

BEAM-BEAM SIMULATION FOR THE 2015 RHIC PROTON RUN WITH ELECTRON LENSES*

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Abstract

Electron lenses had been used for head-on beam-beam compensation for the first time in the 2015 Relativistic Heavy Ion Collider (RHIC) 100 GeV polarized proton run. To improve the off-momentum dynamic aperture with beam-beam interaction, lattices with the achromatic telescopic squeezing (ATS) scheme of beta* are adopted. The phase advances between the electron lenses and one of the two collision points IP8 are set to $k\pi$ to minimize the non-linear beam-beam resonance driving term. In this article, we present the calculated dynamic apertures and tune spectrum from weak-strong beam-beam simulations with head-on beam-beam compensations with these lattices. Simulations are also carried out aiming to understand and explain some observations from this run.

LATTICES AND OPTICS PARAMETERS

To reduce the large beam-beam tune spread in the current proton tune space between $2/3$ and $7/10$, two electron lenses had been installed in the Relativistic Heavy Ion Collider (RHIC) for head-on beam-beam compensation [1]. Electron lenses are located on either side of the interaction point IP10, one for each ring. Previous simulations [2] show that half head-on beam-beam gives a larger dynamic aperture than full compensation. Simulations also show that for half beam-beam compensation, a betatron phase advance of $k\pi$, k is an integer, between the center of the electron lens and one of the beam-beam interaction point IP8 will increase the dynamic aperture because it minimized the beam-beam induced resonance driving terms.

The major beam loss in the previous RHIC proton runs was due to a limited off-momentum dynamic aperture [3]. To compensate the second order chromaticities, the achromatic-telescopic-squeezing (ATS) scheme is adopted for the 2015 100 GeV proton run [4]. FODO cells with $\pi/2$ phase advances are used in the arcs. The betatron phase advances between the first sextupoles to the first triplet quadrupoles are matched to be π . The betatron phase advances between IP6 and IP8 are $(2k + 1)\pi$. The quadrupoles in IR10 and IR4 are used to launch a β -wave to simultaneously squeeze β^* s at IP6 and IP8. There is a little difference between the original lattice designs described in Ref.[4] and the ones actually used in the 2015 operation due to a few power supply current limits.

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DYNAMIC APERTURE CALCULATION

In the dynamic aperture calculation, particles are launched in 10 equal distance phase angles in the first quadrant of $(x/\sigma_x, y/\sigma_y)$ space. The particles are tracked element-by-element up to 10^6 turns along the ring with a 4-th order symplectic integration. For the beam-beam interaction, a 6-d symplectic weak-strong model is used. The electron lens is split into 8 slices and each one is modeled as drift - 4-d beam-beam kick - drift.

First we calculate and compare the dynamic apertures without beam-beam interaction for the 2015 and 2012 run lattices. Figure 1 shows the dynamic apertures in a tune scan along the diagonal in the tune space toward the third order resonances at $(2/3, 2/3)$. The normalized rms emittance is $2.5 \mu\text{m}$. The horizontal axis is the vertical fractional tune and the horizontal tune is always 0.005 above the vertical one. The initial dp/p_0 for the test protons are 12.5×10^{-4} . From the plot, the 2015 Yellow lattice gives a higher dynamic aperture than the 2012 run Yellow lattice, while the 2015 Blue lattice gives a slight lower dynamic aperture than the 2012 Blue lattice when the working point is very close to the third order resonances.

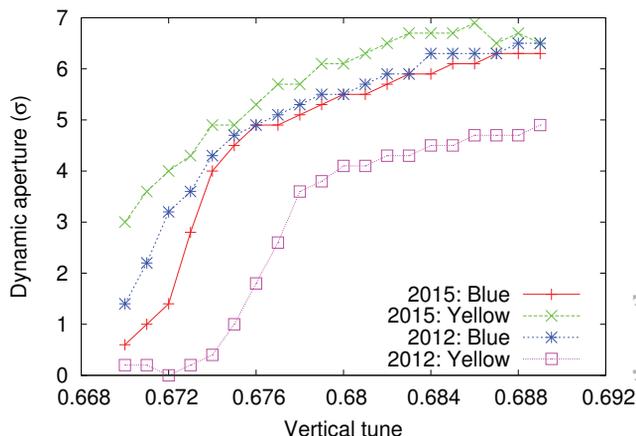


Figure 1: Dynamic aperture without beam-beam interaction as a function of tunes.

Next we calculate the dynamic apertures with beam-beam interaction and with half head-on beam-beam compensation. Figure 2 shows the results. We scanned the proton bunch intensity from 1.0×10^{11} to 3.0×10^{11} . For a fair comparison, we fixed the tunes of the bunch center to $(0.675, 0.67)$ for all cases. From the plot, the dynamic aperture with beam-beam interaction drops when the proton bunch intensity is higher than 2.2×10^{11} for the Blue ring and 1.8×10^{11} for the Yellow ring. The reason is that

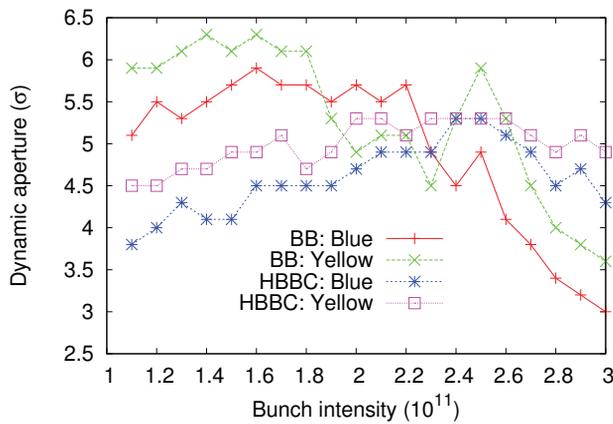


Figure 2: Dynamic aperture with beam-beam interactions and half beam-beam compensation versus bunch intensity.

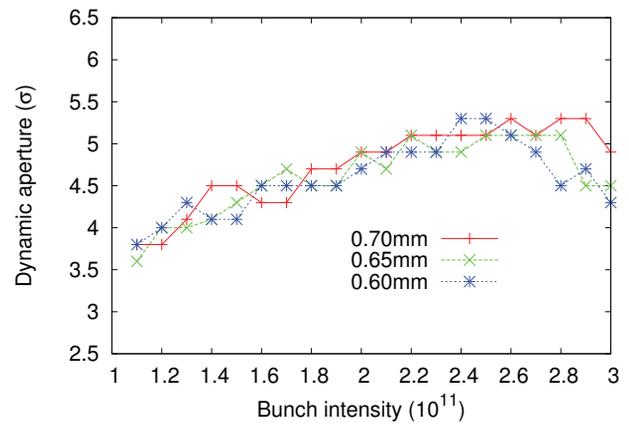


Figure 4: Dynamic aperture with half beam-beam compensation versus different electron beam sizes.

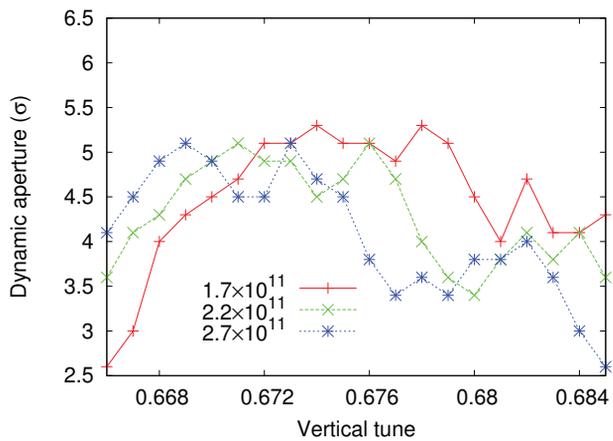


Figure 3: Dynamic aperture with half beam-beam compensation versus the tune settings.

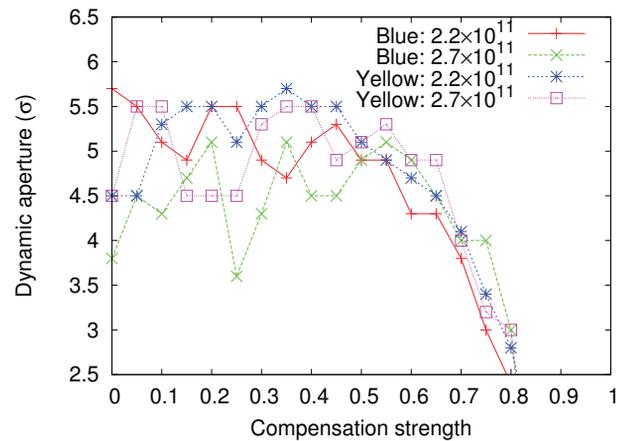


Figure 5: Dynamic aperture versus beam-beam compensation strength.

there is not enough tune space to hold the large beam-beam tune spread. In the last 2012 100 GeV proton run, the maximum proton bunch intensity in the routine physics operation was 1.7×10^{11} . In the 2015 run, it reached 2.2×10^{11} .

Figure 2 also shows the dynamic apertures with half head-on beam-beam compensation. When the bunch intensity is higher than 2.2×10^{11} , the dynamic apertures with half beam-beam compensation are higher than that without compensation for both rings. At low proton bunch intensities, the dynamic apertures with compensation are lower than that without compensation. The reason is that the tune footprint with compensation is smaller and is placed too close to the third resonances. However, as shown in Ref.[4], with a good third order resonance correction, a flat dynamic aperture with head-on beam-beam compensation could be achieved in the shown range of proton bunch intensity.

In the 2015 proton run, we found the beam lifetime with beam-beam compensation was very sensitive to the lattice set tunes. Figure 3 shows the dynamic aperture

with half beam-beam compensation versus the vertical tune of the bunch center. Again the horizontal tune is always 0.005 higher than the vertical one. Three bunch intensities are used. For each bunch intensity, the dynamic aperture drops if the vertical tune is either too low or too high. For a higher bunch intensity, the preferable tunes for a good dynamic aperture is lower. In the operation, we used a non-destructive Schottky tune meter to track the tunes. To maintain a good beam lifetime, the vertical tune measured from Schottky meter should be placed between 0.680-0.683. Higher than 0.683, we observed a worse beam lifetime. Lower than 0.680, we observed a faster emittance growth.

In the 2015 operation, we used different electron sizes. Figure 4 shows the dynamic apertures with different electron beam sizes measured at the center of electron lenses. The horizontal axis is the proton bunch intensity. For half beam-beam compensation, there is a very little difference in the dynamic apertures with these three rms electron beam sizes 0.70 mm, 0.65 mm, and 0.60 mm. The matched electron beam size to the proton bunch is 0.60 mm. From

the previous simulation study [2], the electron beam size with 20% larger than the proton bunch will yield a higher proton dynamic aperture.

Figure 5 shows the dynamic aperture as a function of the compensation strength. From it, over-compensation more than half will reduce the proton dynamic aperture. In the 2015 proton operation, the electron lens were turned on in the first 1 hour at store. The maximum beam-beam parameter we achieved is 0.022, which is 50% larger than the 2012 proton run. In the routine physics operation, we only compensated a quarter of the total beam-beam parameter. Higher compensation strengths were tested with higher bunch intensities during the beam experiments. However, it turned out that a larger compensation strength was not necessary due to the limited brightness of the proton bunch from injectors [1].

TUNE SPECTRUM CALCULATION

The tune spread can be indirectly determined with beam transfer function measurement with a phase-lock loop tune meter in RHIC [1]. In the beam experiments, we measured the tune spreads of the proton beam: 1) only with 1 electron-proton collision, 2) with 2 proton-proton collisions, and 3) with 2 proton-proton collisions and 1 electron-proton interaction. For case 1, the measured tune spreads agreed very well with their expectations. However, for cases 2 and 3, the beam transfer function measurements are dominated by the coherent beam-beam modes and the tune spreads can not be simply obtained.

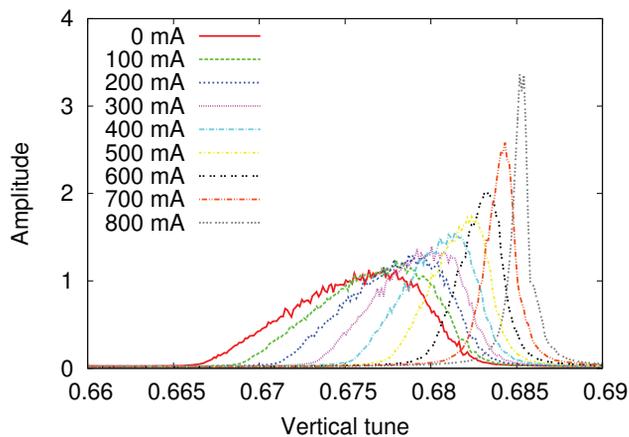


Figure 6: Simulated vertical proton tune spectrum in the 2015 proton run with different electron lens currents.

Figure 6 shows the numerically calculated vertical tune spectrum with different electron lens currents with the beam parameters from the 2015 proton run. In the simulation, we launch 1 million macro-particles to represent a proton bunch. By tracking them 10×8192 turns, we obtained an averaged proton tune spectrum with fast Fourier transformation. For Figure 6, the proton bunch intensity is 1.8×10^{11} and the lattice tunes are fixed at (0.695, 0.685).

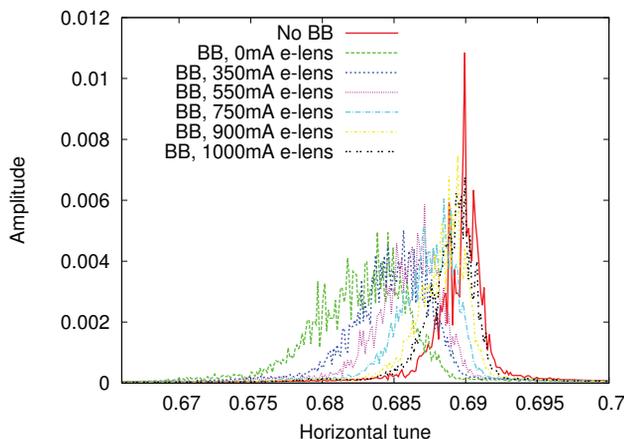


Figure 7: Simulated horizontal proton tune spectrum in the 2015 p-Al run with different electron lens currents.

700 mA electron current is equivalent to half beam-beam compensation. From the plot, with the increase in the electron beam current, the proton tune footprint is moved up and the tune spread is reduced.

In the following 2015 proton-aluminum operation, where the coherent beam-beam modes are absent, we successfully extracted the tune spread with beam-beam interaction and beam-beam compensation from the beam transfer function measurements [1]. The data shows that the tune spread can only be reduced up to that without beam-beam interaction. Figure 7 shows the simulated tune spectrum with different electron lens currents with the beam parameters in the 2015 proton-aluminum run. Simulation results show that the electron lens can not reduce the tune spread from the nonlinear lattice, although it is able to minimize the beam-beam tune spread.

SUMMARY

In the article, based on a 6-D weak-strong beam-beam interaction model, we calculated and compared the dynamic apertures without and with head-on beam-beam compensations with the 2015 RHIC 100 GeV proton run lattices. Parameters of proton bunch and electron beam from the electron lenses are varied. Tune spreads with different beam-beam compensation strengths are simulated. The simulation explained or reproduced some of operational observations and experimental results.

REFERENCES

- [1] W. Fischer, X. Gu, et al., Phys. Rev. Lett. 115, 264801 (2015).
- [2] Y. Luo, W. Fischer, et al., Phys. Rev. ST Accel. Beams 15, 051004 (2012).
- [3] Y. Luo, W. Fischer, and S. White, Phys. Rev. Accel. Beams 19, 021001 (2016).
- [4] S. White, W. Fischer, Y. Luo, BNL-105550-2014-IR, C-A/AP/519, 2014.