OPTIMIZING THE ELECTRON BEAM PARAMETERS FOR HEAD-ON BEAM-BEAM COMPENSATION IN RHIC*

Y. Luo, W. Fischer, A. Pikin, X. Gu, Brookhaven National Laboratory, Upton, NY, USA

Abstract

Head-on beam-beam compensation is adopted to compensate the large beam-beam tune spread from the proton-proton interactions at IP6 and IP8 in the Relativistic Heavy Ion Collider (RHIC). Two e-lenses are being built and to be in stalled near IP10 in the end of 2011. In this article we perform numeric simulation to investigate the effect of the electron beam parameters on the proton dynamics. The electron beam parameters include its transverse profile, size, current, offset and random errors in them.

INTRODUCTION

Current working point in the RHIC polarized proton run is constrained between 2/3 and 7/10. To further increase the proton bunch intensity, for example, 3×10^{11} in the upgrade program [1], there will not be enough tune space to hold the beam-beam tune spread between 2/3 and 7/10. As one solution to it, we are planning to adopt head-on beam-beam compensation to reduce the beam-beam tune spread and to compensate the beam-beam nonlinearities [2, 3, 4].

To apply head-on beam-beam compensation, we will introduce a low energy electron beam in the RHIC rings to head-on collide with the proton beam. Such a device to produce the electron beam is called electron lens (e-lens) [5]. The proton-proton beam-beam interactions take place at IP6 and IP8. E-lenses will be placed around IP10. The β^* at IP6 and IP8 are 0.5 m. β function at the e-lens is 10 m.

To better compensate the nonlinearities from the proton-proton beam-beam interaction at IP8 with the e-lens, we would like to have $k\pi$ phase advances between IP8 and the center of e-lens [6]. The default phase advance between them from the current lattice are (8.5π, 11.1π). In the simulation, we adjust the phase advances to (9π, 11π) by inserting two artificial matrices before and after e-lens. The tunes, chromaticities, and Twiss parameters of proton beam will not be changed after phase adjustment. We also correct the second order chromaticity to minimize the chromatic effect. The second order chromaticities are around 2800 and 200 before and after correction.

In the following, we will investigate the effect of electron beam parameters on the proton beam dynamics. These parameters include the electron beam's transverse profile, beam current, beam size, offset and fluctuations in current and offsets. In these studies, proton beam's dynamic aperture or proton particle loss rate will be calculated. In these studies we focus on half beam-beam compensation with the proton bunch intensity $N_p = 2.5 \times 10^{11}$.

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NUMERIC SIMULATION

In our simulation study we use a 6-d weak-strong synchro-beam map by Hirata to model the beam-beam interactions at IP6 and IP8 since the proton bunch length is comparable to β^* function there. Considering the RHIC e-lens is working in a DC mode, we split it into 8 slices and model each slice as drift–(4-d weak-strong beam-beam kick)–drift. The 4-d weak-strong beam-beam kick is based on the equations given by Bassetti-Erskine. The RHIC multipole field errors are included in simulation. The tunes of the zero-amplitude particles are kept to (28.67, 29.68) with or without beam-beam compensation. The first order chromaticities are set to (1,1). The proton partilce motion is tracked element by element. The code SimTrack [7] is used in this study.

Nominal Case

For the nominal half head-on beam-beam compensation, the electron beam has a round Gaussian distribution and its size is same as that of the proton beam. The number of electrons in the compensation region N_e equals to the proton bunch intensity N_p. Fig. 1 shows the calculated proton particle loss without and with beam-beam compensation. The proton particle loss is calculated with 4800 macro-particles of a hollow 6-D Gaussian proton beam tracked up to 2×10^6 turns. From Fig. 1, half beam-beam compensation improves proton beam lifetime while full compensation doesn't. The $k\pi$ phase advances and second order chromaticity correction further increase the proton beam lifetime.

Profile of Electron Beam

As we know that for better compensation of the nonlinearities of beam-beam interaction at IP8, the electron beam should have same transverse profile as the proton beam to provide same force dependence on proton's coordinates. At the location of e-lens, the proton beam has a round Gaussian distribution.

As an example, here we compare the dynamic apertures in the case of half head-on beam-beam compensation with a round Gaussian and a round uniform distributions of electron beams. The radius of round uniform distribution is cut at $\sqrt{2}\sigma_p$ and $N_e = N_p$. It will provide the same linear tune shift to the proton bunch core and the same force at large amplitude as the round Gaussian distribution. However, its

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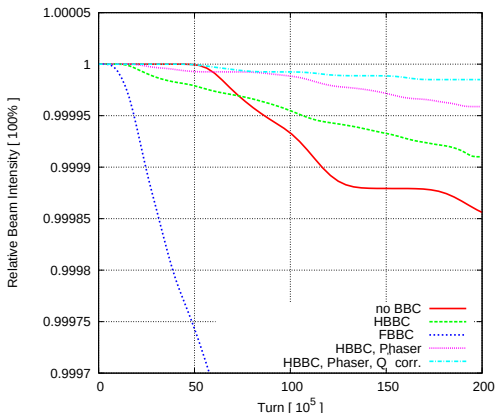

Figure 1: Head-on beam-beam compensation with $N_p = 2.5 \times 10^{11}$.

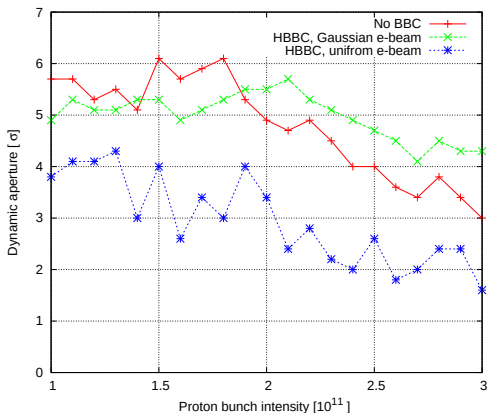

Figure 2: Dynamic aperture with Gaussian and uniform electron distribution.

force over-shots around $1-2\sigma$. Fig. 2 shows the calculated dynamic apertures in a scan of proton bunch intensity with half head-on beam-beam compensation. From this example, we conclude that for head-on beam-beam compensation, round uniform distribution of electron beam is not a good choice.

Size of Electron Beam

From the above discussion, the round Gaussian electron beam should have the same rms transverse beam size as the proton beam. Here we scan the electron beam size from -20% smaller to $+60\%$ larger. In this study we keep the electron number $N_e = 2.5 \times 10^{11}$. Fig. 3 shows the calculated proton particle loss without and with beam-beam compensation. This study shows that, for proton bunch intensity $N_p = 2.5 \times 10^{11}$, with smaller electron beam than the proton beam, the proton beam lifetime will be hurt. With larger electron beam size than the proton, the proton beam lifetime is acceptable but the beam-beam tune spread compensation strength is reduced.

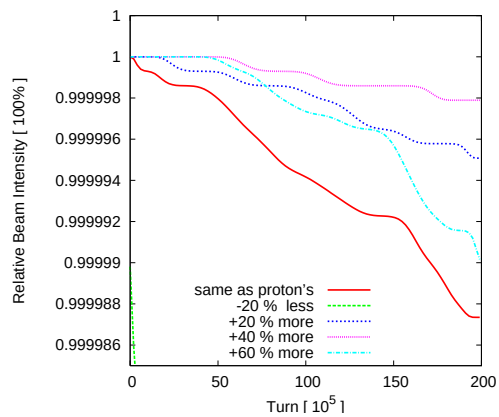

Figure 3: Proton particle loss versus electron beam size.

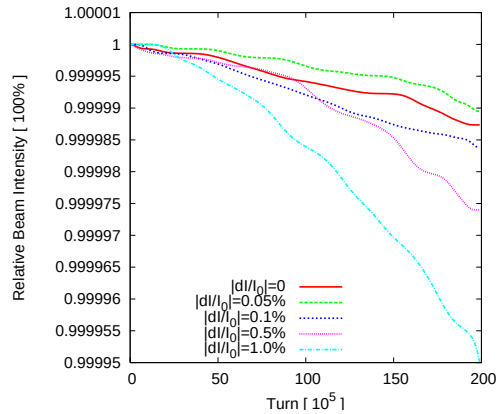

Figure 4: Proton particle loss versus electron current random noise.

Current of Electron Beam

Due to the instability of the power supplies of electron gun, there are fluctuations in the electron beam current [8, 9]. In this study we introduce random noise to it. We define the relative noise percentage $|dI/I_0|$ as the maximum amplitude of random noise divided by the nominal electron beam current. Fig. 4 shows the relative proton beam intensity versus random noise level in the electron beam current. For the proton bunch intensity 2.5×10^{11}, below 0.1% random noise in the electron beam is acceptable. Above 0.5% random noise in the electron beam current will introduce more proton particle loss.

Electron Beam with Truncated Gaussian Tail

With current design of RHIC electron gun, we have a good fit of Gaussian distribution of electron beam up to 2.8 σ from the electron gun simulation [8]. Here we study the effect of truncated round Gaussian distribution of electron beam on the proton beam lifetime. Fig. 5 shows the calculated relative proton beam intensity up to 2×10^6 turns with Gaussian tail cut at different σ. Fig. 6 shows the calculated horizontal emittance of the proton bunch. From them, there is significant proton particle loss and horizontal emit-

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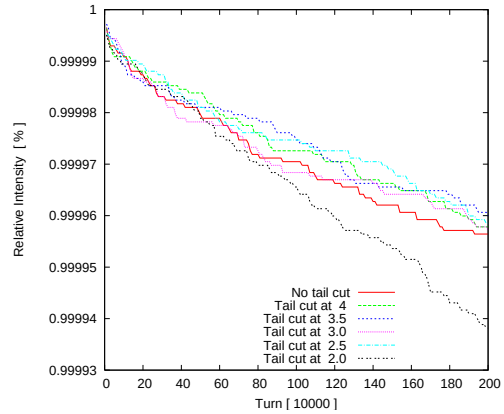

Figure 5: Proton particle loss with tail truncated Gaussian distribution.

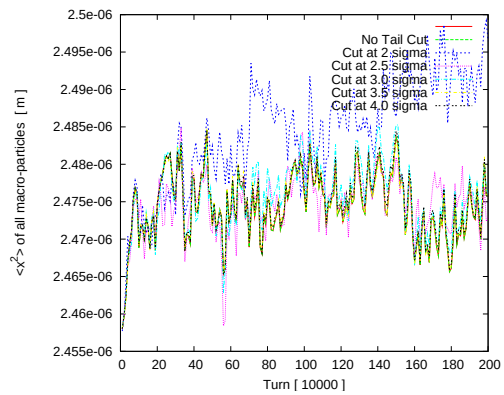

Figure 6: Horizontal emittance with tail truncated Gaussian distribution.

tance growth if the Gaussian distribution is truncated at 2 σ.

Offset of Electron Beam

Over-lapping the electron and proton beams in the main solenoid of e-lens plays a significant role in the head-on beam-beam compensation [8, 9]. Transverse offset of electron beam w.r.t. the proton beam center will cause loss of beam-beam tune spread compensation and inefficient cancellation of beam-beam nonlinearities. Both of them will reduce the proton beam lifetime.

Fig. 7 and Fig. 8 show the calculated proton particle loss with static and random electron beam offset. The random offsets $\pm$ 3 μm, $\pm$ 8 μm, and $\pm$ 19 μm correspond to three levels of requirements to the steering power supply instabilities. From this study, random offset of electron beam gives more worse effect than static offset. From Fig. 8, the random offset noise should be controlled below 8 μm.

SUMMARY

In this article we studied the effect of the electron beam parameters on the proton dynamics. The electron beam parameters include its transverse shape, size, current, offset

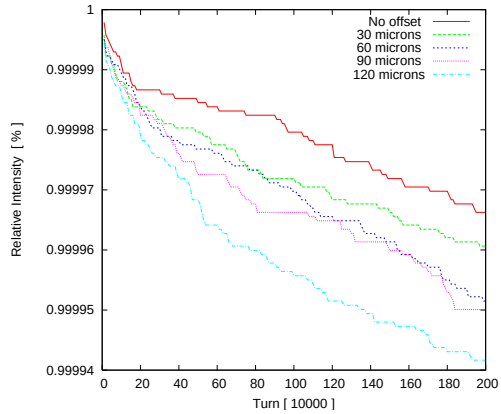

Figure 7: Proton particle with static offset in electron beam position.

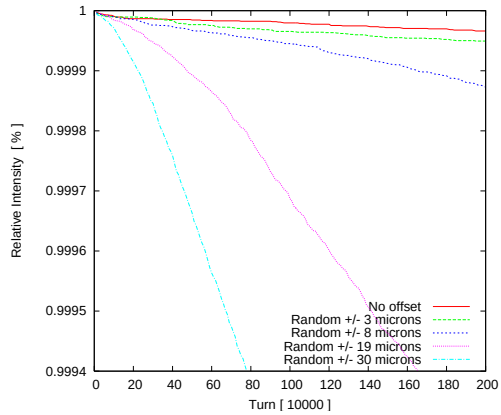

Figure 8: Proton particle with random offset in electron beam position.

and their random errors. From the study, we require that the electron beam size can not be smaller than the proton beam's. And the random noise in the electron current should be better than 0.1%. The offset of electron beam w.r.t. the proton beam center is crucial to head-on beam-beam compensation. Its random errors should be below $\pm 8\mu$m.

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