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Outline of using an electron lens for the RHIC head-on beam-beam compensation (v 0.1)

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In this note, we outline the possible use of an electron lens for the RHIC head-on beam-beam interaction compensation and give the parameters of the proton beam and the electron lens.

1 Introduction

The correction of the beam-beam effect with magnets is in principle very difficult since the amplitude dependence of the generated forces is very different in magnets and beam-beam interactions [1]. In a collider the electro-magnetic field a beam exerts on a particle in the other beam may be compensated for by yet another beam of the opposite current. Such a scheme was implemented with two e^+ and two e^- beams at DCI, but the effects of nonlinear resonances and coherent beam-beam interactions still affected the beam lifetime [2, 3, 4, 5].

Efforts to compensate long-range beam-beam effects have lead to the installation of an electron lens (e-lens) in the Tevatron [6, 7], and a proposal for a wire in the LHC [8]. The so called e-lens is actually an electron beam. Here we investigate if a device like the Tevatron e-lens can be used to mitigate the head-on beam-beam effect in RHIC [9, 10]. This is intended to reduce the beam-beam tune spread and keep the particles away from main betatron and spin resonances.

To compensate the RHIC head-on beam-beam effects at IP6 and IP8, the electron beam of the e-lens should have equal transverse beta functions, since these are also the same at the IP6 and IP8. Such locations can be found in the interaction regions between the Q1 magnets on either side of the interaction point (IP).

With the two beam-beam interactions and an e-lens in a third locations, the beam-beam compensation cannot be perfect. Due to the phase advances between the locations, beam-beam driven resonance terms will not cancel. However, it is possible to compress the tune footprint, reduce the emittance growth rate, increase the collison lifetime, and even increase the bunch intensity. To estimate the benefits from the head-on beam-beam compensation with an e-lens, simulations have to be carried out. Parameter tolerances in the e-lens design also have to be addressed.

In the following, we outline the parameters of the proton beams and the parameters for the e-lens. They can be served as the starting point of further study although they are subject to change.

2 Lattice and beam parameters

Tab. 1 lists the optics and beam parameters for the proton beams in the following simulations. Fig. 1 gives the layout of the RHIC rings and beam-beam interaction points.

The proton beams collides only at IP6 and IP8. The beta functions at the IP6 and IP8 are chosen to be $\beta^* = 0.5$ m. The bunch intensity is chosen to be $N_p = 2.0 \times 10^{11}$. At this moment, the e-lens is located at IP12. The beta functions at IP12 are set to 20m. The beta functions at the other interactions points (IP2, IP4, IP10), are set to 10m. The beam normalized emittance to hold 95% of the proton particles is 15 mm.mrad. The collison energy is 250 GeV.

For the simulation studies, the lattice working point $(28.695, 29.685)$ is used. The linear chromaticities $Q'_{x,y}$ are set to $+1$. The multipole field errors in the triplet quadrupoles and separation dipole magnets in the interaction regions (IRs) have to be included in the simulation study since they greatly reduce the dynamic aperture at the store energy. At present, limited IR mulitpole error corrections can be applied in IR6 and IR8.

Table 1: RHIC parameters used in the simulations.

quantity	unit	value
lattice		
beam-beam collision points	-	IP6, IP8
envelop function at beam-beam collision points $\beta^*_{x,y}$	m	0.5
e-lens location	-	IP12
envelop function at e-lens location $\beta^e_{x,y}$	m	20
envelop function at all other IPs $\beta^*_{x,y}$	m	10
proton beam		
ring circumference	m	3833.8451
energy	GeV	250
relativistic γ	-	266
harmonic number	-	360
rf cavity voltage, accelerating system $h = 360$	kV	300
particles per bunch N_p	-	2×10^{11}
normalized transverse rms emittance $\epsilon_{x,y}$	mm mrad	2.5
transverse rms beam size at collision points $\sigma^*_{x,y}$	mm	0.068
transverse rms beam size at e-lens $\sigma^e_{x,y}$	mm	0.430
transverse tunes (Q_x, Q_y)	-	$(28.695, 29.685)$
chromaticities (ξ_x, ξ_y)	-	$(1, 1)$
beam-beam parameter per IP $\xi_{\mathrm{p}\to\mathrm{p}}$	-	-0.01

3 Beam-beam interaction and compensation

For the head-on proton-proton beam collisions, the transverse kicks a proton experiences from the electromagnetic field of the other bunch are

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

Here N_p is the number of protons in one proton bunch. r_0 is the classic proton radius, $r_0 = \frac{e^2}{4\pi\varepsilon_0 m_p c^2}$. γ is the proton particle's relativistic parameter, $\gamma = 266$ at 250GeV. r is the distance between the test proton particle and the center of the proton beam, $r = \sqrt{x^2 + y^2}$, x and y and the horizontal and vertical displacements of the test proton particle from the center of the bunch moving in the opposite direction. To get Eq. (1), we have assumed that the particle distribution of the proton bunch is 3-D Gaussian and $\sigma_{x,p} = \sigma_{y,p} = \sigma_p \ll \sigma_{s,p}$. The velocity of the proton particles in the proton bunch is the light velocity c.

In the e-lens, the proton bunch 'head-on' collides with the Gaussian electron beam. We assume that the transverse rms beam sizes of the electron beam are the same, that is, $\sigma_{x,e} = \sigma_{y,e} = \sigma_e$. The longitudinal distribution of the electron beam in the DC e-lens is uniform. The effective interaction length between a proton particle and the electron beam is L_{elens}. Similarly, we have the transverse kicks on one proton particle from the oppositely moving DC electron beam are

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

$\beta_e c$ is the speed of the electrons in the electron beam.

For the particles in the core of the proton bunch, $r \ll \sigma_p$ and $r \ll \sigma_e$. According to Eqs. (1) and (2), the incoherent linear beam-beam tune shifts from the beam-beam interaction and p-elens interaction are calculated,

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

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

In Eq. (4), we define the electron beam's emittance as $\varepsilon_e = \sigma_e^2/\beta_{elens}$. To get Eqs. (3) and (4), we have used $\beta^* = \beta^*_x = \beta^*_y$ at the beam-beam interaction points IP6 and IP8, and $\beta_{elens} = \beta_{x,elens} = \beta_{y,elens}$ in the e-lens.

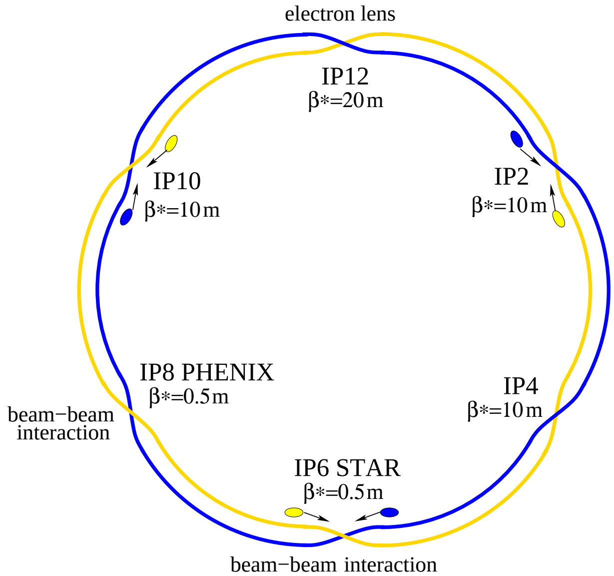

Figure 1: Layout for the simulation.

To fully compensate the incoherent linear beam-beam tune shifts with one e-lens, according Eqs. (3) and (4), we have

$$N_e = \frac{N_{IP} N_p}{1+\beta_e} \frac{\varepsilon_e}{\varepsilon_p}. \tag{5}$$

N_{IP} is the number of beam-beam interactions, for the RHIC, $N_{IP} = 2$. If we further assume $\varepsilon_e = \varepsilon_p$,

$$N_e = \frac{N_{IP} N_p}{1+\beta_e}. \tag{6}$$

To compensate the nonlinear effects from the beam-beam interactions, comparing Eqs. (1) and (2), the transverse beam sizes of the electron beam and the proton bunch should match. And proper betatron phase advances between the beam-beam interactions and the e-lens are required.

4 Parameters for the RHIC e-lens

To compensate the head-on beam-beam interactions for the two RHIC beams, two e-lenses are needed. At this moment, we place the two e-lenses at IP12. The two proton beams are separated vertically at IP12. The two e-lenses for the RHIC Blue and Yellow beams share the same beam pipe.

In the Tevatron e-lenses [13, 14, 15], the electron kinetic energy T_e ranges from 5 keV to 10 keV. For its normal operation, $T_e = 5$KeV. Therefore, in our calculation, the electron speed is chosen to be $\beta_e c = 0.14c$.

Substituting $N_{IP} = 2$ and $N_p = 2.0 \times 10^{11}$ into Eq. (6), we obtain the number of the electrons in the e-lens as $N_e = 3.5 \times 10^{11}$. Like the Tevatron e-lenses, we also choose the effective length of the RHIC e-lens as $L_{elens} = 2$m. The electron beam current in the e-lens is

$$I_e = \frac{eN_e}{L/(\beta_e c)} \simeq 1.2A. \tag{7}$$

The electron beam is assumed to be round and Gaussian. Assuming $\varepsilon_e = \varepsilon_p$, we then have

$$\sigma_e = \sqrt{\varepsilon_p * \beta_{elens}} = \sqrt{\frac{\varepsilon_{p,norm} * \beta_{elens}}{\gamma}}. \tag{8}$$

Substituting normalized proton emittance $\varepsilon_{p,norm} = 2.5$mm.mrad, $\gamma = 266$, and $\beta_{elens} = 20$m into Eq. (8), we have $\sigma_e = 0.433$mm.

Tab. 2 summarizes the nominal parameters for the RHIC e-lens. Fig. 2 shows a schematic plot of the Tevatron e-lenses I and II. The Tevatron e-lenses are used for gap cleaning and the tune shift compensation of 3 pacman bunches.

Table 2: Nominal RHIC e-lens parameters.

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

The parameters for the e-lens shown in Tab. 2 are for the full compensation of the incoherent linear beam-beam tune shift. For partial head-on beam-beam compensation or possible increase in the proton bunch intensity, the electron beam current for the e-lens should be adjusted accordingly. At this moment, with an effective e-lens length of $L_{elens} = 2$m, we require that the electron beam current can be continuously adjusted between 0 and $1.8A$.

The nominal transverse electron beam size is 0.43mm. However, if the beta function at the e-lens location is different from 20 m or the proton beam emittance changes, this number should be adjusted accordingly. Operationally we also require that the electron beam size is somewhat larger than the proton beam size. In the Tevatron e-lenses, SC solenoids are used to stabilize the electron beam. For the Tavatron e-lens II, the main solenoid field in the e-lens is about 6.5 Tesla.

5 Items to be studied

To check the benefits from the head-on beam-beam compensation with e-lens, detailed simulation studies have to be done. The preliminary simulation study shows that the e-lens will help to reduce the beam-beam tune spread. However, this benefit solely doesn't justify the use of an e-lens for the RHIC. With the e-lens on, the proton beam's lifetime, emittance growth rate, and the integrated luminosity have to be evaluated.

To check the short- and long-term stability of the proton motion, the tune diffusion, action diffusion, dynamic aperture, Laypunov component and resonance driving terms can be used. Single particle tracking codes like SixTrack [16] can be used for this study. To evaluate the particle loss and emittance growth of the proton beam with the e-lens on, multi-particle tracking codes like Lifetrack [17] have to be used. The coherent beam-beam effect and the Landau damping effect also have to be checked. For full head-on linear beam-beam tune shift compensation, the resulting tune spread may become too small and Landau damping may be lost.

The robustness of the head-on beam-beam compensation with the e-lens is another key point. The effects due to the variation in the proton bunch intensity and the fluctuation in the electron beam current have to be evaluated. Due to the abort gap there are super-pacman bunches, which have only one head-on collision. These may require special attention. The profile of the electron beam and the alignment of the proton and electron beams in the e-lens are crucial for head-non beam-beam compensation. The known 10 Hz orbit vibrations and the tune ripples have to be included into the simulations.

For the e-lens paramters, some margins have to be reserved. The electron beam current should be continuously adjustable from 0 to 1.8 A. The shape and transverse size of the electron beam have to be accurately controlled. The technique of centering the proton and the electron beams also has to be addressed.

By now, we place the two e-lenses at IP12 and separate the proton beams vertically by 10 mm, about 23 σ_p. Therefore, the two e-lenses for the Blue and Yellow beams share the same beam pipe. This arrangement is subject to change. For example, these two e-lenses may be placed at two different locations. By now, the beta function at the e-lens is chosen to be 20 m, which also is subject to change. Change of the beta function at the e-lens will result in the change in the transverse electron beam size. It is desired that the transverse size of the electron beam can be changed more or less.

6 Summary

RHIC head-on beam-beam compensation with an e-lens is proposed. In this note, the preliminary parameters for the proton beam and the e-lens are listed. Items to be studied, including the simulation and the design of the e-lens system, are outlined. This study may take about 1 year.

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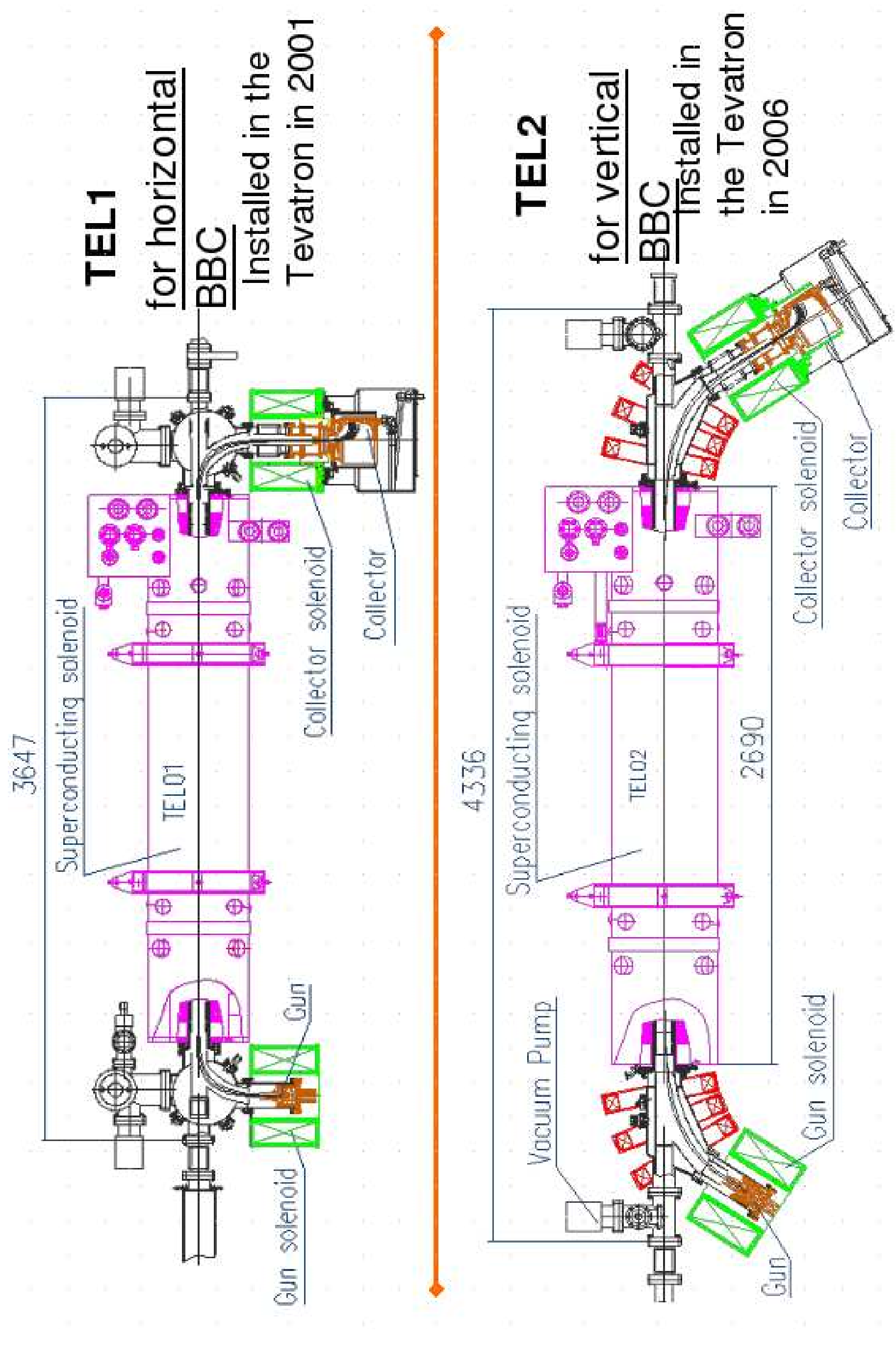

Figure 2: Layout for the Tevatron e-lens I and II.