term dynamic aperture. The lost particles are normally these with large amplitude in the bunch tail. In the RHIC pp operation, we observed that the beam has a much worse lifetime in the begining than that in the rest of physics store.

Fig. 4 shows the simulated horizontal emittances of the proton beam under different beam-beam conditions. The different starting values of the calculated emittances are due to the unmatched initial particle distributions and the not prefect initial Gaussian distribution. Here only particles below 5σs are used for the emittance calculation.

From Fig. 4, it is difficult to compare the emittance growth rates under different beam-beam conditions in such a short time. If we focus on the changes of $< x^2 >$ and $< y^2 >$ of particles below 3 σ in the tracking, we didn't see clear difference between them either. The study of stability of single particle motion does hint that with head-on beam-beam compensation particles in the bunch core have smaller action diffusion.

In the current lattice design of RHIC head-on beam-beam compensation, the phase advances between the proton-proton and proton-electron beam-beam interaction points are not optimized. In the simulation, the phase advances between IP8 and IP10 where the e-lens is are (8.4π,10.9π). To cancel nonlinear resonance driving terms from the beam-beam interactions, phase advances of exactly $k\pi$ in both transverse planes between the proton-proton and proton-electron interaction points are required. How to minimize the nonlinear effects from the head-on beam-beam compensation is the key point to successfully apply the technique of head-on beam-beam compensation.

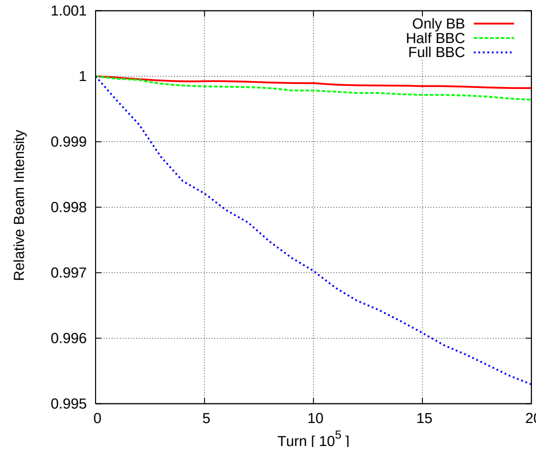

Figure 3: Simulated beam decay with BB compensation.

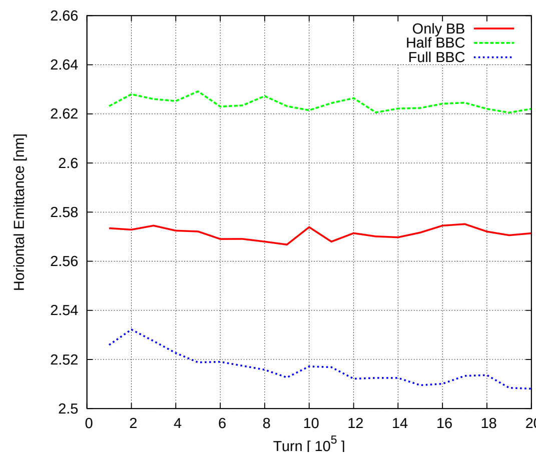

Figure 4: Simulated emittances with BB compensation.

CONCLUSION

To evaluate the effects from the proposed RHIC head-on beam-beam compensation on the proton beam's lifetime and emittance growth, multi-particle tracking simulations were carried out. From the preliminary study, the particle loss with half head-on beam-beam compensation is comparable to that without compensation. Full head-on beam-beam compensation reduces the beam lifetime. A comparison of the emittance growth over 10^7 turns under different beam-beam conditions is difficult due the noisiness of the signal. A further study of how to minimize the nonlinear effects from the head-on beam-beam compensation to improve beam lifetime is in progress.

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