HEAD-ON BEAM-BEAM COMPENSATION WITH ELECTRON LENSES IN THE RELATIVISTIC HEAVY ION COLLIDER*

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Abstract

The working point for the polarized proton run in the Relativistic Heavy Ion Collider is constrained between 2/3 and 7/10 in order to maintain good beam lifetime and polarization. To further increase the bunch intensity to improve the luminosity, a low energy Gaussian electron beam, or an electron lens is proposed to head-on collide with the proton beam to compensate the large tune shift and tune spread generated by the proton-proton beam-beam interactions at IP6 and IP8. In this article, we outline the scheme of head-on beam-beam compensation in the RHIC and give the layout of e-lens installation and the parameters of the proton and electron beams. The involved physics and engineering issues are shortly discussed.

INTRODUCTION

To maintain collisional beam lifetime and proton polarization in the polarized proton (pp) run in the Relativistic Heavy Ion Collider (RHIC), the working points for the proton beams are constrained between 2/3 and 7/10 [1] by betatron and polarization resonances. The nominal uncollisional tunes for the current pp runs are (28.685, 29.695) and (28.695, 29.685) for the two RHIC rings. In the 2008 RHIC pp run, the bunch intensity has reached 1.8×10^{11} in one of the beams. To further increase the bunch intensity to 2.0×10^{11} or even higher, there will be not enough tune space between 2/3 and 7/10 to hold such a large tune shift and tune spread generated by the proton-proton head-on beam-beam interactions. Fig. 1 shows the tune footprint with proton bunch intensity 2.0×10^{11}.

One solution is to adopt head-on beam-beam compensation [2, 3]. In the Tevatron, two low energy electron beams, usually called electron lenses or e-lenses, have been successfully installed. They are routinely used as gap cleaner, and one of the lenses has been shown to improve the lifetime of selected anti-proton bunches [4]. In our study, we investigate if such a device like the Tevatron e-lens can be used to mitigate the head-on beam-beam effects in the RHIC pp operation. The head-on beam-beam compensation scheme should compensate both linear and nonlinear effects from the proton-proton beam-beam interactions.

In this article, we outline the scheme of head-on beam-beam compensation in the RHIC and give the parameters of the proton and electron beams. The involved physics and engineering issues are shortly discussed.

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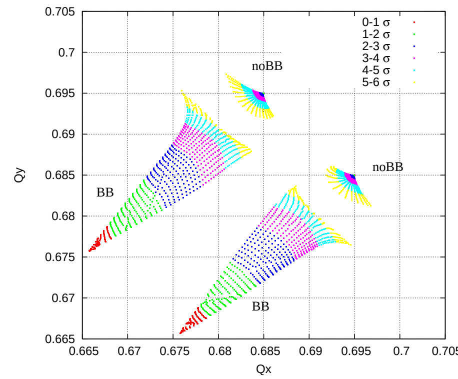

Figure 1: Tune footprint with $N_p = 2 \times 10^{11}$.

BEAM-BEAM COMPENSATION

For the head-on proton-proton beam collisions, the transverse angle kicks to a proton particle from the opposite proton round Gaussian bunch are given by

$$\left(\begin{array}{c} \Delta x' \\ \Delta y' \end{array} \right)_{p-pbunch} = \frac{2N_p r_0}{\gamma r^2}(1 - e^{-\frac{r^2}{2\sigma_p^2}}) \left(\begin{array}{c} x \\ y \end{array} \right), \quad (1)$$

where N_p is the number of protons in the opposite proton bunch. r_0 is the classic proton radius, γ is the proton particle's relativistic parameter, $r = \sqrt{x^2 + y^2}$, σ_p is the transverse rms beam size.

In the electron lens, the proton bunch 'head-on' collides with the round Gaussian electron DC beam. The effective interaction length is L_{elens}. Similarly, the transverse kicks on a proton particle from the electron beam are given by

$$\left(\begin{array}{c} \Delta x' \\ \Delta y' \end{array} \right)_{p-ebeam} = -\frac{2N_e r_0}{\gamma r^2}(1-e^{-\frac{r^2}{2\sigma_e^2}})(1+\beta_e) \left(\begin{array}{c} x \\ y \end{array} \right), \quad (2)$$

where N_e is the number of electrons of the electron beam in the effective interaction region. $\beta_e c$ is the speed of the electrons, σ_e is the transverse rms electron beam size.

Therefore, for the core particles in the proton bunch, the incoherent linear beam-beam tune shifts from the proton-proton and proton-electron interactions are

$$\Delta Q_{x,y}|_{p-p} = -\frac{N_p r_0 \beta^*}{4\pi\gamma\sigma_p^2} = -\frac{N_p r_0}{4\pi\gamma\varepsilon_p}, \quad (3)$$

$$\Delta Q_{x,y}|_{p-e} = \frac{N_e r_0 \beta_{elens}}{4\pi\gamma\sigma_e^2}(1+\beta_e) = \frac{N_e r_0}{4\pi\gamma\varepsilon_e}(1+\beta_e). \quad (4)$$

Here we define the electron beam's emittance $\varepsilon_e = \sigma_e^2/\beta_{elens}$. To fully compensate the incoherent linear beam-beam tune shifts with an e-lens, According Eqs. (3) and (4), we have

$$N_e = \frac{N_{IP} N_p}{1+\beta_e}. \quad (5)$$

N_{IP} is the number of proton-proton beam-beam interaction points. Here we have assumed $\varepsilon_e = \varepsilon_p$.

To compensate the nonlinear effects from the proton-proton beam-beam interactions, according to Eq. (1) and (2), the transverse beam sizes of the electron beam and the proton bunch in the compensation region should be the same and the phase advances between the proton-proton beam-beam and proton-electron interaction points should be multiples of π.

LATTICE AND OPTICS PARAMETERS

Location of RHIC E-lens

For the RHIC polarized proton run, the two proton beams collide at IP6 and IP8. The proton beam in the Blue ring circulates clockwise, while the proton beam in the Yellow ring circulates anti-clockwise. In the current design, the e-lenses for the RHIC head-on beam-beam compensations are put close to IP10. Fig. 1 shows the layout of the RHIC ring.

Two e-lenses are needed for the RHIC head-on beam-beam compensation, one for the Blue ring and another one for the Yellow ring. The e-lens for the Blue ring is named BEL, and the e-lens for the Yellow ring is named YEL. In the current design, they are assumed to be 2 m long. They are symmetrically placed 1.5 meter away from IP10. Fig. 2 shows the installation places of the RHIC e-lenses in IR10. The phase advances between IP8 and the e-lenses are not optimized at this point.

The two proton beams are to be separated vertically. A separation of 10 mm can be reliably reached in RHIC operation. The radius of the current beam pipe in IR10 is 60 mm. The electron beams are guided into the compensation regions from the DX horizontal separation magnet side and dumped on the IP10 side. The proton beam of the Blue ring interacts with the electron beam in the BEL, and the proton beam of the Yellow ring interacts with the electron beam in the YEL.

Proton Beam Parameters

Tab. 1 lists the proton beam parameters for the RHIC head-on beam-beam compensation study. The proton energy is 250 GeV, the relativistic factor $\gamma = 266$. The bunch intensity is chosen as $N_p = 2.0 \times 10^{11}$. The beta functions at IP6 and IP8 are $\beta^*_{x,y} = 0.5$ m. The beta functions at IP10 are $\beta^e_{x,y} = 10$ m. The beta functions at the other crossing points (IP2, IP4, IP10) are 10 m. The beta functions at the two ends of the e-lenses are 10.2 m and 11.2 m. In the beginning, the proton beam rms transverse emittance is assumed to be 2.5 mm·mrad (or 15 mm·mrad for the 95% emittance) and in the end of store it is 4.2 mm·mrad (or 25 mm·mrad for the 95% emittance).

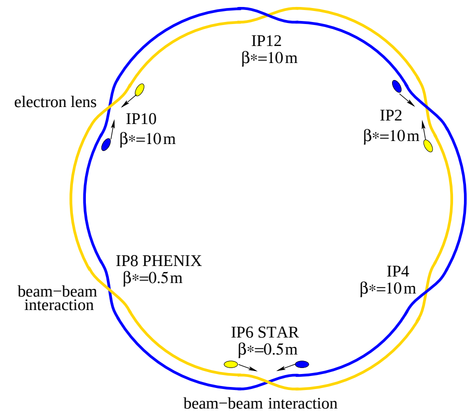

Figure 2: Layout of RHIC head-on BB compensation.

Table 1: RHIC parameters used in the simulations.

lattice	
RHIC ring circumference	3833.8451 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

The normalized rms longitudinal bunch area of the proton beam is assumed to be 0.17 eV·s. With the accelerating rf cavities, the harmonic number is 360 and the total rf voltage is 300 kV. The relative rms momentum spread of the proton beam is $\delta_{rms} = (\frac{\Delta p}{p_0})_{rms} = 0.14 \times 10^{-3}$, the rms bunch length of the proton beam is $\sigma_l = 0.44$m.

For the simulation study, the non-collisonal working points of the proton beam are chosen as $(28.685, 29.695)$ and $(28.695, 29.685)$. The linear chromaticities are set to $Q'_{x,y} = +1$. The multipole magnetic field errors in the triplet quadrupoles and separation dipole magnets in the IRs are included.

E-lens Parameters

Tab. 2 summarizes the nominal parameters of the RHIC e-lenses, which are close to the Tevatron electron lenses. In the current RHIC e-lens design, the interaction region of the proton and electron beams are 2 m long. The electron

Table 2: Nominal RHIC e-lens parameters.

electron kinetic energy K_e	5 keV
electron speed $\beta_e c$	0.14 c
electron transverse rms size σ_e	0.433 mm
effective e-lens length L_{elens}	2.0 m
total electron particles in e-lens N_e	3.5 $\times 10^{11}$
electron beam current I_e	1.2 A

beam is a DC beam and has a round Gaussian transverse profile. The kinetic energy of the electrons is assumed to be $E_k = 5$ keV.

The best head-on beam-beam compensation requires that the electron beam has the same transverse profile as that of the proton beam. However, in the current design, we assume the electron beam size is constant in the whole luminosity production store. The electron beam size is set to be same as the proton beam size at the end of store, that is, $\sigma_e = 0.40$mm.

For the full head-on beam-beam compensation with matched beam sizes, the number of electrons in the electron beam in the e-lens is 3.5×10^{11}, which gives an electron beam current about 1.2 A. Full and half head-on beam-beam compensations will compensate full and half of the linear beam-beam tune shifts respectively.

A superconducting solenoid is needed to stabilize the electron motion in the e-lenses. To cancel their betatron coupling effect to the proton beams, the directions of the solenoid magnetic fields in the BEL and YEL should be opposite.

ITEMS BEING STUDIED

To check the benefits and side effects from the head-on beam-beam compensation with e-lenses in the RHIC, detailed numeric simulation studies have been carried out. In the study of stability of single particle motion [5], tune diffusion, action diffusion, Lyapunov exponent, and dynamic aperture are calculated and compared under conditions without and with head-on beam-beam compensation. Both the tune diffusion and Lyaponuv exponents analysis in short-term trackings hint that head-on compensation in RHIC stabilizes the proton particles below 3σ since it pulls these particles away from the $2/3$ betatron resonance. However, it is also found that the head-on compensation in the RHIC will destabilize the particles beyond 4σ. This is confirmed with the long-term dynamic aperture calculation. This means that the head-on beam-beam compensation in the current design introduces more nonlinear effects into the proton beam dynamics. Resonance driving terms are to be calculated with and without head-on beam-beam compensation.

To evaluate the effects from the head-on beam-beam compensation on the proton beam's lifetime and emittance growth, multi-particle trackings are being carried out [6]. The 6-D simplectic element-by-element tracking code SixTrack is modified for this study. By now, the simulation calculation of particle loss up to 10^7 turns (or 2 min of real time) is well defined and is ready to benchmark with the real RHIC operation observations. However, the simulation calculation of the emittance growth in such a short time seems very difficult. 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 gives the worst beam lifetime. This may be explained by the dynamic aperture reduction with head-on beam-beam compensation. The long-term action diffusion calculations does show that the core particles below 3σ become more stable when the head-on beam-beam compensation is on [7].

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. The phase advances between two proton-proton interaction points are (10.6π,8.6π), while the phase advances between e-lens(IP10) and IP8 are (8.4π,10.9π). To cancel nonlinear resonance driving terms from the beam-beam interactions, exactly $k\pi$ phase advances 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 this technique.

CONCLUSION

Electron lenses have been proposed for the head-on beam-beam compensation in the polarized proton run in the RHIC. Detailed simulation studies are being carried out to check its effects on the proton beam lifetime and emittance growth. Simulation shows that head-on beam-beam compensation is very efficient to reduce the beam-beam tune shift and tune spread. It will stabilize core particles in the proton bunch and destabilize the particles in the bunch tail in the current design. How to minimize the nonlinear effects from the head-on beam-beam compensation is being studied.

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