6-D 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 run in the Relativistic Heavy Ion Collider (RHIC), we propose a low energy round Gaussian electron beam to collide head-on with the proton beam. Such a device to provide the electron beam is called electron lens. In this article we carry out 6-D weak-strong beam-beam simulation to study the stability of proton particles and the proton beam lifetime in the presence of head-on beam-beam compensation in the RHIC 250 GeV polarized proton run.

INTRODUCTION

The working point for the polarized proton run in the Relativistic Heavy Ion Collider (RHIC) is constrained between [2/3, 7/10]. When the vertical tune is close to 7/10, both the proton polarization and the beam-beam lifetime will be reduced. To further increase the bunch intensity above 2×10^{11} and to 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.

One solution is to adopt head-on beam-beam compensation. We propose a DC low energy electron beam to head-on collide with the proton beam [1]. Such a device to provide the electron beam is called electron lens (e-lens). The electron beam has the similar Gaussian transverse distribution as that of the proton beam at the compensation point. The e-lenses are located close to IP10. Table 1 lists the proton beam parameters for this simulation study.

Different from early simulation studies [2, 3, 4], in this article we adopt the 6-D weak-strong synchro-beam map a la Hirata to simulation the proton-proton beam-beam interaction at IP6 and IP8. This is justified by the fact that the β^* at IP6 and IP8 is comparable to the rms proton bunch length. In the simulation model, the effective interaction length of the RHIC e-lenses is 2.0 m long and are 1.0 m away from IP10. The e-lens is split into 8 slices and each slice is modeled as drift–4D weak-strong beam-beam kick–drift.

The particle motion in the magnetic elements is tracked with a 4th order symplectic integration. To save the time involved in the numeric tracking, we use thin multipoles in the lattice model. The tunes of zero amplitude particles are always matched to (28.67, 29.68) with beam-beam and compensations if included. The linear chromaticities is set to (+1, +1). For simplicity, we define full and half head-on beam-beam compensation to compensate full and half of the proton-proton beam-beam parameter.

Table 1: Beam Parameters Used in the Simulation

normalized transverse rms emittance	2.5 mm.mrad
β^*s at IP6 and IP8	0.5 m
βs at the e-lens	10.0 m
transverse rms beam size at IP6 and IP8	0.068 mm
transverse rms beam size at e-lens	0.40 mm
effective length of e-lens	2.0 m
phase advances between IP6 and IP8	(10.6π, 9.7π)
phase advances between IP8 and e-lens	(8.5π, 11.1π)
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

DYNAMIC APERTURE CALCULATION

In this section we calculate the dynamic aperture up to 10^6 turn tracking. The particle's initial momentum deviation is +0.0005. The dynamic aperture is searched in 5 angles in the first quadrant in the x-y plane. The dynamic aperture is measured in the unit of RAMs transverse beam size.

To better compensate the nonlinearities from the proton-proton beam-beam interaction at IP8 with the e-lens, we adjusted the betatron phase advances between IP8 and the center of e-lens to be multipoles of π. In this study, the betatron phase advances between IP8 and the center of e-lens are $(7\pi, 9\pi)$ after phase adjustment. On top of that, we also investigate the effect of the second order chromaticity correction on the dynamic aperture.

Figure 1 shows the dynamic apertures in the scan of proton bunch intensities from 1.2×10^{11} to 3.0×10^{11}. In this study, half head-on beam-beam compensation is applied. From Figure 1, below a proton bunch intensity of 2.0×10^{11}, half beam-beam compensation doesn't help improve the dynamic aperture. For proton bunch intensity from 2.0×10^{11} to 2.5×10^{11}, phase advances of $k\pi$ between IP8 and the center of the e-lens increase the dynamic apertures. The second order chromaticity correction increases the dynamic apertures with bunch intensity from 2.0×10^{11} up to 2.8×10^{11}.

Figure 2 shows the dynamic aperture in the scan of the

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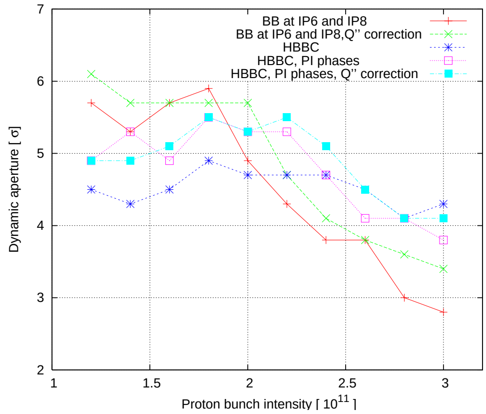

Figure 1: Calculated dynamic aperture with half head-on beam-beam compensation in the scan of proton bunch intensity. Proton bunch intensity is 2.5×10^{11}.

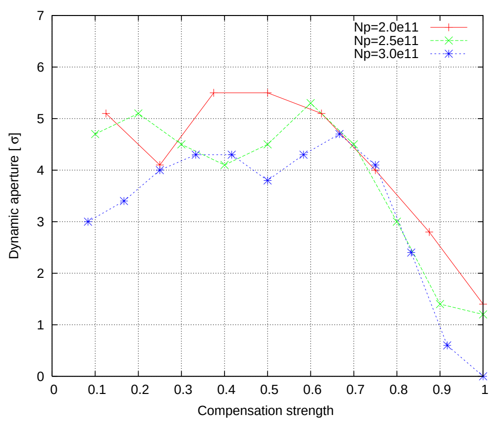

Figure 2: Calculated dynamic aperture versus the compensation strength for three proton bunch intensities. The phase adjustment and second order chromaticity correction are included.

compensation strength. Compensation strength is defined as the electron beam intensity divided by twice the proton bunch intensity. From Figure 2, head-on beam-beam compensation compensation with compensation strength above 0.7 reduces the dynamic aperture for all the three bunch intensities. For bunch intensity 2.0×10^{11}, the peak dynamic aperture occurs at compensation strength 0.4-0.5, while for bunch intensities 2.5×10^{11} and 3.0×10^{11}, the peak dynamic aperture occur at compensation strength 0.6-0.65.

Figure 3 shows the calculated dynamic aperture versus the electron beam size divided by the proton beam size. From Figure 3, the dynamic aperture quickly drops when the electron beam size is smaller than that of proton bunch. The peak minimum dynamic aperture happen when the electron beam size is 20-40% bigger than the proton bunch's.

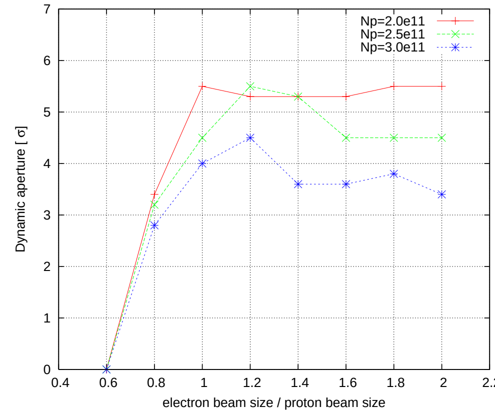

Figure 3: Calculated dynamic aperture versus electron beam size for three proton bunch intensities. The phase adjustment and second order chromaticity correction are included.

BEAM LIFETIME CALCULATION

In this section we calculate the particle loss rate of a proton bunch in the presence of head-on beam-beam compensation. To save the computing time, we track 4800 macro-particles of a hollow 6-D Gaussian distribution up to 2×10^6 turns. The boundary below which the particles are assumed to be alive in the lifetime tracking is carefully chosen with the dynamic aperture calculation and will be verified after the lifetime tracking. The normalized beam intensity shown in the following plots is calculated based on how many particles are lost among the 4800 macro-particles and the total particle number of the 6-D Gaussian bunch they represent.

Figure 4 shows the normalized beam intensity without and with half beam-beam compensation for three proton bunch intensities. From Figure 4, in the 2×10^6 turn tracking, half beam-beam compensation reduces proton particle loss for bunch intensities 2.5×10^{11} and 3.0×10^{11}. However, for bunch intensity 2.0×10^{11} half beam-beam compensation increases the proton particle loss.

Figure 5 shows the normalized proton beam intensity with phase adjustment and second order chromaticity correction. Comparing Figure 4 and Figure 5, the phase advances of $k\pi$ between IP8 and e-lens help increase the proton lifetime. On top of it, the second order chromaticity correction further improve the proton lifetime, especially for bunch intensities 2.0×10^{11} and 2.5×10^{11}. For bunch intensity 3.0×10^{11}, the improvement is smaller.

Figure 6 shows the normalized proton beam intensity with different electron beam sizes. The proton bunch intensity is 2.5×10^{11}. From Figure 6, a electron beam size with 20% and 40% larger than the proton's gives better proton beam lifetime. The electron beam size with 20% smaller than the proton's gives a lot particle loss and is out of the vertical range in Figure 6.

Figure 7 shows the normalized proton beam intensity in the tune scan. In this scan, the proton bunch intensity

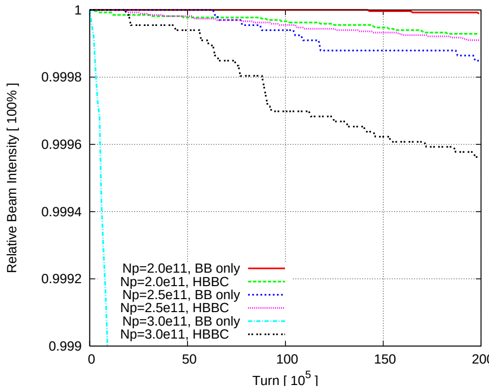

Figure 4: Particle loss without and with half head-on beam-beam compensation.

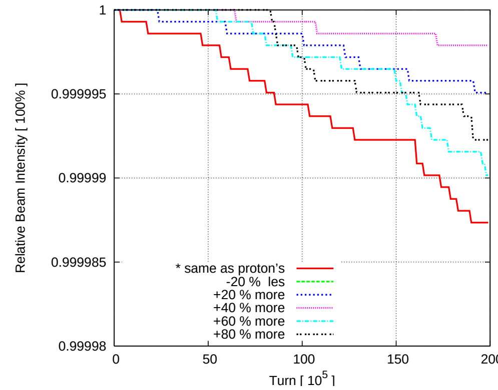

Figure 6: Particle loss with half head-on beam-beam compensation in the scan of electron transverse beam size.

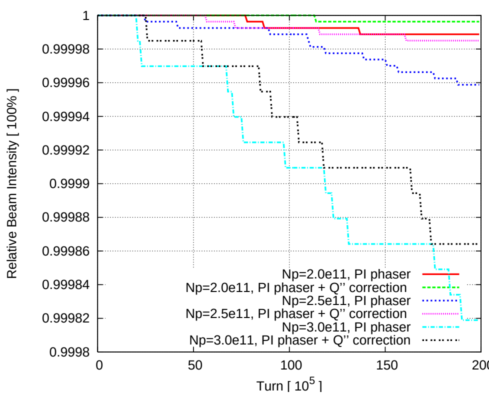

Figure 5: Particle loss without and with second order chromaticity correction.

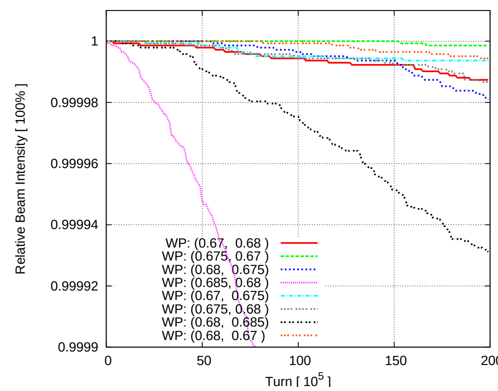

Figure 7: Particle loss with half head-on beam-beam compensation in the scan of proton working point.

is 2.5×10^{11} and half beam-beam compensation is applied. The phase adjustment and second order chromaticity correction are included. From Figure 7, the working points (28.675, 29.67) and (28.67, 29.675) give best proton beam lifetime in the presence of half beam-beam compensation, while the working points (28.685, 29.68) and (28.68, 29.685) give worst beam lifetime. Also from Figure 7, normally the proton beam lifetime is better with a working point below the diagonal than that with the horizontal and vertical swapped working point above diagonal.

CONCLUSION

In this article, with a 6-D weak-strong beam-beam model, we calculated the effects of head-on beam-beam compensation on the 10^6 turn dynamic aperture and the particle loss rate of a proton bunch. The simulation results show that half head-on beam-beam compensation improves the proton particle dynamic aperture and the proton beam lifetime for proton bunch intensity above 2.0×10^{11}. The phase advances of $k\pi$ between the IP8 and the center of e-lens and second order chromaticity correction further help improve the proton lifetime. We also found that slightly larger transverse electron beam size than that of proton beam in the e-lens gives a larger proton lifetime. The scan of proton working point shows that (28.67, 29.675) and (28.675, 29.67) give larger lifetime with half beam-beam compensation. All the simulations in the article were done with SimTrack [5]. SimTrack is a c++ library for optical calculation and particle tracking in high energy circular accelerators.

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