DYNAMIC APERTURE MAXIMIZATION WITH HEAD-ON BEAM-BEAM COMPENSATION IN RHIC*

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Abstract

To reduce the large beam-beam tune spread and to compensate the beam-beam non-linear resonance driving terms, two electron lenses are being installed in the RHIC tunnel for head-on beam-beam compensation. In this article we discuss the approaches to maximize the proton dynamic aperture by adjusting the phase advances between beam-beam interaction points and the electron lenses. We present the beam-beam compensation lattice design, dynamic aperture calculation results, and comparisons between the lattices used in the previous RHIC proton operation.

INTRODUCTION

The working point in the polarized proton collision operation in the Relativistic Heavy Ion Collider (RHIC) is constrained between 2/3 and 7/10 to achieve a good beam lifetime with beam-beam interaction and to preserve the proton polarization on the energy acceleration and at the physics store. To further improve the luminosity, with an upgraded polarized proton source, the proton bunch intensity will be increased from currently 1.8×10^{11} up to 3.0×10^{11}. However, with such a high bunch intensity, there is not enough tune space between 2/3 and 7/10 to accommodate the large beam-beam tune spread.

To reduce the large beam-beam tune spread and compensate the large beam-beam resonance driving terms (RDTs), head-on beam-beam compensation with electron lenses (e-lenses) is adopted in RHIC [1]. Figure 1 shows the layout of RHIC head-on beam-beam compensation. The two proton beams 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 non-linear beam-beam 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.

For the next 100 GeV polarized proton run, we will commission head-on beam-beam compensation for the first time in RHIC. To best utilize head-on beam-beam compensation and to maximize the proton dynamic aperture, we redesigned the proton lattices for both RHIC rings. On top of the above $k\pi$ phase advances between IP8 and the e-lenses, we also attempt to maximize the off-momentum dynamic aperture by adjusting the phase advances between the two collisional IP6 and IP8. In the following, we first discuss

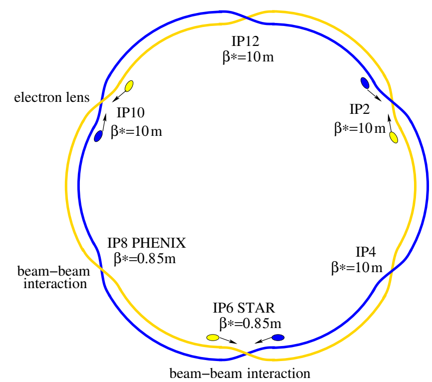

Figure 1: Layout of RHIC head-on beam-beam compensation. Proton beams collide at IP6 and IP8. E-lenses are located on both sides of IP10.

the phase requirements for head-on beam-beam compensation, then present the newly designed lattices and the calculated proton dynamic apertures compared with the previous RHIC proton operation lattices.

PHASE ADVANCE CONSIDERATIONS

For head-on beam-beam compensation in the proton operation in RHIC, simulation results show that full compensation gives a lower dynamic aperture than that with half beam-beam compensation. With half beam-beam comnpensation, if the phase advances between IP8 and the center of e-lenses is $k\pi$, k being an integer, the non-linear beam-beam RDTs from beam-beam interaction at IP8 will be exactly compensated by the e-lens at IP10 to the first order. For this purpose, we added two shunt power supplies to the main quadrupoles in the arc between IP8 and IP10.

In the previous proton runs, we observed that the particle loss at store took place in the transverse plane with beam-beam interaction. The proton loss rate was found to be proportional to the particle leakage rate from the proton bunch center to the tail. Since the particles in the bunch tail have bigger momentum errors, we concluded that the proton loss at store was caused by the low off-momentum dynamic aperture [2]. To improve it, we need to compensate the chromatic effects and compensate the higher order chromaticities.

In the early studies, we identified that the non-linear chromaticities for the RHIC proton lattices are mainly contributed by the triplet quadrupoles in the two interaction regions IR6 and IR8 where βs are much bigger than other non-collisional interaction regions [3]. From the

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Table 1: Optics Parameters of E-lens and Standard Lattices.

Parameter	E-lens Lattices	Standard Lattice
Blue ring:		
Integer tunes	(27, 29)	(28, 29)
$\xi^{(2)}_{x,y}$	(167,-324)	(-1894, 213)
$\Delta\Phi_{x,y}\|_{\mathrm{IP6}->\mathrm{IP8}}$	$(10.5\pi, 8.5\pi)$	$(10.9\pi, 8.5\pi)$
$\Delta\Phi_{x,y}\|_{\mathrm{IP8}->\mathrm{elens}}$	$(8\pi,11\pi)$	$(8.4\pi,10.1\pi)$
Yellow ring:		
Tunes	(27,28)	(28, 29)
$\xi^{(2)}_{x,y}$	(-119,-60)	(-4160,-1045)
$\Delta\Phi_{x,y}\|_{\mathrm{IP6}->\mathrm{IP8}}$	$(7.5\pi, 11.5\pi)$	$(8.3\pi, 11.0\pi)$
$\Delta\Phi_{x,y}\|_{\mathrm{IP8}->\mathrm{elens}}$	$(11\pi,9\pi)$	$(10.7\pi,8.8\pi)$

perturbation theory, the second order contributions from quadrupoles are mostly determined by the first order off-momentum β-beat $d\beta/d\delta$, $\delta = dp/p_0$. Therefore, for the asymmetric optics at IP6 and IP8 in RHIC, we can minimize $d\beta/d\delta$ at the triplet quadrupoles by adjusting the phase advances between IP6 and IP8 to be $(p+1/2)\pi$, with p an integer [4].

OPTICS DESIGN

For the next RHIC proton run, the particle energy will be 100 GeV. According to the operational experiences in the previous RHIC 100 GeV proton runs, to obtain acceptable store beam lifetime, we choose $\beta^* = 0.85$ m, the same as in the 2012 100 GeV proton run. The luminosity gain will mainly come from the increased proton bunch intensity. With half beam-beam compensation with e-lenses, we expect that the maximum proton bunch intensity at store exceeds 2.5×10^{11}.

Table 1 shows the main optics parameters for the new lattice design for beam-beam compensation, together with the lattices used in the previous RHIC proton runs. For simplicity, we name the previous RHIC run lattices "standard lattices" and the newly designed lattices for beam-beam compensation "e-lens lattices". From Table 1, the e-lens lattices meet all above phase advance requirements: $k\pi$ between IP8 and e-lens and $(p+1/2)\pi$ between IP6 and IP8.

As an example, Figure 2 shows the fractional vertical tunes versus dp/p_0 for the e-lens lattices and the standard lattices. With the phase advances between IP6 and IP8 being $(p+1/2)\pi$, the second order chromacticities are largely reduced. Figure 3 shows the RDTs of $3Q_x$ along the ring. Large $3Q_x$ RDTs affect negatively the beam lifetime at injection and cause beam loss and emittance growth on the energy and rotator ramps. From Figure 3, for the e-lens lattices, the RDTs of $3Q_x$ in the Yellow ring are bigger than that from the Blue ring. To meet these phase advance requirements, the e-lens lattices reduce the arc FODO cell's phase advances from optimum 90° to 74° and generate extra β and dispersion beats between IP8 and IP10 with shunt qudrupole power supplies between them.

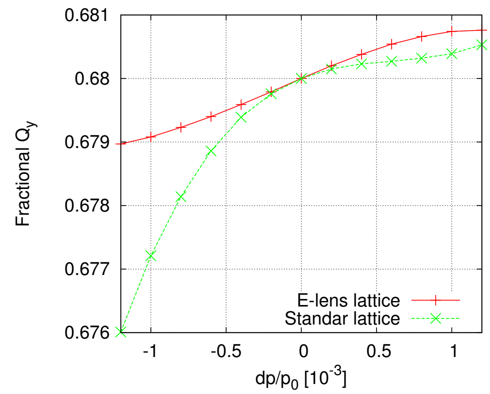

Figure 2: Yellow vertical tunes versus dp/p_0. Phase advances $(p+1/2)\pi$ between IP6 and IP8 reduce $\xi^{(2)}_{x,y}$. The Yellow vertical plane shows the largest nonlinear chromaticity in the standard lattice (Table 1).

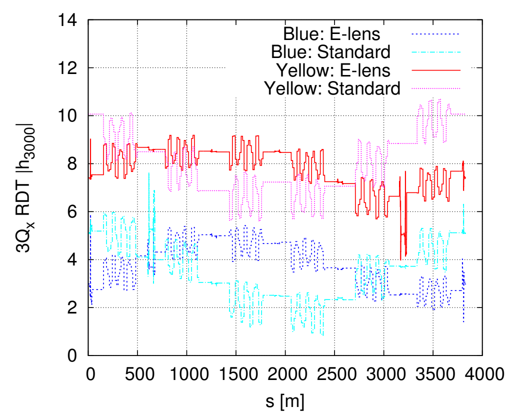

Figure 3: RDTs of the $3Q_x$ resonance for e-lens and standard lattices. $3Q_x$ RDTs are bigger in Yellow than Blue rings.

DYNAMIC APERTURE CALCULATIONS

Figure 4 shows the proton dynamic aperture without beam-beam interaction at store energy. The zero-amplitude tunes are scanned along the diagonal in the tune space. In this study, the vertical tune is always lower than the horizontal tune by 0.01. The Blue e-lens lattice gives a bigger dynamic aperture than the Yellow e-lens lattice when the tunes are close to 2/3. The Yellow standard lattice gives the lowest dynamic aperture in the scan, which is due to its large $3Q_x$ RDT and negative vertical second order chromaticity.

Figure 5 shows the dynamic aperture with beam-beam interaction at IP6 and IP8. The zero-amplitude tunes are (0.68,0.67). The dynamic aperture for the e-lens lattices are above 5 σ when the proton bunch intensity is below 2×10^{11}. The Yellow e-lens lattice gives a larger dynamic aperture than the standard Yellow lattice. The dynamic aperture begins to drop for all cases when the proton bunch intensity is above 2×10^{11}, which justifies head-

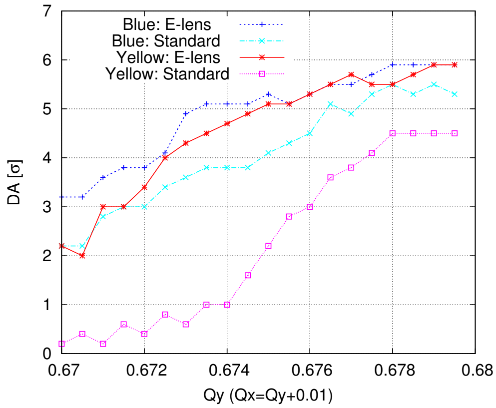

Figure 4: Dynamic aperture without beam-beam interaction at store. The initial $dp/p_0 = 12.5 \times 10^{-4}$.

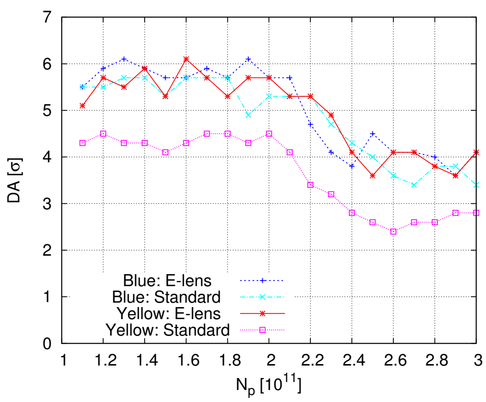

Figure 5: Dynamic aperture with beam-beam interaction at store. The zero-amplitude tunes are (0.68,0.67).

on beam-beam compensation for proton bunch intensities above 2×10^{11}.

Figure 6 shows the dynamic apertures with half head-on beam-beam compensation (HBBC). With HBBC the e-lens lattices give a bigger dynamic aperture than the standard lattices. For the Blue e-lens lattice the dynamic aperture is about 5 σ for all bunch intensities. While for the Yellow e-lens lattice, it is above 4.5σ for bunch intensities between 2.0-3.0$\times 10^{11}$.

The Yellow e-lens lattice gives a lower dynamic aperture than the Blue e-lens lattice when bunch intensities are below 2×10^{11}. One possible reason is the large Yellow $3Q_x$ RDT. Here we correct all the first order sextupole resonance driving terms with 12 sextupole families. The focusing or defocusing sextupoles in each arc are grouped into one family. With correction, the $3Q_x$ RDT is reduced by more than half and the second order chromaticties are still below 400. Figure 7 shows the dynamic apertures with the sextupole first order RDT correction. The dynamic aperture of HBBC with correction improves slightly but is still low when the proton bunch intensity is below 2.0$\times 10^{11}$.

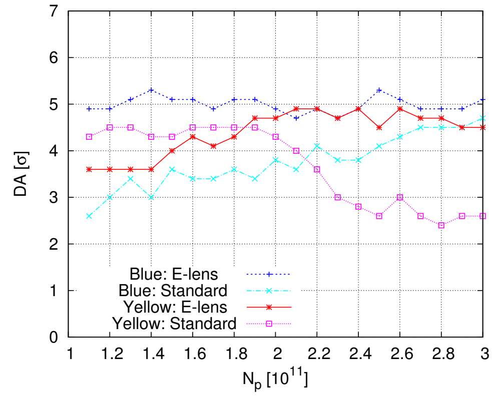

Figure 6: Dynamic aperture with half beam-beam compensation at store.

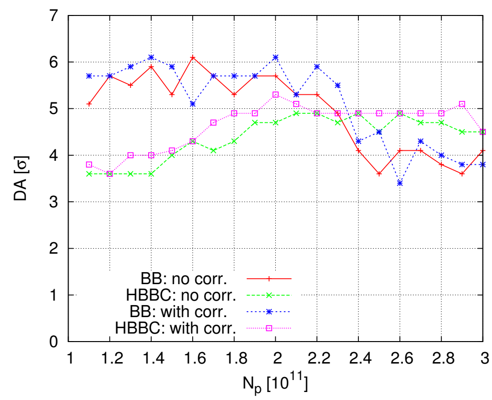

Figure 7: Dynamic aperture for the Yellow e-lens lattice with $3Q_x$ correction.

SUMMARY

We re-designed lattices for the head-on beam-beam compensation with e-lenses in RHIC. Phase advances between IP8 and the e-lenses are set to $k\pi$ to compensate non-linear beam-beam RDTs and the phase advances between IP6 and IP8 are set to $(p + 1/2)\pi$ to reduce the second order chromaticities. Dynamic aperture calculations show that the dynamic aperture is improved with e-lens lattices without and with beam-beam compensation, compared to the previous RHIC proton run lattices.

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