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BEAM-BEAM EFFECTS WITH STOCHASTIC COOLING IN THE 2012 RHIC 100 GEV HEAVY ION RUN*

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Abstract

The 3-D stochastic cooling has been implemented in RHIC for the first time in the 2012 heavy ion run. In the U-U run, the U beam's transverse emittances were cooled from initially about 13.5 mm.mrad down to 2.5 mm.mrad. The beam-beam parameters reached a maximum of -0.005. In the Cu-Au run, due to the unbalanced transverse beam sizes of the Cu and Au beams in the first several hours at the store, the Cu beam lifetime was significantly reduced by the beam-beam interaction. To maintain the Cu beam lifetime and to maximize the integrated luminosity, we intentionally reduced the cooling rate for the Au beam until the Cu beam got cooled. In this article, we review the beam-beam effects in the 2012 RHIC heavy ion run and carry out numerical simulations to interpret the observations.

INTRODUCTION

For ion collisions, the beam-beam parameter, or the linear incoherent beam-beam tune shift, for the weak beam is

$$\xi_1 = -\frac{N_{i,2} r_p}{2\pi\epsilon_{n,rms,2}} \times \frac{Z_1 Z_2}{A_1}. \qquad (1)$$

Here r_p is the classic proton radius. $\epsilon_{n,rms}$ is the rms normalized transverse emittance. In the following we use 95% normalized transverse emittance which is 6 times rms normalized transverse emittance. The Z and A are the ion's charge state and atomic number. The subscript 1 is for the weak beam and the subscript 2 is for the strong beam. In Eq. (1), we assume that there are two beam-beam interaction points at IP6 and IP8.

In the previous RHIC Au runs, the beam-beam interaction is negligible since the beam-beam parameter was 0.003. In the 2012 RHIC heavy ion runs, we collided 94.6 GeV U-U and 100 GeV Cu-Au ions. By adding the horizontal cooling, the 3-D stochastic cooling [1] was eventually implemented in RHIC for the first time. To eliminate the particle loss due to limited off-momentum dynamic aperture, we used a lattice which gives a large momentum aperture. Together with the stochastic cooling, the beam loss was entirely due to the luminosity burn-off in the 2012 RHIC U-U run [2].

For the U ion beam, the typical bunch intensity was 0.3×10^9, which was smaller than the Au beam in the previous Au-Au runs. The stochastic cooling was more efficient for a low bunch intensity beam. As results, the transverse emittances of the U beam were cooled from the initially 13.5 mm.mrad down to 2.5 mm.mrad in less than 2 hours. The beam-beam parameters increased from initially -0.001 to -0.005.

In the Cu-Au run, the bunch intensities for the Cu and Au beam were about 4.0×10^9 and 1.3×10^9 respectively at the end of the run. Therefore, the stochastic cooling rate for the Cu beam was 3 times slower than the Au beam. When turning on 3-D cooling with full cooling power for the two beams from the beginning of store, we observed that the Cu beam lifetime was significantly reduced through the beam-beam interaction with unbalanced transverse beam sizes. The beam-beam parameter for the Cu beam reached -0.011 from initially -0.004. To maintain the Cu beam lifetime and to maximize the integrated luminosity, we intentionally reduced the cooling rate or even turned off the Au beam until the Cu beam emittances were cooled down.

In the following, for each of 2012 RHIC U-U and Cu-Au runs, we first review the typical observations of bunch intensities, beam emittances, and beam decay. Then, we carry out numerical simulation to calculate the dynamic aperture to interpret the observations. The 10^6 turn dynamic aperture is calculated with SimTrack [3]. The nonlinear field errors in the interaction regions are included.

U-U RUN

As an example, Fig. 1 shows the typical bunch intensities and measured normalized emittances in the 2012 U-U run. The fill number is 16853. The default store length was 6 hours. The average transverse emittances were initially 12 mm.mrad. In less than 2 hours, the equilibrium between the intrabeam scattering and the stochastic cooling was reached. The equilibrium transverse emittances were 2.5 mm.mrad, which is the smallest emittance achieved in the RHIC so far. According to Eq (1), we calculated the beam-beam parameter as -0.001 at the beginning of store and -0.005 after the equilibrium was reached.

Fig. 2 shows the calculated off-momentum dynamic apertures with varied transverse emittances. The working point is fixed at (28.2315, 29.2267) which was used in operation. The transverse emittance is varied from 2.5 mm.mrad to 15 mm.mrad with a step size of 2.5 mm.mrad. The bunch intensity is 0.3×10^9. Four different initial momentum errors $\delta = (dp/p_0)$ are used. The RF bucket height is 0.0018. From Fig. 2, for all off-momentum errors, the particle's dynamic aperture drops with the increase of the transverse emittance. With the transverse

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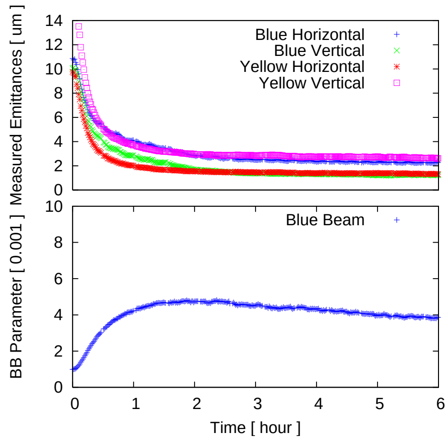

Figure 1: Bunch intensities and measured emittances in the U-U run. The fill number is 16853.

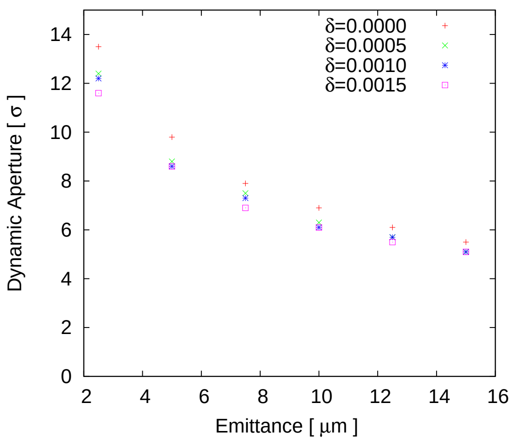

Figure 2: Off-momentum dynamic aperture versus transverse emittance. 4 different off-momentum errors are used.

emittance 15 mm.mrad, the dynamic aperture is 5 σ. With the transverse emittance 2.5 mm.mrad, the dynamic aperture is more than 11 σ even with a large momentum error 0.0015.

Fig. 3 shows the dynamic aperture in a tune scan along the diagonal in the tune space. The horizontal axis is the fractional vertical tune. The fractional horizontal tune is always 0.005 higher. The initial relative momentum deviation is 0.0015. We used three normalized transverse emittances. From Fig. 3, when the fractional tunes are close to the 9th order betatron resonance located at $2/9$, the dynamic aperture is reduced. In the 2012 U-U run, we observed non-luminous beam loss in the Blue ring in a few stores. The default Blue working point was (28.2315, 29.2267). After we increased the vertical tune by 0.0005, the non-luminous beam loss was eliminated.

CU-AU RUN

Fig.4 shows an example of measured transverse emittances and the beam decays with 3-D cooling with full

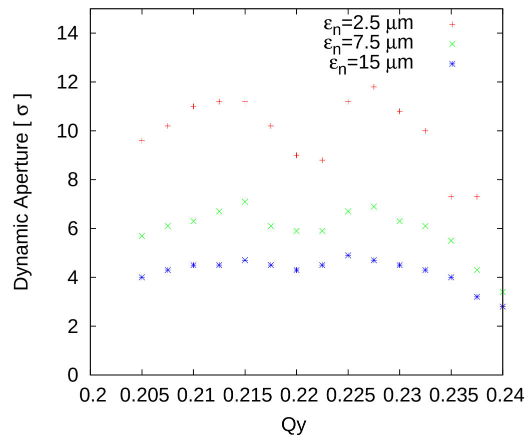

Figure 3: Off-momentum dynamic aperture in a tune scan along the diagonal. 3 different emittances are used.

cooling power from the beginning of store. The fill number is 16911. Since the Cu bunch intensity was more than 3 times than the Au beam, it took a longer time for the stochastic cooling to cool the Cu beam emittances down to comparable to that of Au beam emittances. We observed that the Cu beam lifetime was significantly reduced through the beam-beam interaction with unbalanced transverse beam sizes. When the difference between the emittances of the two beams is bigger, the more Cu beam loss was observed.

Fig. 5 shows the calculated beam-beam parameters for both beams for the same store. At the beginning of store, the transverse emittance was about 12 mm.mrad for the Cu beam and 10 mm.mrad for the Au beam. The beam-beam parameter for the Cu beam was -0.004. The beam decay of Cu beam was below 5%/hour. After 1 hour, the Au beam's transverse emittance was cooled down to 5 mm.mrad, while the Cu beam's emittance was still about 12 mm.mrad. The beam-beam parameter for the Cu beam increased to about -0.009. The beam decay of the Cu beam increased to 30%/hour. After that, with the continuous cooling down of the Cu beam emittance, the Cu beam decay was slowly improving.

Here we perform numerical simulation to calculate the beam-beam effect to the Cu beam's dynamic aperture. Fig. 6 shows the Cu beam's dynamic aperture in the first 4.5 hours in the store. The measured bunch intensity and emittances in Fig. 5 were used. In this study, the initial relative momentum deviation is set to $dp/p_0 = 0.0015$. The dynamic aperture is given in units of Cu beam's rms transverse beam size. From Fig. 6, when the Au beam was fully cooled at 1 hour from the beginning of store, the Cu beam's dynamic aperture is lowest. With the slowly cooling down of Cu beam emittance, the Cu beam's dynamic aperture is slowly increased.

To avoid the large beam loss in the Cu beam and to maximize the integrated luminosity, we decided to turn off or reduce the Au beam's cooling rate in the beginning of store

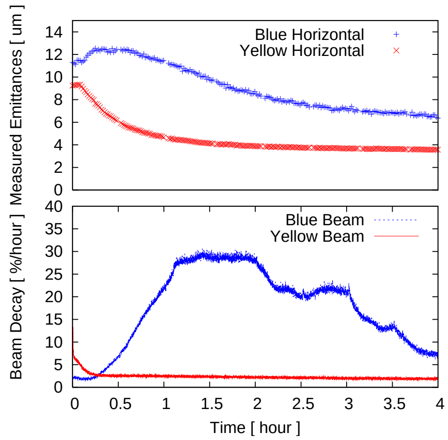

Figure 4: Bunch intensities and measured emittances in Cu-Au run. The fill number is 16911.

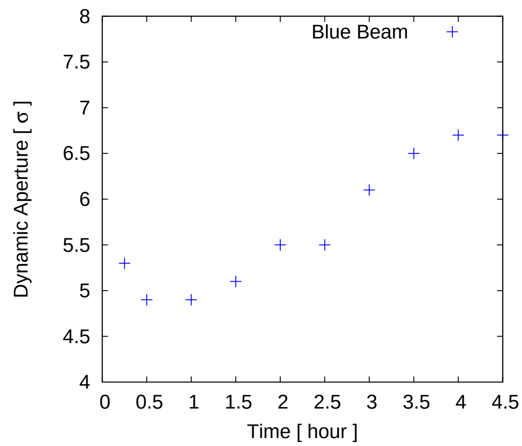

Figure 6: Calculated off-momentum dynamic aperture for fill 16911.

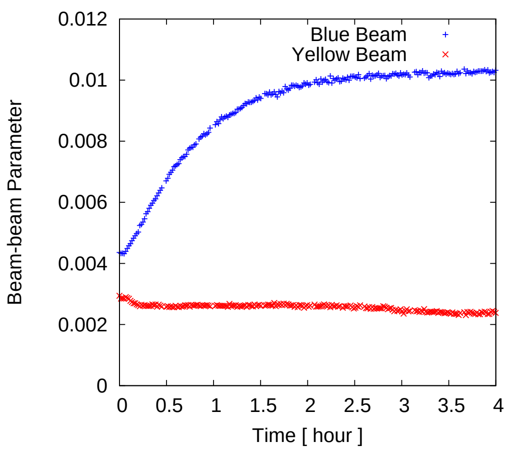

Figure 5: Calcaulated beam-beam paramters for fill 16911.

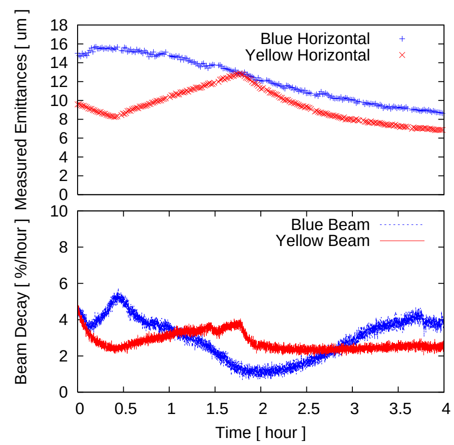

Figure 7: Bunch intensities and measured emittances with reduced Au cooling rate. The fill number is 16917.

until the Cu beam got cooled. Fig. 7 shows the beam emittances and beam decays in the fill 16917 where we intentionally turned off the Au vertical cooling between 0.5 hour to 1.5 hour into the store. When the Cu and Au beam emittances were comparable to each other, then we turned on the yellow vertical cooling again. By doing so, we kept the Cu beam decay below 6%/ hour. Later on in the rest of 2012 Cu-Au run, we continued to balance the luminosity and the beam decay through the Au beam's stochastic cooling gains. The Cu beam decay was kept below 4%/hour in the whole stores. And the store length was set to 14 hours, which is the longest store length in the RHIC heavy ion runs.

SUMMARY

In this article we reviewed and simulated the beam-beam effects on the beam lifetime in the 2012 RHIC U-U and Cu-Au runs. In the U-U run, the beam's transverse emittance was cooled down to 2.5 mm.mrad and the beam-beam parameter increased to 0.005. In the Cu-Au run, we observed that the Cu beam lifetime was reduced due to the unbalanced beam transverse sizes. By reducing the Au beam's cooling rate in the first several hours in the store, we maintained the Cu beam bunch intensity and maximized the store integrated luminosity, and the store length was set to 14 hours, which is the longest store length in the RHIC heavy ion runs.

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