BURN-OFF DOMINATED URANIUM AND ASYMMETRIC COPPER-GOLD OPERATION IN RHIC*

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Abstract

In the 2012 RHIC heavy ion run, we collided uranium-uranium (U-U) ions at 96.4 GeV/nucleon and copper-gold (Cu-Au) ions at 100 GeV/nucleon for the first time in RHIC. The new Electron-Beam Ion Source (EBIS) was used for the first time to provide ions for the RHIC physics program. After adding the horizontal cooling, 3-D stochastic cooling became operational in RHIC for the first time, which greatly enhanced the luminosity. In this article, we first review the improvements and performances in the 2012 RHIC ion runs. Then we discuss the approaches to achieve the burn-off dominated uranium beam lifetime at physics stores. And we also discuss the low copper beam lifetime in the asymmetric copper-gold collision with different intra-beam scattering (IBS) and stochastic cooling rates and the operational solutions to maximize the integrated luminosity.

PERFORMANCES

Improvements

The first high energy U-U collisions in RHIC were enabled by the versatile new Electron-Beam Ion Source (EBIS) [1]. EBIS can produce beams of essentially any ion species, and can switch rapidly between two different species. It was used for the first time to provide ions for the RHIC physics program.

To counter the intra-beam scattering (IBS) caused emittance growth in the RHIC heavy ion runs, stochastic cooling was implemented in RHIC in the past few years [2]. The longitudinal system was implemented in the Yellow ring in 2007, and longitudinal cooling in the Blue ring and the vertical stochastic cooling in both rings in 2010. In 2012, by adding cooling in the horizontal plane, full 3-D stochastic cooling became operational for the first time in RHIC for both rings.

In the previous 2010 and 2011 Au-Au runs, we observed large beam loss after RF re-bucketing and at store with the vertical cooling on. These losses were from particles with large off-momentum deviation. For the 2012 ion run, we chose a lattice with integer tunes (28, 29), which are 3 units lower than what was used in the previous ion runs. With this lattice, simulation shows that the off-momentum dynamic aperture increases from 2 σ to 5 σ with the maximum relative off-momentum deviation $\Delta p/p_0 = 0.0018$ [3].

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The RHIC orbit feedback system became operational for the first time in the 2011 proton run. In the 2012 ion run, with numerous improvements in the control software and hardware, the orbit feedback became more robust. Together with tune/coupling feedback, the RHIC beam control feedback systems greatly reduces the beam time necessary for machine start-up and store tuning [4].

U-U Run

The 2012 RHIC U-U run began on April 19, 2012 and ended on May 15, 2012. The physics mode lasted for 22 days. Figure 1 shows the integrated luminosities for the two physics detectors PHENIX and STAR, together with their minimum and maximum projected luminosities. The minimum projected luminosity was based on the bunch intensity 0.6×10^9. However, the typical bunch intensity at the beginning of store was 0.3×10^9.

The luminosity in the U-U run was greatly enhanced with 3-D stochastic cooling. With 3-D cooling, the rms normalized transverse beam emittance was cooled down to 0.42 π mm mrad in 2 hours from 2.2 π mm mrad at the beginning of store. Figure 2 shows the luminosity with and without stochastic cooling. With 3-D cooling, the peak luminosity was 3 times the initial one, which was observed for the first time in a collider. The integrated luminosity per store is about 5 times that without any cooling. Despite the lower bunch intensity the integrated luminosity goals of both detectors were reached.

Figure 3 shows an example of the Zero Degree Calorimeter (ZDC) coincidence rates from the two detectors STAR and PHENIX, the actual beam loss rates, and the burn-off contributions to the beam loss in one store (fill number 16830). As mentioned above, this year we adopted a lattice which provides a large off-momentum dynamic aperture. The particle loss due to the momentum aperture limitation was essentially eliminated. Together with stochastic cooling, the beam loss was almost entirely due to burn-off [5], which is also the first time this was observed in a collider.

Cu-Au Run

The 2012 RHIC Cu-Au run began on May 15 and ended on June 25. Physics mode ran for 38 days. 3-D stochastic cooling was operational on May 23. Figure 4 shows the integrated luminosities for PHENIX and STAR. The achieved integrated luminosities for both detectors were above the maximum projection. We also reached

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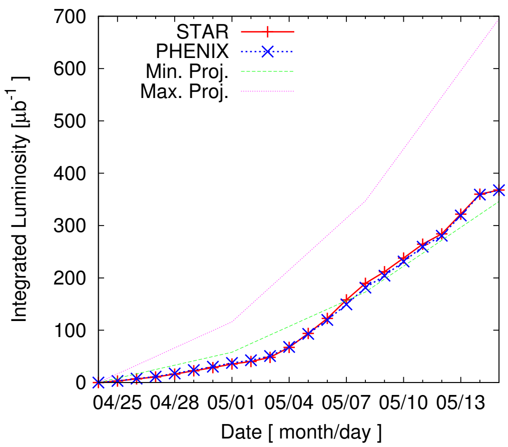

Figure 1: Integrated luminosities in 2012 RHIC U-U run. The minimum and maximum projections are shown.

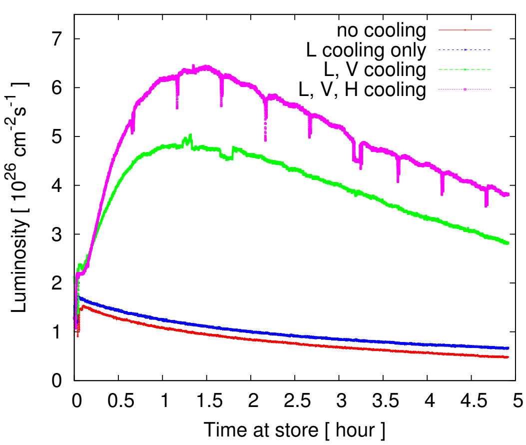

Figure 2: Luminosity without and with stochastic cooling in the 2012 RHIC U-U run. The rate drops every half hour were caused by the automatic store orbit corrections followed by interaction re-steering.

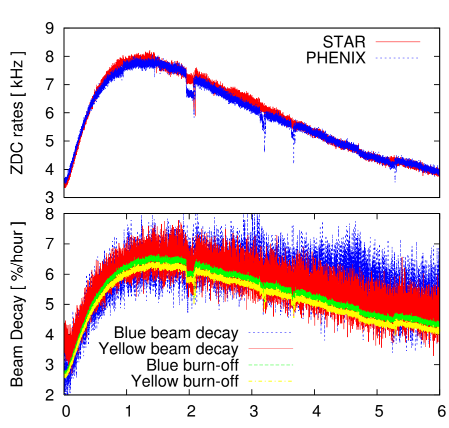

Figure 3: One example of the ZDC rates, beam decays, and burn-off contribution to the beam loss in 2012 RHIC U-U run. The burn-off is calculated based on the analytical cross section of 487.3 b [5].

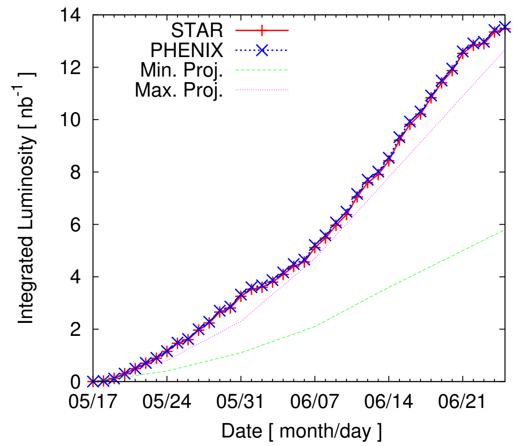

Figure 4: Integrated luminosities in 2012 RHIC Cu-Au run. The minimum and maximum projections are shown.

PHENIX's narrow vertex integrated luminosity goal. Narrow vertex luminosity only counts the collisions within $\pm$10 cm of the IP.

Figure 5 shows the averaged bunch intensities at the beginning of the store. To boost the bunch intensity in RHIC, double bunch merging in the Booster and AGS was tested and implemented. In principle, double bunch merging in the Booster and AGS could increase the bunch intensity in RHIC by a factor of 4. However, since double bunch merging increased the ion beams transverse and longitudinal emittances, careful tuning of the Booster, AGS, and the AGS-to-RHIC transfer line was always required. Continuous efforts were also made to improve the transmission efficiency from RHIC injection to store by fine tuning the working points, chromaticities, and transition loss. The Cu bunch intensity was doubled and the Au bunch intensity increased by 50% through out the course of the Cu-Au run. We achieved the most intense ion bunch in RHIC up to date.

In the Cu-Au run, Cu bunch intensity was more than 3 times the Au bunch intensity. The IBS emittance growth rate of the Cu beam is half of that of the Au ion beam, while the stochastic cooling rate of the Cu beam is one third of the Au ion beam. In the beginning of this run, we observed large Cu beam losses which were caused by the beam-beam interaction between the Cu and Au bunches with different transverse beam sizes. To maintain the Cu beam bunch intensity and to maximize the integrated luminosity, we intentionally reduced the Au beam's cooling rate in the first several hours of each store.

BURN-OFF DOMINATED BEAM LIFETIME IN U-U COLLISION

Beam Loss in Previous Runs

In the RHIC heavy ion runs, the IBS increases the longitudinal and transverse emittances. With a smooth ring

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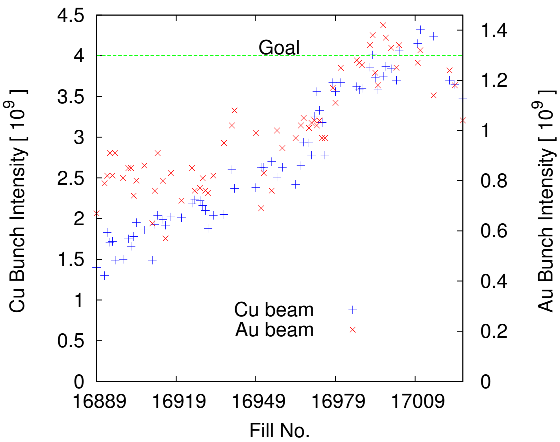

Figure 5: Averaged bunch intensities at the beginning of each individual store in the 2012 RHIC Cu-Au run.

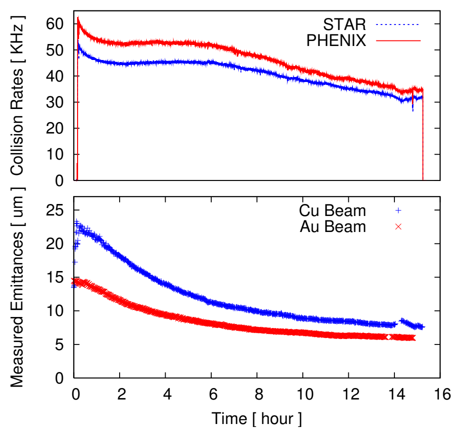

Figure 6: Experimental rates and beam transverse emittances in one physics store in 2012 RHIC Cu-Au run.

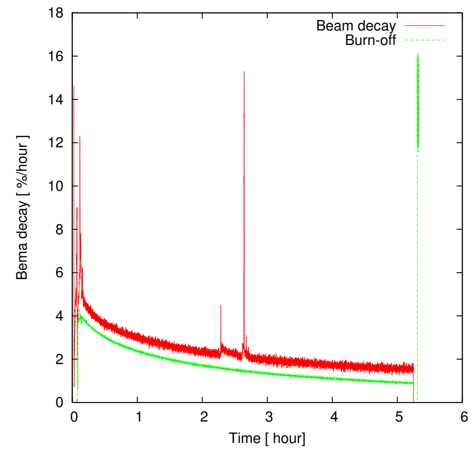

Figure 7: The Au beam decay in 2007 with only longitudinal cooling. RHIC Fill number is 9039.

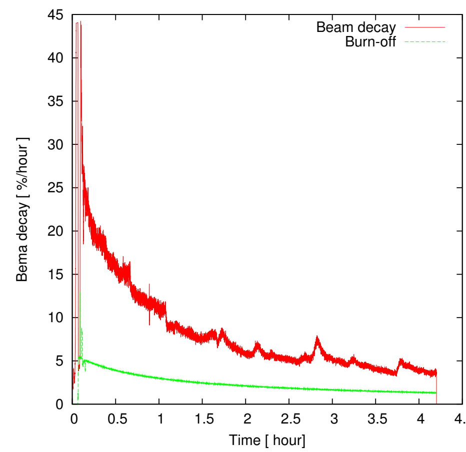

Figure 8: The Au beam decay in 2011 with only longitudinal cooling. RHIC Fill number is 15843.

approximation, the longitudinal and transverse IBS growth rates can be calculated as [6]

$$\tau_{||}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} \frac{r_i^2 c N_i \Lambda}{8\beta\gamma^3\epsilon_{n,rms,x}^{3/2} < \beta_x^{1/2} > \sqrt{\pi/2}\sigma_l\sigma_p^2}, \quad (1)$$

$$\tau_{\perp} = \frac{\sigma_p^2}{\epsilon_x} < \frac{H_X}{\beta_x} > \tau_{||}^{-1}. \quad (2)$$

According to Eqs. (1) and (2), it is possible to reduce $< \frac{H_X}{\beta_x} >$ to reduce the transverse emittance growth coupled from the longitudinal plane[7, 8]. Therefore, during the 2008-2011 RHIC ion runs, we used a lattice with FODO phase advances increased in the arcs and the integer tunes increased by 3 units. We named this lattices as “IBS-suppression” lattices and the previous lattices as “standard” lattices.

However, during the 2008-2011 RHIC heavy ion runs with the IBS-suppression lattice, we observed a large beam loss after RF re-bucketing and during store with transverse cooling [3]. RF re-bucketing aims to shorten the bunch length to increase luminosity but it increases the beam momentum spread. RF re-bucketing takes place in the beginning of the store without collision. The bunch’s maximum momentum deviation is increased from 0.9 $\times 10^{-3}$ to 1.7×10^{-3} with RF re-bucketing.

Figures 7 and 8 show the beam decays in the Yellow ring in the fill 9039 in the 2007 Au-Au run and in the fill 15843 in the 2011 Au-Au run. In both fills, there was only longitudinal cooling. Along with the total beam decay, we also show the beam decay contributed by the beam burn-off due to luminosity. The burn-off is calculated from luminosity and the analytical value of total cross section of Au-Au collision. The IBS-suppression lattices caused much more non-luminosity particle loss than the standard lattices.

Off-Momentum DA

With longitudinal cooling, the beam loss in the longitudinal plane is eliminated. If there is any beam loss, it should happen in the transverse plane due to the limited transverse off-momentum dynamic aperture. From Figs. 7 and 8, the IBS-suppression lattices have smaller off-momentum dy-

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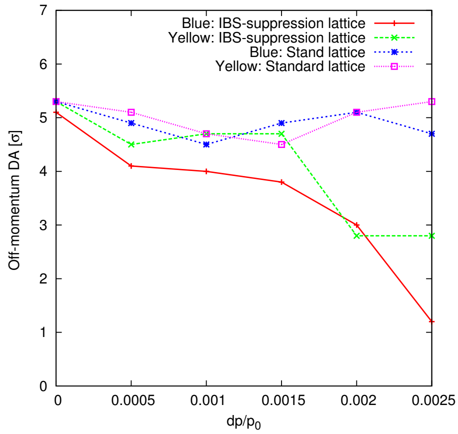

Figure 9: Off-momentum dynamic apertures with IBS-supression lattices and standard lattices for both rings.

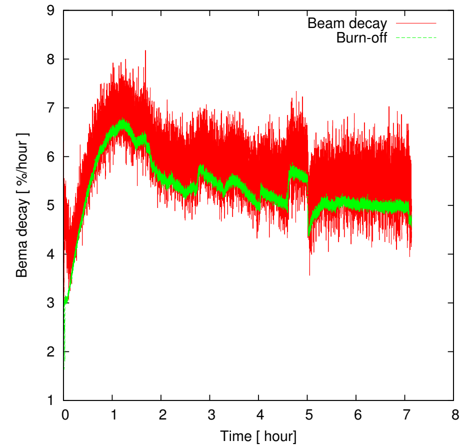

Figure 10: The Au beam decay in 2012 with transverse and longitudinal cooling. The beam loss was almost entirely from burn-off.

namic aperture than the standard lattices. In the 2011 Au-Au run with the longitudinal and vertical cooling, we observed about 50% of particle loss was non-luminous. According to Eq. (2), small transverse emittance increases the longitudinal IBS growth rate.

Figure 9 shows the calculated off-momentum aperture for both Blue and Yellow rings with IBS-suppression and standard lattices. For the IBS-suppression lattice, the off-momentum dynamic aperture begins to drop sharply to below 4σ when the relative momentum deviation is bigger than 0.0015. While for the standard lattice, the off-momentum DA is better than 4.7σ up to $dp/p_0 = 0.0025$. With RF re-bucketing, the RF bucket height is 1.9×10^{-3}.

Based on the beam loss observations in the previous runs and the calculated off-momentum apertures, we decided to adopt standard lattices for the 2012 U-U and Cu-Au runs. In the 2012 U-U run, 3-D stochastic cooling was fully operational in RHIC. The typical bunch intensity in RHIC is 0.3×10^9. Comparing to the previous Au-Au operation, the IBS growth rate is smaller and the stochastic cooling is more efficient.

Figure 10 shows the Au beam decay and the burn-off contribution in Fill 16830. With transverse cooling on, the initial luminosity is not the highest. Accordingly, the luminosity burn-off continues to increase until the peak luminosity is reached. The beam loss is almost entirely from the burn-off [5], which means that there is almost no loss due to limited transverse off-momentum dynamic aperture with the standard lattices.

BEAM-BEAM INTERACTION IN ASYMMETRIC CU-AU COLLISION

Different IBS and Cooling Rates

The IBS growth rate is proportional to $N_i Z^4/A^2$ while the stochastic cooling rate is proportional to $1/N_i$, where N_i is bunch intensity, Z and A are the ion charge state and atom number. In the 2012 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 IBS emittance growth rate of the Cu beam is half of that of the Au ion beam, while the stochastic cooling rate of the Cu beam is one third of the Au ion beam.

In the beginning of this run, with full cooling power for both beams, we observed that the Cu beam lifetime was significantly reduced when the two beams' emittances were quite different. The bigger difference between the emittances of the two beams was, the more Cu beam loss was observed. Later on we concluded that the bad Cu beam lifetime was caused by the beam-beam interaction between the Cu and Au beams with different transverse beam sizes [9]. As an example, Figure 11 shows the measured transverse emittances and the beam decays with 3-D cooling with full cooling power from the beginning of store.

Beam-Beam Interaction

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

$$\xi_1 = -\frac{N_{i,2} r_p}{2\pi\epsilon_{n,rms,2}} \times \frac{Z_1 Z_2}{A_1}. \quad (3)$$

Here r_p is the classic proton radius. $\epsilon_{n,rms,2}$ is the 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 the previous RHIC Au runs, the beam-beam interaction was negligible since the beam-beam parameter was -0.003. In the 2012 Cu-Au run, when turning on 3-D cooling with full cooling power for the two beams from the beginning of store, the beam-beam parameter for the Cu beam reached -0.011 from initially -0.004.

Here we perform numerical simulation to calculate the beam-beam effect to the Cu beam's dynamic aperture. Figure 12 shows the Cu beam's dynamic aperture in the first 4.5 hours in the store. The measured bunch intensity and

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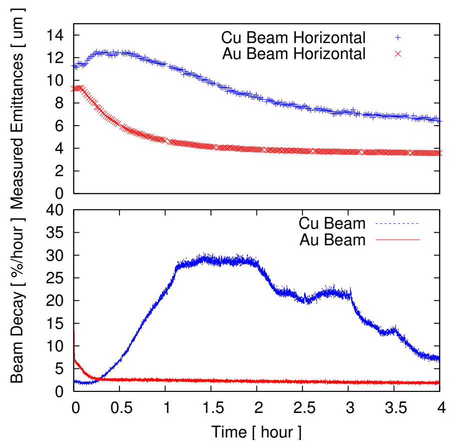

Figure 11: Bunch intensities and measured emittances in Cu-Au run. The fill number is 16911.

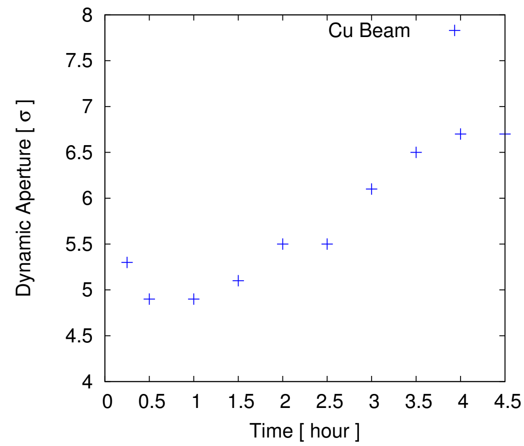

Figure 12: Calculated off-momentum dynamic aperture for fill 16911.

emittances in Fig. 11 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. 12, when the Au beam was fully cooled at 1 hour from the beginning of store, the Cu beam's dynamic aperture is lowest. With slow cooling of the 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 gain in the beginning of the store until the Cu beam got cooled. Figure 13 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 for the RHIC heavy ion runs.

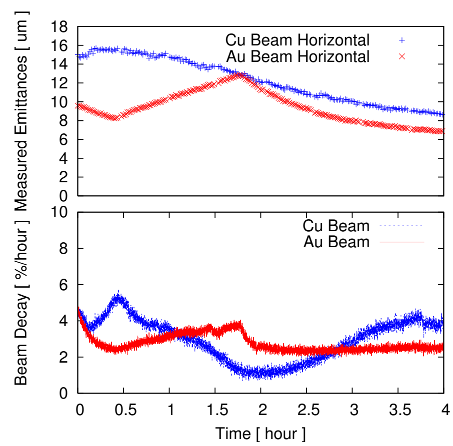

Figure 13: Bunch intensities and measured emittances with reduced Au cooling rate. The fill number is 16917.

CONCLUSIONS

The 2012 RHIC heavy ion run was a great success. It marked the first collisions of high energy U-U and Cu-Au ions in RHIC. With a versatile EBIS, powerful 3-D stochastic cooling, and double bunch merging in the injectors, high precision beam control systems, and many efforts of machine fine tuning, we reached both detectors' integrated luminosity goals. In the U-U run, with a new lattice which gives a higher off-momentum aperture and 3-D cooling, the particle loss is dominated by the burn-off. In the Cu-Au run, due to different IBS and cooling rates from both beams, we intentionally slowed down the Au beam cooling rate in the Yellow ring in the first several hours to match the two beams' transverse beam sizes and maximize the integrated luminosity.

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