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# DYNAMIC APERTURE CALCULATIONS FOR THE 2012 RHIC 100 GEV POLARIZED PROTON RUN\*

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## Abstract

In this article, we summarize the dynamic aperture calculations for the 2012 RHIC 100 GeV polarized proton run. We varied  $\beta^*$  at the interaction action points, calculated the off-momentum dynamic aperture, and investigated the dependence of dynamic aperture on the proton bunch intensity and the proton beam transverse emittance. Based on the off-line optics model, we also applied second order chromaticity correction in the Yellow ring and compared the calculated dynamic apertures without and with the correction. In the end we compared the off-momentum dynamic apertures with different voltages of 197 MHz Landau RF cavity.

## INTRODUCTION

The  $\beta^*$ s at the interaction points (IPs) in the recent RHIC 100 GeV polarized proton (p-p) runs were 1.0 m in 2006 run and 0.7 m in 2009 run. In 2009, we observed a poor beam lifetime and a short luminosity lifetime. Simulation and experiment proved that the  $\beta^* = 0.7$  m lattice gives a lower dynamic aperture [1].

Since the 2011 RHIC 250 GeV p-p run, to avoid the longitudinal and transverse emittance blow-ups, we began to use a 9 MHz RF cavity for beam injection and energy acceleration. At physics store, besides the 28 MHz RF cavities, we turned on the 197 MHz Landau RF cavity to overcome the longitudinal instability.

Figure 1 shows the RF momentum acceptance versus the full width bunch length. Here we define the full bunch length as  $6\sigma_L$ . In this calculation, we used 20 KV 9 MHz, 350 KV 28 MHz, and 200 KV 197 MHz RF cavities. At the beginning of store, the full proton bunch length was 15 ns, which gave the maximum momentum spread about  $dp/p_0|_{max} = 1.25 \times 10^{-3}$ .

## DA VERSUS $\beta^*$

In the preparation for the 2012 RHIC 100 GeV p-p run lattices, we performed numerical simulations based on a 6-D weak-strong beam-beam interaction model [2] to decide which  $\beta^*$  we should adopt for this run. Fig. 2 shows the dynamic aperture as a function of  $\beta^*$ . In this calculation, the transverse rms emittance is 2.5 mm.mrad. The initial relative momentum deviation is 0.0005. Only 300 KV 28 MHz RF cavities are used. From Fig. 2, the dynamic aperture drops with the decrease of  $\beta^*$ . The reason is that with a

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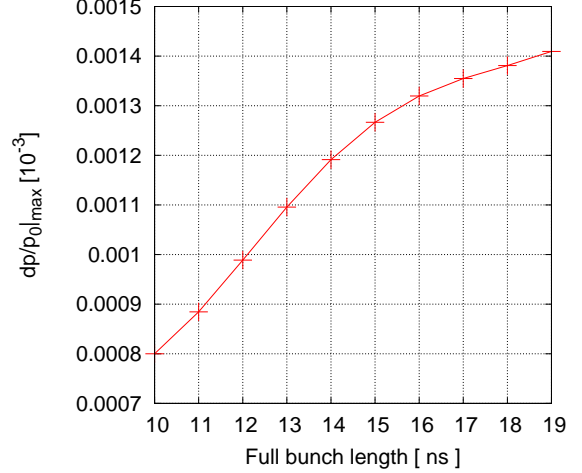


Figure 1: The RF momentum acceptance versus the full width bunch length.

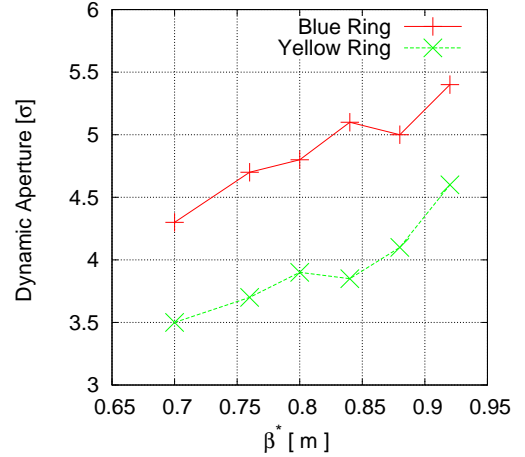


Figure 2: Calculated dynamic aperture versus  $\beta^*$ s at IP6 and IP8.

low  $\beta^*$ , the nonlinear chromaticities and the nonlinear field errors in the interaction regions will reduce the dynamic aperture. Based on Fig. 2, we chose  $\beta^* = 0.85$  m for the 2012 RHIC 100 GeV p-p run.

Also from Fig. 2, the dynamic aperture for the Yellow ring is about  $1\sigma$  smaller than that for the Blue ring. Fig. 3 shows the off-momentum tunes versus the relative off-momentum error. The Yellow ring has large negative second order chromaticities. With beam-beam interaction, the tunes of large amplitude particles will be pushed to the third order resonance located at  $Q_y = 2/3$ .

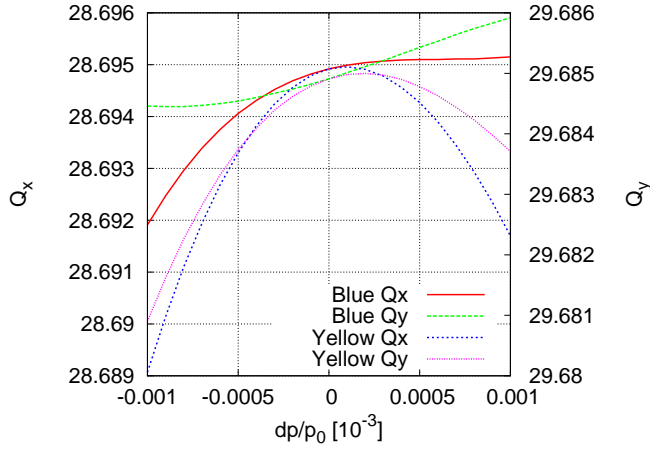


Figure 3: Off-momentum tunes versus the relative off-momentum deviation.

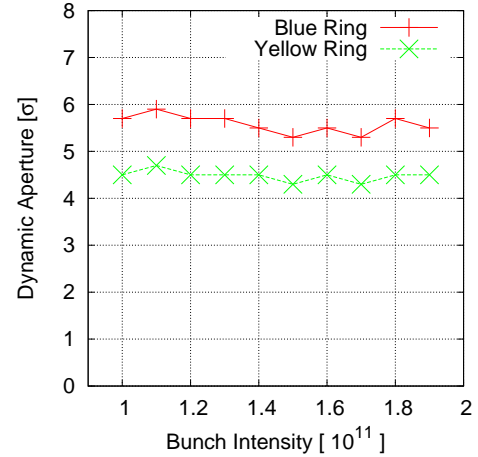


Figure 5: Calculated dynamic aperture versus the proton bunch intensity.

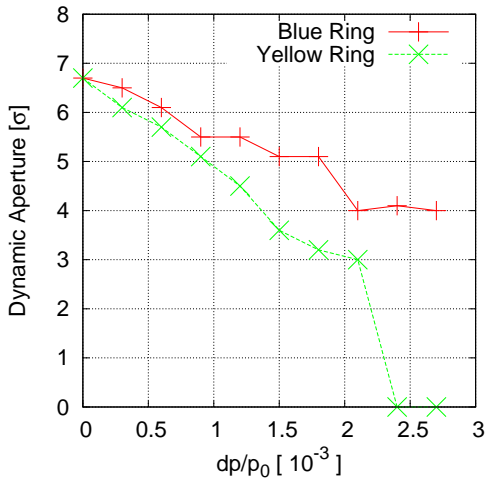


Figure 4: Calculated off-momentum dynamic apertures for both rings.

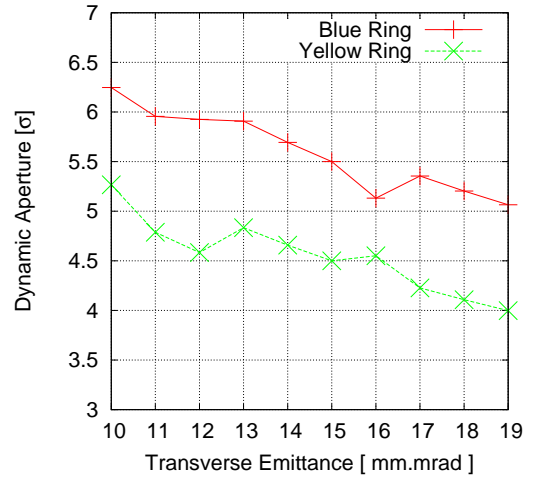


Figure 6: Calculated dynamic aperture versus the proton transverse emittance.

## MOMENTUM APERTURE

Here we calculate the off-momentum dynamic aperture with the lattices with  $\beta^* = 0.85$  m. In this calculation, we used 20 KV 9 MHz, 350 KV 28 MHz, and 200 KV 9 MHz RF cavities. The initial relative momentum error was varied from 0 to 0.0027 with a step size of 0.0003. Fig. 4 shows the results.

From Fig. 4, the off-momentum dynamic aperture drops with the increase of off-momentum error. And the Yellow off-momentum dynamic aperture drops faster than the Blue ring. When  $dp/p_0 > 2.1 \times 10^{-3}$ , there is no off-momentum dynamic aperture for the Yellow ring. The off-momentum dynamic aperture in the Blue ring is around  $4 \sigma$  up to  $dp/p_0 = 2.5 \times 10^{-3}$ . In the 2012 RHIC 100 GeV p-p run, we observed that Yellow ring beam loss during the RF re-bucketing from 9 MHz to 28 MHz RF cavities. RF-rebucketing is aimed to shorten the bunch length but it

increases the momentum spread.

## PROTON BUNCH INTENSITY

To increase the luminosity, we continued to push the proton bunch intensity at store. In the 2012 RHIC 100 GeV p-p run, the maximum bunch intensity at the beginning of store was  $1.7 \times 10^{11}$ . Assuming the rms transverse emittance 2.5 mm.mrad, the beam-beam parameter was about -0.017. Fig. 5 shows the dynamic aperture versus the proton bunch intensity. The initial relative momentum deviation is 0.0005.

From Fig. 5, up to bunch intensity  $2.0 \times 10^{11}$ , there is no significant drop in the dynamic aperture. In this article, we adopted a weak-strong beam-beam model and didn't take into account of the coherent beam-beam effect. In a dedicated beam experiment, with a bunch intensity  $1.7 \times 10^{11}$ , we lowered the tunes toward the third order resonance line

$Q_y = 2/3$ . We observed a large beam loss when the coherent mode was at 0.669. The beam loss was due to an incoherent effect instead of coherent beam-beam mode since the beam loss only took place in one ring. [3].

## TRANSVERSE BEAM EMITTANCE

Fig. 6 shows the dynamic aperture versus the proton beam's transverse emittance. The horizontal axis is 95 % normalized emittance which is 6 times the rms normalized emittance. In this study, the initial relative momentum deviation is 0.0005. From Fig. 6, the dynamic aperture drops when the transverse emittance increases. The dynamic aperture is measured in units of rms transverse beam size  $\sigma$  which varies with the transverse emittance. With a larger transverse emittance, the particles will sample larger IR nonlinear fields.

## SECOND ORDER CHROMATICITY

Here we focus on the second order chromaticity correction in the Yellow ring. Based on the off-line lattice model, the uncorrected second order chromaticities are (-4500, -2600). With the sorted sextupole families [4], we were able to correct the second order chromaticities down to (-320, -130). However, due to the tight machine schedule, these correction strengths were not applied on line. The actual measured second order chromaticities were (-3900, -2300).

Fig. 7 shows the off-momentum dynamic aperture without and with second order chromaticity in the Yellow ring. With the correction, the off-momentum dynamic aperture is slightly bigger than that without correction. The off-momentum dynamic aperture is improved to above  $2\sigma$  when  $dp/p_0 > 0.0021$ .

## 197 MHZ RF CAVITY VOLTAGE

In the 2012 RHIC 100 GeV run, we used 200 KV 197 MHz Landau cavity to overcome the observed longitudinal instability. However, during the proton polarization measurement with a carbon polarimeter, we had to reduce the Landau cavity's voltage to below 100 KV to achieve a better signal-to-noise ratio in the polarization measurement.

Fig. 8 shows the dynamic aperture of the Yellow ring with three sets of 197 MHz RF cavities. In this study, the initial off-momentum deviation is 0.0005. From it, there is not clear difference in the dynamic aperture up to  $dp/p_0 = 0.0015$ . Above that, higher 197 MHz RF cavity voltage gave less off-momentum aperture. However, too low 197 MHz RF cavity voltage will cause loss of Landau damping to cure the longitudinal instability.

## SUMMARY

In the article, based on the 6-D weak-strong beam-beam simulation, we carried out numerical simulations to investigate the dependence of dynamic aperture in the 2012 RHIC

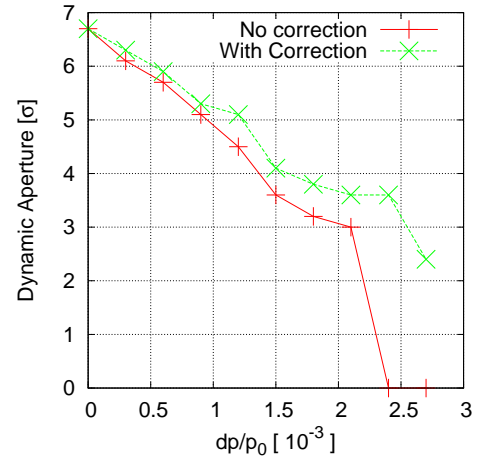


Figure 7: Calculated off-momentum dynamic aperture without and with second order chromaticity correction in the Yellow ring.

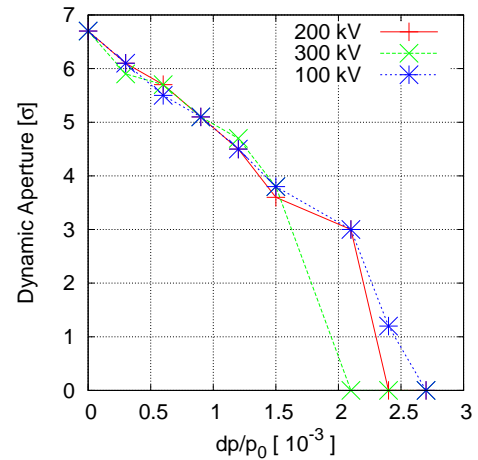


Figure 8: Calculated off-momentum dynamic apertures with different 197 MHz Landau cavity voltage.

100 GeV p-p run on the  $\beta^*$ s at the interaction points, on the proton bunch intensity and the proton transverse beam emittance. Simulation shows that the off-momentum dynamic aperture is smaller in the Yellow ring than that in the Blue ring and it can be slightly improved through the second order chromaticity correction.

## REFERENCES

- [1] Y. Luo, et al., BNL C-AD AP Note 349, 2009.
- [2] Y. Luo, in Proceedings of 2010 IPAC, Kyoto, Japan (2010).
- [3] S. White, in Proceedings of 2012 IPAC, New Orleans, USA (2012).
- [4] Y. Luo, et al., in Proceedings of 2010 IPAC, Kyoto, Japan (2010).