OFF-MOMENTUM DYNAMIC APERTURE
FOR LATTICES IN THE RHIC HEAVY ION RUNS*

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Abstract

To reduce transverse emittance growth rates from intra-beam scattering in the RHIC heavy ion runs, a lattice with an increased phase advance in the arc FODO cells was adopted in 2008-2011. During these runs, a large beam loss due to limited off-momentum dynamic aperture was observed during longitudinal RF re-bucketing and with transverse cooling. Based on the beam loss observations in the previous ion runs and the calculated off-momentum apertures, we decided to adopt the lattice used before 2008 for the 2012 U-U and Cu-Au runs. The observed beam decay and the measured momentum aperture in the 2012 U-U run are presented.

INTRODUCTION

In the RHIC heavy ion runs, the intra-beam scattering (IBS) increases the longitudinal and transverse emittances. With a smooth ring approximation, the longitudinal and transverse IBS growth rates can be calculated as [1]

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

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

According to Eqs. (1) and (2), to reduce the transverse emittance growth coupled from the longitudinal plane, it is possible to reduce $<\frac{H_X}{\beta_x}>$. Therefore, in 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 [2]. For simplicity, we name the lattice with the original tunes (28.23, 29.22) as the standard lattice, while the lattice with the tunes (31.23, 32.22) as the IBS-suppression lattice. For the RHIC current power supply connections, it is easier with the IBS-suppression lattice to further squeeze β^* at IPs without exceeding the power supply current limits.

However, in the previous 2008-2011 RHIC heavy ion runs with the IBS-suppression lattice, we observed a large beam loss during RF re-bucketing and with transverse cooling [3, 4]. In the following, we first review the beam loss in the previous heavy ion runs, followed by the off-momentum dynamic aperture calculation. In the end, we present the results from the 2012 U-U run. In the 2012 U-U and Cu-Au runs we adopted the standard lattice to improve the momentum aperture.

BEAM LOSS IN PREVIOUS RUNS

In this section we review the beam loss observed in the previous RHIC heavy ion runs. We will focus on the early beam loss right after RF re-bucketing and the beam loss into the store with transverse cooling. RF re-bucketing aims to shorten the bunch length to increase luminosity but it increases the beam's momentum spread. It takes place in the beginning of store. The maximum momentum deviations are about 0.9×10^{-3} and 1.7×10^{-3} without and with re-bucketing, respectively.

To counter the IBS emittance growths we were implementing stochastic cooling in the RHIC rings in the past few years [5]. Longitudinal stochastic cooling became available in the Yellow ring since 2007 and in both rings since 2008. Vertical cooling became available in the Blue ring since 2010 and in both rings since 2011. In 2012 U-U run, all the 6 plane stochasting cooling became operational.

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 momentum aperture. Transverse cooling reduces the transverse emittance but increases the longitudinal IBS growth rate. Current longitudinal cooling is not strong enough to prevent the particles with large momentum deviation from leaking from the center bucket to the adjacent buckets. Again, if limited by momentum aperture, some of these particles will be lost in the transverse plane.

Figures 1 and 2 show the beam decays in the Yellow ring in the fill 9039 in the 2007 Au run and in the fill 15843 in the 2011 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 the experiment rates collected by the detectors. In Fig. 1 the beam loss in the whole store is basically from the luminosity burn-off. In Fig. 2, the early loss is 3-4 times of luminosity burn-off contribution. Clearly the IBS-suppression has a smaller transverse momentum aperture.

Figure 3 shows that the beam decay in the Yellow ring in the fill 16025 in the 2011 Au run. In this store, both longitudinal and vertical stochastic cooling were on. There was no debounched beam during this store. If averaged over the whole store, 50% of the beam loss were caused by the limited transverse momentum aperture.

OFF-MOMENTUM DA CALCULATION

In this section we will calculate the off-momentum dynamic aperture for the IBS-suppression lattice and the standard lattice. Table 1 lists the beam and lattice parame-
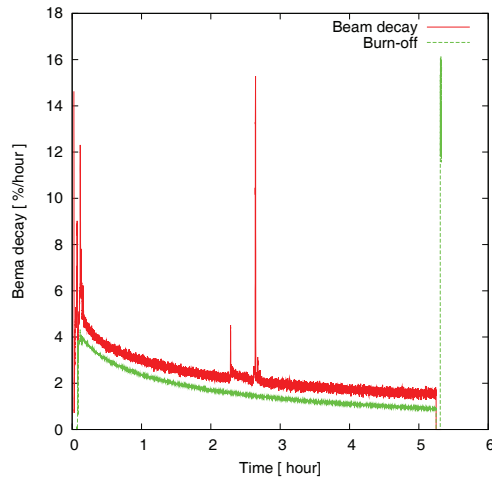
Figure 1: 2007 Yellow beam decay with only longitudinal cooling. RHIC Fill number is 9039.
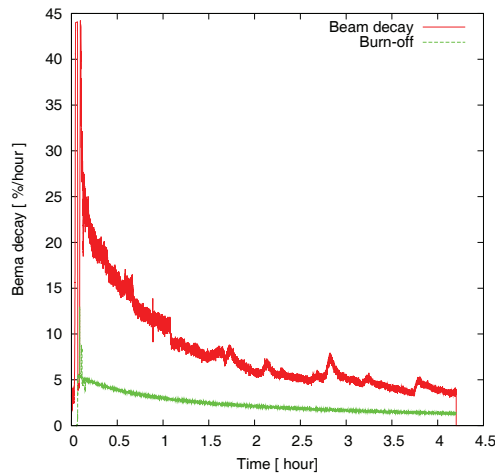

Figure 2: 2011 Yellow beam decay with only longitudinal cooling. RHIC Fill number is 15843.
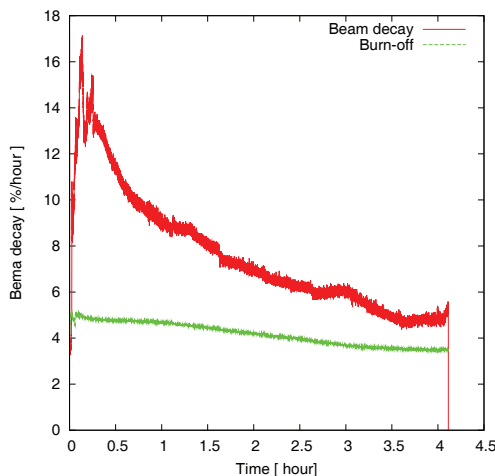

Figure 3: 2011 Yellow beam decay with transverse and longitudinal cooling. RHIC Fill number is 16025.

Table 1: Beam and Lattice Parameters Used in the Simulation

Parameter	IBS-suppression	standard
Circumference	3833.8451 m	
Beam energy	100 GeV	
Trans. rms emittance	2.5 nm	
Long. rms bunch area	1.0 eV.s	
Hori. and vert. tunes	(31.23, 32.22)	(28.23, 29.22)
$\beta*$ at IP6 and IP8	0.7 m	
$\xi_{x,y}^{(1)}$	(1,1)	(1,1)
Blue ring $\xi_{x,y}^{(2)}$	(-5000,-1000)	(2400,1100)
Yellow ring $\xi_{x,y}^{(2)}$	(3800,1700)	(-1400,700)

ters. In this study, we vary the relative momentum deviation from 0 to 2.5×10^{-3} with a step size of 0.5×10^{-3}. We focus on comparing the minimum off-momentum aperture calculated in 10 angles in the first quadrant in the $(x/\sigma_x, y/\sigma_y)$ plane. The particles are tracked element-by-element up to 10^6 turns [6]. The total voltages for the 28 MHz and 197 MHz RF cavities are 350 KV and 4.0 MV respectively. The beam-beam interaction is not included in tracking since its effect is negligible. In this study, second order chromaticity correction is not included [7].

Figure 4 shows the calculated off-momentum aperture for both Blue and Yellow rings with IBS-suppression and standard lattices. The fractional tunes are set to (0.23, 0.22). For the IBS-suppression lattice, the off-momentum dynamic aperture begins to drop sharply to below 4σ when the initial momentum deviation is bigger than 0.0015. While for the standard lattice, the off-momentum DA is better than 4.7σ up to $dp/p_0 = 0.0025$.

Figure 5 shows the calculated off-momentum aperture in a tune scan between 0.2 and 0.24 for both rings with both lattices. The initial relative momentum deviation of particles is $dp/p_0 = 0.0015$. In Fig. 5, the horizontal axis is the fractional horizontal tune. The fractional vertical tune is always 0.005 below the horizontal one. For the standard lattice, the off-momentum DA is higher on both side of 0.222, which is the 9th order betatron resonance. For the Blue ring, the standard lattice has higher off-momentum aperture than the IBS-suppression lattice. For the Yellow ring, both lattices give similar DA when the horizontal tune is below 0.227. Above 0.227, the Yellow ring with IBS-suppression lattice gives much smaller DA. In 2010 Au run, we shifted the Yellow working point down to (0.214, 0.205) to reduce the beam loss during RF re-bucketing.

OBSERVATIONS IN 2012 U-U RUN

Based on the beam loss observations in the previous Au runs and the calculated off-momentum apertures, we decided to adopt standard lattices for the 2012 U-U and Cu-Au runs. The 2012 U-U run started on April 19 and ended May 16. In the 2012 U-U run, the bunch intensity in RHIC ranged from 0.2×10^9 in the beginning to about 0.3×10^9 at
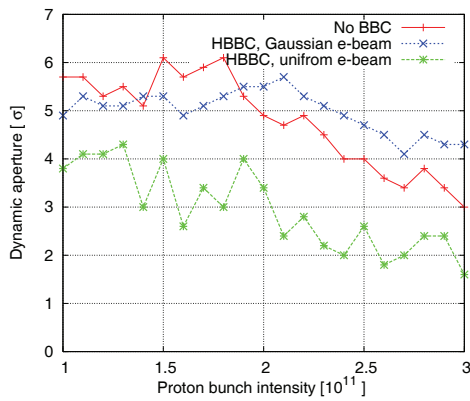
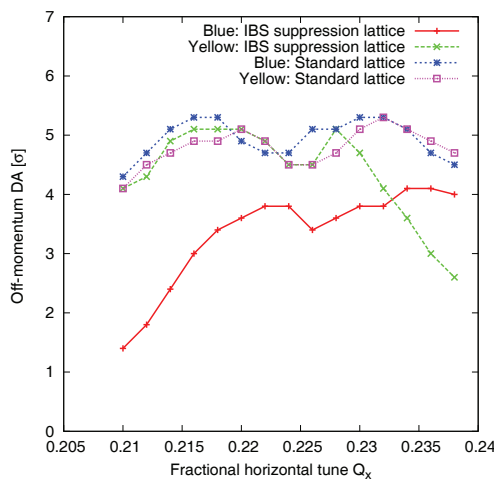Figure 4: Off-momentum DAs for both rings and both lattices.

Figure 5: Off-momentum DAs in a tune scan for both lattices. Initial $dp/p_0 = 0.0015$.

the end of run. Therefore, the IBS growth rates are smaller and the stochastic cooling is more efficient than during the previous Au runs. In the 2012 U-U run, 6-plane stochastic cooling was fully operational in RHIC.

Figure 6 shows the Yellow beam decay and luminosity 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 entirely from the luminosity burn-off, which means that there is no particle loss due to limited transverse momentum aperture with the standard lattice.

The maximum momentum aperture for the standard lattice was measured in a dedicated beam experiment. Without RF re-bucketing, we changed the 28 MHz RF frequency to shift the beam to the inside and outside of the beam pipe while observing the beam loss. We observed beam decay above 200%/hour in both ring with a 2 mm radial shift, which corresponds to $dp/p_0 = 0.0018$. Considering that the beam's relative momentum spread is about 0.0004, we conclude that the standard lattice has a mo-
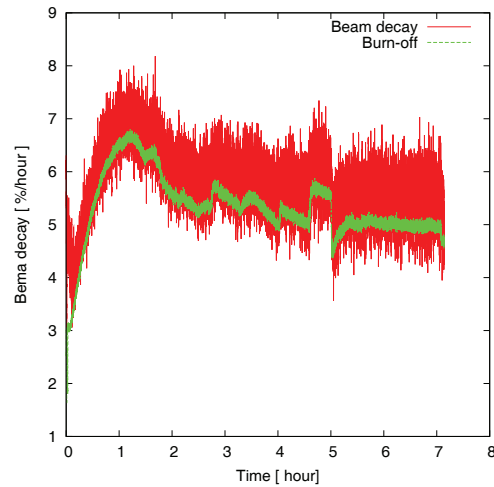

Figure 6: 2012 Yellow beam decay with transverse and longitudinal cooling.

mentum aperture around 0.002 without second order chromaticity correction. We plan to use a 56 MHz superconducting RF cavity to increase the longitudinal focusing in the future. The bucket height with the 2 MV 56 MHz RF cavity and 4 MV 197 MHz cavities is about 0.0025. Therefore, the standard lattice will provide enough momentum aperture for this upgrade.

SUMMARY

In this article we reviewed the beam loss observed in the previous RHIC heavy ion runs and calculated and compared the off-momentum dynamic apertures for the IBS-suppression lattice and the standard lattice. Based on this, we adopted the standard lattice for the 2012 U-U and Cu-Au runs. In the 2012 U-U run, we did not observe beam loss due to a limited momentum aperture. All the beam losses are from burn-off, and the maximum momentum aperture measured in a beam experiment is about 0.002.

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