THE EFFECTS OF THE RHIC E-LENSES MAGNETIC STRUCTURE LAYOUT ON THE PROTON BEAM TRAJECTORY*

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Abstract

We are designing two electron lenses (E-lens) to compensate for the large beam-beam tune spread from proton-proton interactions at IP6 and IP8 in the Relativistic Heavy Ion Collider (RHIC) [1]. They will be installed in RHIC IR10. First, the layout of these two E-lenses is introduced. Then the effects of e-lenses on proton beam are discussed. For example, the transverse fields of the e-lens bending solenoids and the fringe field of the main solenoids will shift the proton beam. For the effects of the e-lens on proton beam trajectory, we calculate the transverse kicks that the proton beam receives in the electron lens via Opera at first. Then, after incorporating the simplified E-lens lattice in the RHIC lattice, we obtain the closed orbit effect with the Simtrack Code [2].

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has operated for a decade. It has two rings in a horizontal plane with two head-on beam-beam interactions (IP6 and IP8) and four long-range beam-beam interactions.

The proton beam in the Blue ring circulates clockwise, while that in the Yellow ring circulates anti-clockwise. In long-range beam-beam interactions the beams are separated vertically by 10 mm. The current beam pipe at IP10 has a 65 mm radius.

Like in other colliders, the beam-beam interaction limits the luminosity of RHIC's polarized proton operation. To compensate for the large beam-beam tune spread due to head-on proton-proton interactions at IP6 and IP8 in RHIC, we are designing two e-lenses that we will install between the two DX dipoles at RHIC IR10. Here, we discuss the layout of these two E-lenses first.

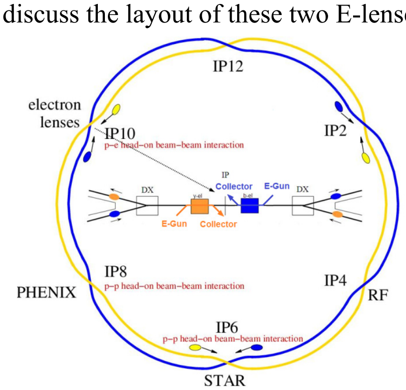

Figure 1: Layout of RHIC and of the E-lenses.

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Furthermore, to clarify the effects of such electron lenses on RHIC proton beam, we detail the layout of the RHIC lattice that includes the simplified e-lens lattice (Figure 1). Then, with this lattice in place, we evaluated, via the Simtrack code, the proton beam's closed orbit, its beta functions and tune change.

THE LAYOUT OF THE TWO ELECTRON LENSES

Each of RHIC's e-lenses has one DC electron gun, one main superconducting magnet, one electron collector, and a beam transport system. This beam transport system has six solenoids, from the gun side to the collector side, viz., GS1, GS2, GSB, CSB, CS2, and CS1. To avoid affecting the DC electron guns with an unwanted electromagnetic field, we placed two DC electron guns away from the IP, while the two collectors are located near the IP (Figure 1).

Furthermore, to compensate for head-on beam-beam collision, it is advantageous to have the direction of the electron beam must opposite to that of the proton beam. This means that when the e-lenses are operating, the blue (yellow) ring's proton beam must pass first through the yellow (blue) electron lenses. At this time, the blue (yellow) proton beam is being transported in the same direction as the yellow (blue) electron beam, but separated from it vertically by 10 mm. Then, the blue (yellow) proton beam continues, progressing through the blue (yellow) electron lens, so that its transport direction is opposite that of the blue (yellow) electron beam.

Also, due to the 10 mm vertical separation between the two proton beams, the electron beams must be separated similarly. Two layouts of the e-lens can meet this requirement. First, we can set the vertical center of the two electron lenses at the same vertical position (i.e., the centre of vacuum pipe, Y=0), and use steering magnets to move the electron beam either up by 5mm, or down by 5 mm. Or we can achieve the same outcome mechanically, offsetting one of the electron lenses by 5 mm up from Y=0, and the other 5 mm down. Then, the electron beam will interact head-on with the proton beam. The latter approach, the mechanical one, does not entail having magnets to move the electron beam 5 mm up and down, and so, it is easier to control.

Figure 2 illustrates the configuration of the magnetic structure of the two electron lenses with these constraints. The vertical layout in Figure 2 is shown with a scale that exaggerated the displacement. The electron beam in one electron lens interacts head-on only with one proton beam.

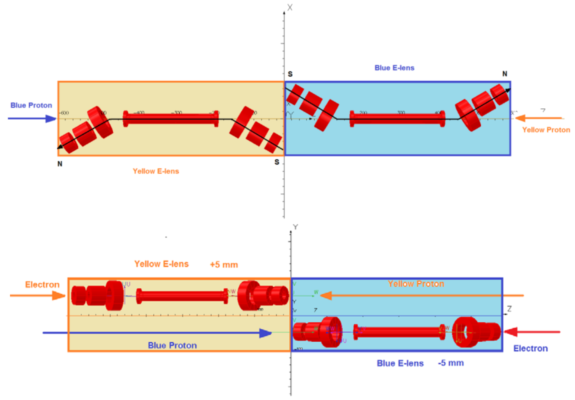

Figure 2: Layout of Two Electron Lenses. Top: top view, bottom: side view.

In addition to these constraints, the two lenses should have a different magnetic polarity (SN-NS or NS-SN) and therefore, locally compensate each other for both linear coupling and spin effects. Furthermore, the central line of the solenoids GSB_Y, CSB_Y, CSB_B, and GSB_B, located, respectively, at -490 cm, -145 cm, 145 cm, and 490 cm have a 30 degree angle to the directions of proton-beam transport. This configuration will induce dipole, quadrupole, and skew dipole and quadrupole components when the proton beam passes through the two e-lenses (Fig. 3).

The multipole magnetic field components in Fig. 3 generated by e-lens are analyzed and compared by Fourier fit method via Opera.

In cylindrical coordinates, we can express the radial and azimuthal components of magnetic field B in the form [3]:

$$B_r(r,\theta) = \sum_{n=1}^{\infty}(b_n \sin(n\theta) + a_n \cos(n\theta)) \quad (1)$$

$$B_\theta(r,\theta) = \sum_{n=1}^{\infty}(b_n \sin(n\theta) - a_n \cos(n\theta)) \quad (2)$$

Where b_n is the amplitudes of the $2n$ pole normal term and a_n is the amplitudes of $2n$ pole skew term in the "European Convention".

The multipole magnetic field, B_θ can be computed on a reference radius R_{ref} at different longitudinal positions and fitted as Fourier series. Then, according to formula (2), the coefficients of this Fourier series are the multipole magnetic field components. The reference radius R_{ref} = 75 mm.

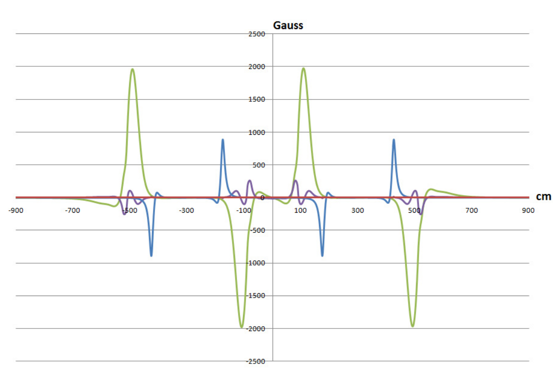

Figure 3: High-Order Magnetic Field Components.

SINGLE-PASS TRAJECTORIES OF THE PROTON BEAM TRACKED BY OPERA

The dipole component field of the two electron lenses can deflect the trajectories of protons. To verify this effect and find a method to correct it, we tracked, by Opera, the centroid of the blue proton beam as it passed through these two electron lenses.

In our simulation, the blue proton beam starts from -900 cm with eight different initial vertical angles; the horizontal angle is set to zero. The energy of the proton beam is 250 GeV, and the Lorentz factor is 266.

Figure 4 reveals that the blue proton beam has the same angle before and after the two electron lenses. However, within them, the blue proton beam is deflected. If its initial angle is about 100 µrad, the blue proton beams' trajectories within the two electron lenses can be set to be parallel to the Z-axis.

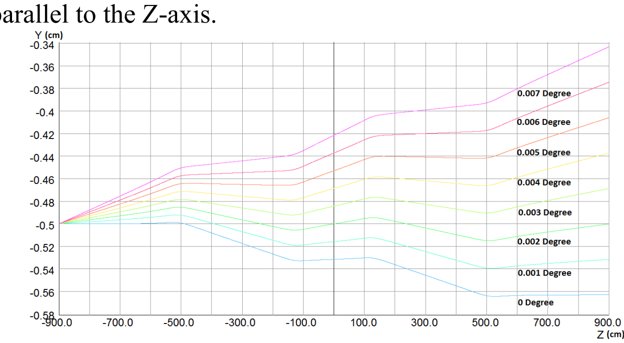

Figure 4: Proton Beam's Vertical Trajectories in Electron Lenses.

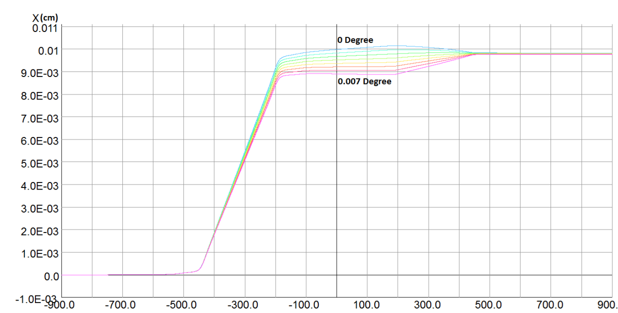

Figure 5: Proton Beam's Horizontal Trajectories in Electron Lenses.

Figure 5 plots the blue proton beam's horizontal trajectories. After passing through the two electron lenses, it exhibits a shift of about 0.01 cm in horizontal plane. In horizontal plane, because the blue proton beam passes first through the yellow 5 mm E-lens, it is deflected by the fringe field of the yellow E-lens by about 0.009 cm; this value is much greater than the change in the beam's position caused by the fringe field of the blue e-lens, which is less than 0.001 cm.

CLOSED ORBIT CALCULATION WITH SIMTRACK CODE

To include the e-lenses elements lattice in the RHIC lattice, these elements, such as the transverse field of GSB and the fringe field of the main solenoid, must be simplified and replaced by an element that can be used in some tracking codes, such as Simtrack.

By using the Simtrack code, we determined the entire ring's closed orbit with the RHIC lattice that encompasses the electron lenses' lattice: the results are shown in Figure 6 and Figure 7.

For the tracking, the 2011 Blue 250GeV polarized proton lattice was used. Its tune was set to (28.67, 29.675), and its chromaticity was set to (1.0, 1.0) without head-on beam-beam collisions at IP 6 and IP8. Because of this, the initial angle of the proton beam is set before it goes into the e-lens lattice, this is one reason that the proton beams have different shift between Opera and Simtrack code tracking.

Figure 6 and Figure 7 is the whole ring vertical and horizontal proton beam's closed orbit. The green lines in Figure 6 and Figure 7 are the closed orbits without the e-lenses' lattice, which have zero transverse offset. At IP10, which locates at 1278m, the vertical and horizontal proton beam's closed orbit changes 1.3 mm and 0.18 mm respectively.

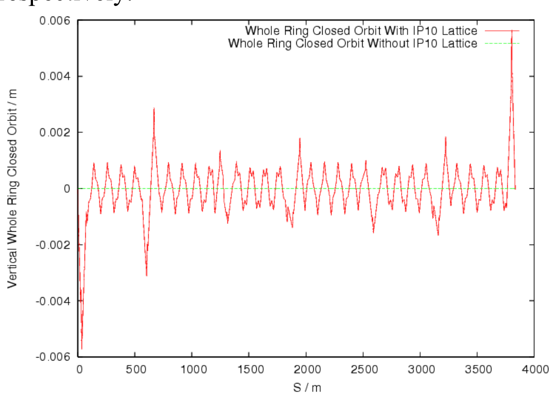

Figure 6: The Vertical Closed Orbit with (Red) and without (Green) the E-lens Lattice.

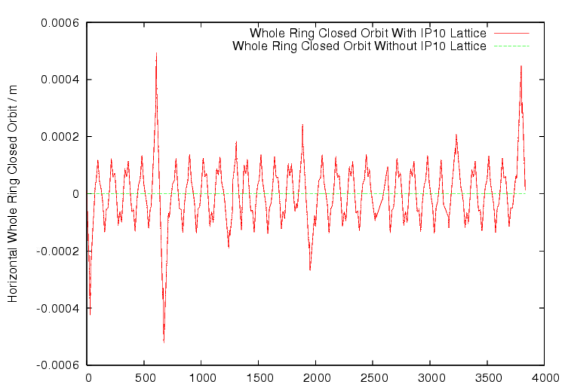

Figure 7: The Horizontal Closed Orbit with (Red) and without (Green) the E-lens Lattice.

Table 1 lists the parameters for the proton beam with and without Elens lattice. The horizontal tune changed 0.0001 and vertical tune changed 0.0003. Other parameters also have no big difference with and without Elens lattice.

Table 1: Proton Beam Parameters With and Without Elens.

	Without Elens Lattice		With Elens Lattice	
	X	Y	X	Y
Tune	28.6949	29.6849	28.6950	29.6846
Chrom1	0.88269	0.91706	0.81190	0.90590
Chrom2	1867.42	1977.68	1871.67	1962.08
Beta# (m)	0.7148	0.7080	0.7265	0.7109
Alpha#	-0.1445	-0.0410	-0.1911	0.0045

This is the twiss parameters at the starting point IP6.

DISCUSSION

In this paper, we discuss our design of the vertical- and horizontal-layout of two RHIC electron lenses.

Then, we simulated, with Opera, the single pass trajectories of the proton beam (centre of mass) in these two electron lenses. With about a 100-μrad initial vertical angle, the proton beam becomes parallel to the Z-axis that is, the axis of the electron beam. This gives us an approximate estimate angle which we need if we want to align proton beam to electron beam in RHIC lattice.

After that, an e-lens lattice is created without considering the higher order magnetic field, and misalignments of its elements. We tracked the closed orbit by the Simtrack code, with the 2011 blue 250-GeV polarized proton beam's lattice which includes the simplified e-lens lattice. The vertical proton beam's closed orbit changes 1.3 mm and horizontal is about 0.18mm. The horizontal and vertical tune changed 0.0001 and 0.0003 respectively. And these orbit and tune changes are easily correctable with the RHIC orbit and tune feedback system [4, 5].

These trackings and simulations give us a better understanding about the proton beam's behaviour inside the E-lens, and also afford some useful clues on the alignment between the proton beam and the electron beam when we apply head-on beam-beam compensation.

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