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compensation with realistic RHIC lattices***

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SIMULATION STUDY OF HEAD-ON BEAM-BEAM COMPENSATION WITH REALISTIC RHIC LATTICES*

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Abstract

To reduce the beam-beam resonance driving terms with half head-on beam-beam compensation in the RHIC polarized-proton operations, the betatron phase advances between the interaction point IP8 and the center of the electron lenses located around IP10 should be $k\pi$, where k is an integer. Realistic beam-beam compensation lattices meeting the phase advance requirements were developed and used in the beginning of 2013 polarized proton run, although head-on beam-beam compensation was not implemented yet. In this article, with these lattices and a 6-D weak-strong beam-beam simulation model, we calculate the proton dynamic apertures with and without beam-beam compensation. Preliminary results with second order chromaticity correction are also presented.

INTRODUCTION

To reduce the large beam-beam tune spread, head-on beam-beam compensation with electron lenses (e-lenses) is adopted for the RHIC polarized-proton (p-p) operation [1]. Figure 1 shows the layout of RHIC head-on beam-beam compensation. The proton bunches collide at IP6 and IP8. Two e-lenses are being installed on either side of IP10, one for the Blue ring and one for the Yellow ring.

To cancel the nonlinear beam-beam resonance driving terms (RDTs) from collision at IP8, we require the betatron phase advances between IP8 and the e-lens center to be $k\pi$, where k is an integer. The RHIC arc quadrupoles are currently on the same current circuits. For the phase adjustment purpose, we added two shunt power supplies to the arc main quadrupoles between IP8 and IP10.

One realistic lattice solution meeting the above phase requirements had been developed [2] and was used in the beginning of the 2013 polarized proton run. The real head-on beam-beam compensation was absent because both e-lenses were only partially installed [3]. We observed a poor beam lifetime at injection, and a low polarization transmission efficiency on the energy and rotator ramps [4]. The reason for lower polarization is under study. Later on these lattices were replaced with the lattices used in the previous p-p run. The lattices used in the previous run do not meet the phase advance requirements for head-on beam-beam compensation.

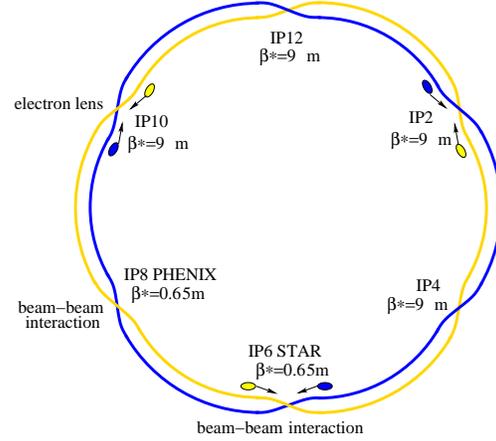


Figure 1: Layout of RHIC head-on beam-beam compensation. Proton beams collide at IP6 and IP8. E-lenses are located around IP10.

Table 1: Main parameters of standard and e-lens lattices.

Parameter	E-lens Lattices	Standard Lattice
Blue ring:		
Integer tunes	(27, 29)	(28, 29)
$\xi_{x,y}^{(2)}$	(-1950, -1870)	(2420, 4520)
$\Delta\Phi_{x,y} _{IP6 \rightarrow IP8}$	(10.4 π , 8.4 π)	(10.7 π , 8.7 π)
$\Delta\Phi_{x,y} _{IP8 \rightarrow elens}$	(8 π , 11 π)	(8.3 π , 10.8 π)
Yellow ring:		
Tunes	(29, 30)	(28, 29)
$\xi_{x,y}^{(2)}$	(2900, -4160)	(-5720, -1140)
$\Delta\Phi_{x,y} _{IP6 \rightarrow IP8}$	(8.6 π , 11.3 π)	(8.3 π , 11.0 π)
$\Delta\Phi_{x,y} _{IP8 \rightarrow elens}$	(11 π , 9 π)	(10.7 π , 9.0 π)

LATTICE PARAMETERS

For simplicity, we name these newly developed lattices with $k\pi$ phase advances between IP8 and the center of e-lenses as e-lens lattices, and the lattices used in the previous p-p runs as standard lattices. Table 1 shows the main parameters of both lattices.

Different integer tunes other than (28, 29) of the standard lattices were chosen for the e-lens lattices to reduce the phase advance differences between arcs. For the current e-lens lattice solution, the integer tunes are (27, 29) for the Blue ring and (29, 30) for the Yellow ring. The betatron phase advances between IP8 and the center of the e-lenses are (8 π , 11 π) in the Blue ring and (11 π , 9 π) in the Yellow ring.

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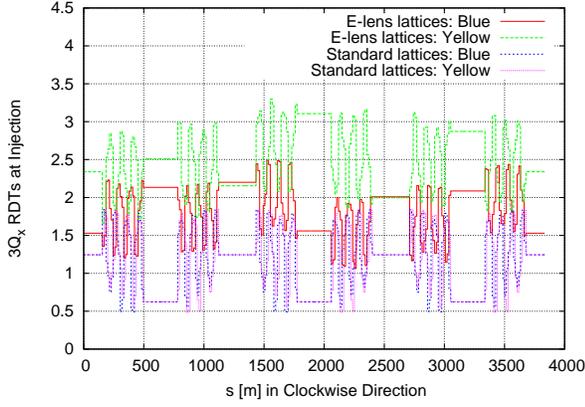


Figure 2: $3Q_x$ RDTs of e-lens at injection, compared with the standard lattices.

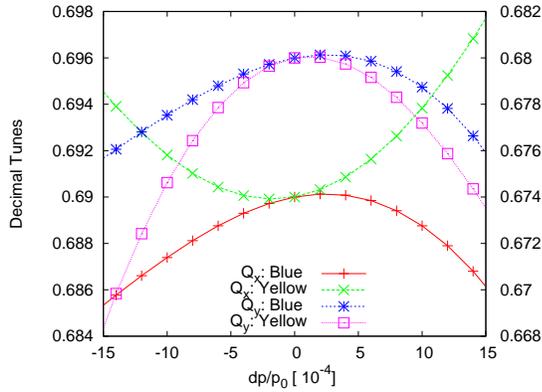


Figure 3: Off-momentum tunes with the e-lens lattices.

In the RHIC p-p runs, we normally keep the vertical fractional tune lower than the horizontal fractional tune on the energy and rotator ramps to maintain the proton polarization. Experiments show that a lower vertical tune yields better polarization transmission efficiency on ramps [5].

For example, Figure 2 shows the horizontal third order resonance RDTs of the e-lens lattices at injection, compared with the standard lattices. Here we only take into account the contributions from arc sextupoles. The e-lens lattices give larger $3Q_x$ RDTs than the standard lattices. With the e-lens lattices in the 2013 p-p run, we had to inject beams with higher tunes close to $Q_y = 0.7$ which is a depolarization resonance. On the ramps, it was also hard to push the vertical tunes close to $Q_y = 2/3$ without losing beam intensity.

Figure 3 shows the off-momentum tunes of the e-lens lattices. For the Yellow ring e-lens lattice, the vertical second order chromaticity is -4200 . Therefore, the vertical tunes of off-momentum particles may be pushed onto the vertical third order resonance $Q_y = 2/3$ when we place the on-momentum vertical tune close to $2/3$ on ramps. At store, large second order nonlinear chromaticities reduce the off-momentum dynamic aperture. With the e-lens lattices in the 2013 p-p run, we observed much worse beam

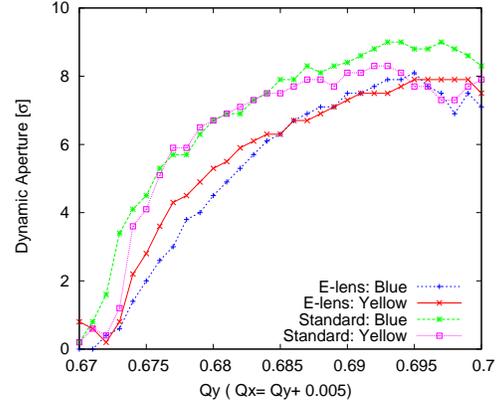


Figure 4: Dynamic aperture without beam-beam.

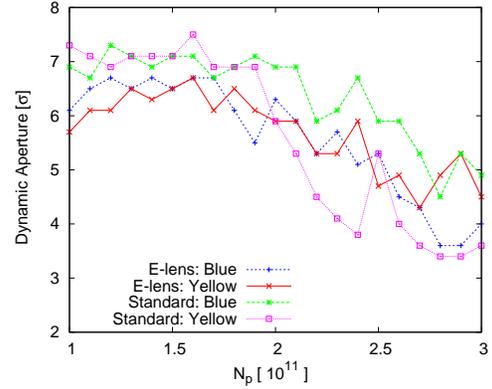


Figure 5: Dynamic aperture with beam-beam interaction. The zero amplitude tunes are set to $(0.68, 0.67)$.

lifetime at store in the Yellow ring than in the Blue ring.

DYNAMIC APERTURE CALCULATION

In this section we will calculate and compare the proton dynamic apertures under different beam-beam conditions. With a 6-D weak-strong beam-beam model [6], we track test particles element-by-element for up to 10^6 turns. We focus on the minimum aperture from 10 equally separated directions in the first quadrant of phase space $(x/\sigma_x, y/\sigma_y)$. The initial $\Delta p/p_0$ of particles is 5.5×10^{-3} , which is 3 times the rms relative momentum deviation. As in operations, we use 360 kV 28 MHz and 300 kV 197 MHz RF cavities in simulation. The 95% normalized transverse emittance is 15π mm mrad. The dynamic aperture is given in units of rms transverse beam size σ .

Figure 4 shows the dynamic apertures without beam-beam interaction in a tune scan along the diagonal in the tune space. The horizontal axis is the vertical fractional tune. The horizontal fractional tune is always 0.005 higher than the vertical one. From Figure 4, the dynamic apertures without beam-beam for the e-lenses are about 1σ smaller than the standard lattices. The reason may be related to the amplitudes of the third order resonance RDTs.

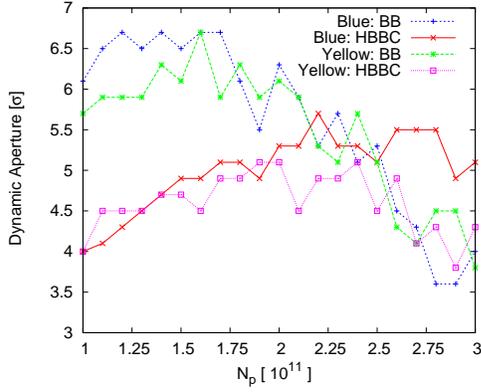


Figure 6: Dynamic aperture with half head-on beam-beam compensation.

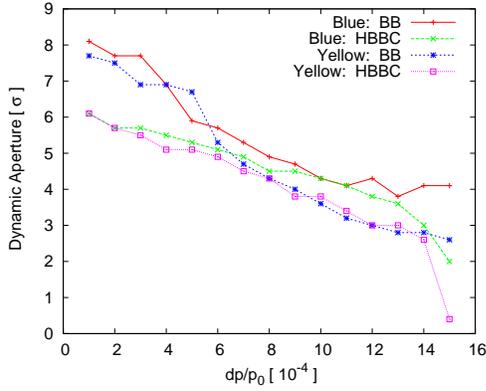


Figure 7: Off-momentum dynamic apertures for e-lens lattices.

Figure 5 shows the proton dynamic aperture with beam-beam interactions at IP6 and IP8 versus the proton bunch intensity. In this study, we always keep the zero amplitude tunes to (0.68, 0.67) for all bunch intensities. The proton bunch intensity varies from 1.0×10^{11} to 3.0×10^{11} , which corresponds to a beam-beam parameter from 0.01 to 0.03. From Figure 5, the dynamic apertures begin to drop when the bunch intensity exceeds 2.0×10^{11} for all shown cases. It confirms that there is not enough tune space between 2/3 and 7/10 to accommodate the large beam-beam tune spread when the proton bunch intensity is bigger than 2.0×10^{11} . Below 2.0×10^{11} , the e-lens lattices give smaller dynamic apertures than the standard lattices.

Figure 6 shows the dynamic apertures with half head-on beam-beam compensation (HBBC). HBBC compensates half of the total beam-beam parameter from two collisions. With HBBC, there is no clear improvement in the dynamic aperture, except in the Blue ring when the bunch intensity is bigger than 2.5×10^{11} .

In the above dynamic aperture calculation, the initial relative off-momentum deviation is set to $\Delta p/p_0 = 5.5 \times 10^{-4}$. Figure 7 shows the off-momentum dynamic apertures versus the momentum error for the e-lens lattices.

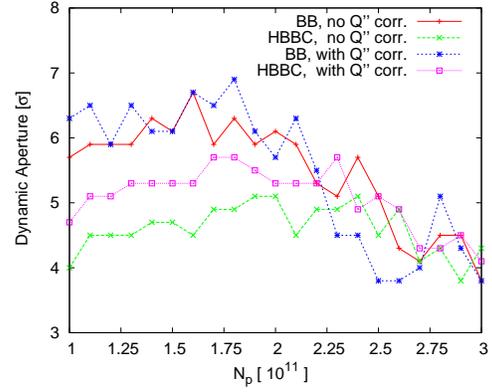


Figure 8: Yellow ring dynamic aperture with second order chromaticity correction on top of half head-on beam-beam compensation.

For all cases shown, the off-momentum dynamic aperture drops with the increase of momentum error. Only with beam-beam, the dynamic aperture in the Yellow ring is 1σ smaller than the Blue ring when $\Delta p/p_0$ is larger than 6.0×10^{-4} .

Next we calculate the effects of second order chromaticity correction. With second order chromaticity correction, there is not much improvement in dynamic aperture for the Blue ring. Figure 8 shows the dynamic aperture in the Yellow ring with correction. The correction strengths are calculated using the HARMON module of MAD8. There is some improvement in the dynamic aperture with HBBC when proton bunch intensity is below 2.5×10^{11} .

SUMMARY

In this article we calculated the dynamic apertures with the realistic e-lens lattices. Simulation results show that the e-lens lattices give smaller dynamic aperture with beam-beam than the lattices used in previous proton runs. With half head-on beam-beam compensation, improvement in dynamic aperture is only seen in the Blue ring when bunch intensity is bigger than 2.5×10^{11} . In the future lattice design for head-on beam-beam compensation, besides the phase advance requirement, we also need to minimize the nonlinear chromaticities and third order resonance driving terms to improve the dynamic aperture.

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