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BEAM-BEAM OBSERVATIONS IN RHIC*

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Abstract

The relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory has been in operation since 2000. Over the past decade the luminosity in the polarized proton (p-p) operations has increased by more than one order of magnitude. The maximum total beam-beam tune shift with two collisions has reached 0.018. The beam-beam interaction leads to large tune spread, emittance growth, and short beam and luminosity lifetimes. In this article, we review the beam-beam observations during the previous RHIC p-p runs. The mechanism for particle loss is presented. The intra-beam scattering (IBS) contributions to emittance and bunch length growths are calculated and compared with the measurements. In the end we will discuss current limits in the RHIC p-p operations and their solutions.

INTRODUCTION

RHIC consists of two superconducting rings, the Blue ring and the Yellow ring. They intersect at 6 locations around the ring circumference. The beam in the Blue ring circulates clockwise and the beam in the Yellow ring circulates counter-clockwise. The two beams collide at two interaction points (IPs), IPI6 and IP8. Figure 1 shows the layout of RHIC. RHIC is capable of colliding heavy ions and polarized protons (p-p). The maximum achieved total beam-beam parameter with two collisions was 0.003 in the 100 GeV Au-Au collision and 0.018 in the p-p collision. In this article we only discuss the beam-beam effects in the p-p runs.

The working point in the RHIC p-p runs is chosen to provide a good beam-beam lifetime and to maintain the proton polarization during the energy ramp and physics store. Current working point is constrained between 2/3 and 7/10. 2/3 is a strong 3rd order betatron resonance. 7/10 is a 10th order betatron resonance and also a spin depolarization resonance [1]. Experiments and simulations have shown that the beam lifetime and the proton polarization are reduced when the vertical tune of the proton beam is close to $7/10$.

The main limits to the beam lifetime in the RHIC p-p runs are the beam-beam interaction, the nonlinear magnetic field errors in the interaction regions (IRs), the nonlinear chromaticities with low β^*s, the horizontal and vertical 3rd order betatron resonances, and the machine and beam parameter modulations.

To further increase the luminosity, we can either increase the bunch intensity or reduce β^*. Figure 2 shows the proton tune footprints including beam-beam interactions. In this calculation, the proton bunch intensity is 2.0×10^{11} and the 95% normalized transverse emittance is 15π mm.mrad. The total beam-beam parameter with two collisions is 0.02. From Figure 2, there is not enough tune space to hold the large beam-beam tune spread when the proton bunch intensity is larger than 2.0×10^{11}.

To minimize the beam-beam tune spread and to compensate the nonlinear beam-beam resonance driving terms, head-on beam-beam compensation with electron lenses (e-lenses) is adopted for RHIC [2, 3, 4]. Two e-lenses are being installed on either side of IP10, one for the Blue ring and one for the Yellow ring. The goal of head-on beam-beam compensation is to double current RHIC luminosity in the p-p operations.

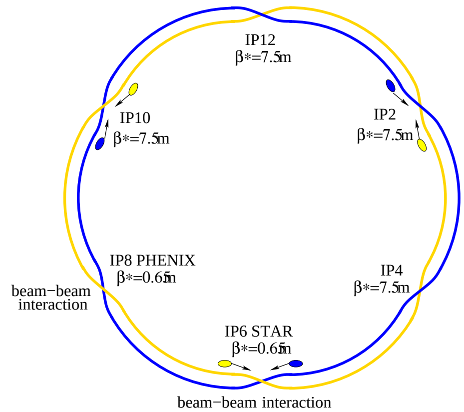

Figure 1: Layout of RHIC. Two beams collide at IP6 and IP8.

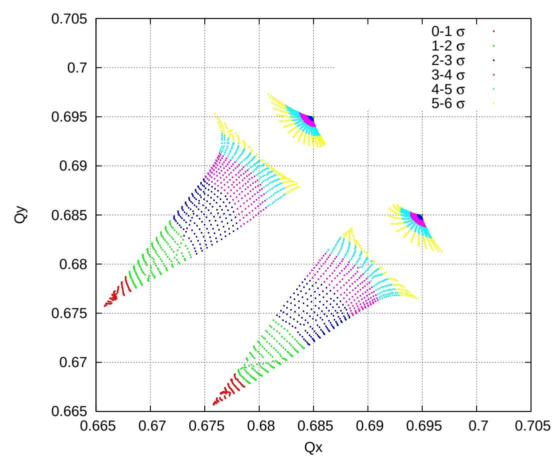

Figure 2: Tune footprints without and with beam-beam. The bunch intensity is 2.0×10^{11}.

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Table 1: Parameters in 2012 255 GeV p-p runs

Parameter	Unit	Value
No of colliding bunches	-	107
Protons per bunch	10^{11}	1.7
Trans. emittances	mm.mrad	20
β^* at IP6/IP8	m	0.65
Long. emittances	eV.s	2
Voltage of 28 MHz RF	kV	360
Voltage of 197 MHz RF	kV	300
rms momentum spread	10^{-4}	1.7
rms bunch length	m	0.45
Beam-beam parameter per IP	-	0.007
Hour glass factor	-	0.85
Peak luminosity	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	165

OBSERVATIONS

Previous p-p runs

The luminosity in the p-p collision is given by

$$L = \frac{3N_\mathrm{p}^2 N_\mathrm{b} \gamma f_\mathrm{rev}}{2\pi\epsilon_\mathrm{n}\beta^*} H(\frac{\beta^*}{\sigma_\mathrm{l}}). \tag{1}$$

Here N_p is the proton bunch intensity, and N_b the number of bunches, γ the Lorentz factor, f_rev the revolution frequency. ϵ_n is the 95% normalized emittance and σ_l the rms bunch length. $H(\frac{\beta^*}{\sigma_\mathrm{l}})$ is the luminosity reduction due to hour-glass effect. The total beam-beam parameter, or the totoal linear incoherent beam-beam tune shift with two collisions is

$$\xi = \frac{3N_\mathrm{p} r_\mathrm{p}}{\pi\epsilon_\mathrm{n}}. \tag{2}$$

Here r_p is the classical radius of proton. We assumed 2 collisions at IP6 and IP8.

In the 2009 RHIC 100 GeV p-p run, with β^*=0.7 m and a bunch intensity of 1.5×10^{11}, we observed a shorter beam lifetime of 7 hours compared to 12 hours in the 2008 RHIC 100 GeV p-p run with $\beta^* = 1.0$ m [5, 6, 7, 8]. In the 2012 RHIC 100 GeV p-p run, $\beta^* = 0.85$ m lattices were adopted, the beam lifetime was 16 hours with a typical bunch intensity of 1.65×10^{11} [9].

In the 2011 250 GeV and 2012 255 GeV p-p runs, a common 9 MHz RF system was used to produce a long bunch length on the energy acceleration to maintain both transverse and longitudinal emittances [9, 10]. When the beams reached store energy, the bunches were re-bucketed to 28 MHz RF system. To achieve an even shorter bunch length, we added 300 kV 197 MHz RF voltages at store. In these two runs, β^* at the collision points was 0.65 m. The maximum bunch intensity reached 1.7×10^{11}. The store length was 8 hours. Table 1 shows the lattice and typical beam parameters in the 2012 RHIC 255 GeV p-p runs.

Beam Lifetime

In the previous RHIC p-p runs, after the beams were brought into collision, we normally observed a large beam loss in the first 1 hour followed by a slow beam loss in the rest of store. The instant maximum beam loss rate in the beginning could reach 30%/hour. The beam loss rate of the slow loss was typically 1-2%/hour. The burn-off contribution to beam loss rate is less than 1%/hour.

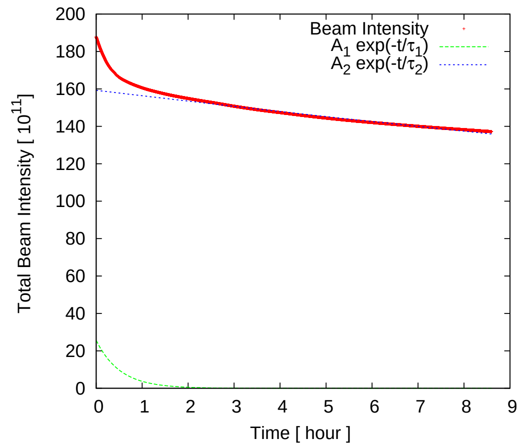

Figure 3: An example of Blue ring beam intensity evolution at store which was fitted with Eq. (3). Fill No. is 16697.

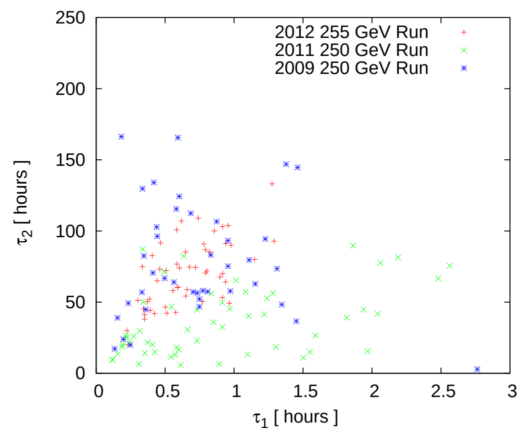

Figure 4: The Blue ring beam loss fit parameters τ_1 and τ_2 in the previous 250 GeV runs.

Empirically, the total beam intensity can be fitted with double exponentials [11],

$$N_p(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2), \tag{3}$$

where $N_p(t)$ is the bunch intensity, and $A_{1,2}$ and $\tau_{1,2}$ are fit parameters. Figure 3 shows an example of beam intensity evolution at store which was fitted with Eq. (3). Figure 4 shows (τ_1,τ_2) of the physics stores in the past three 250 GeV or 255 GeV p-p runs. The reasons for the fast and slow beam losses will be discussed in the next session.

Transverse Emittance and Bunch length

The transverse emittances are routinely measured with ionization profile monitors (IPMs) in RHIC. Figure 5 shows an example of IPM measured emittances at store.

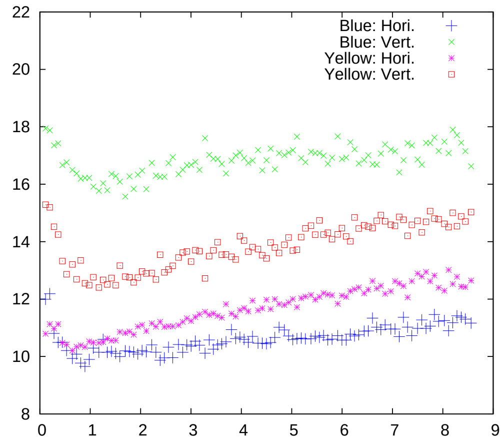

Figure 5: IPM measured transverse emittances at store for Fill 16697.

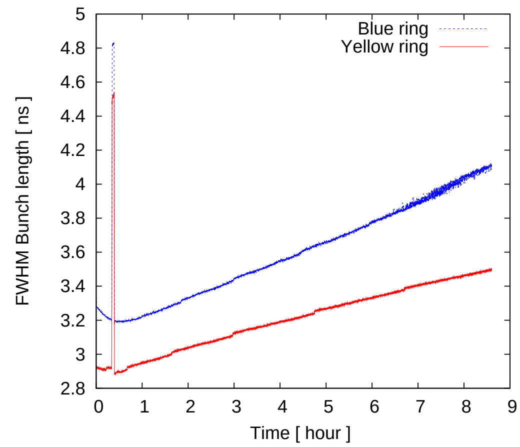

Figure 6: WCM measured FWHM bunch length at store for Fill 16697.

IPMs require knowledge of β functions and need periodic calibrations of micro-channels. An averaged all-plane emittance of both rings can be derived from luminosity based on Eq. (1). In the previous RHIC p-p runs, after beams were brought into collision, the measured emittances decreased in the first 1 hour then slowly increased in the rest of store. The early emittance reduction was related to the large beam loss in the beginning of store. Experiments showed that the emittance growth with beam-beam was smaller than that without beam-beam.

Bunch length was measured with a wall current monitor (WCM). Figure 6 shows one example of averaged full width half maximum (FWHM) bunch lengths at store. The spikes around 0.4 hour in the plot were due to polarization measurement. To improve signal/noise ratio during the polarization measurement, the voltages of 197 MHz RF cavities were reduced to 20 kV temporarily. After beams were brought into collision, the bunch length decreased in the first 1 hour then slowly increased in the rest of store. The early bunch length reduction was related to the large beam loss at the beginning of store. And the bunch length growth with beam-beam was less than that without beam-beam interaction.

EXPLANATIONS

Beam Loss Rate and Beam-beam

The store beam loss rate was mainly determined by the beam-beam interaction. Without beam-beam interaction, the beam loss rate can be better than 1%/hour depending on machine tunning. After the beams were brought into collision, the instant beam loss rate could reach a maximum of 30%/hour. The beam loss rates for bunches with 1 and 2 collisions were different. In RHIC, 10 out of 109 bunches have only one collision instead of two collisions. For example, for Fill 15386, for bunches with 1 collision, the fitted (τ_1, τ_2) are (1.5 hours, 100 hours). While for the bunches with 2 collisions, they are (0.8 hour, 30 hours).

Particle Loss Mechanism

The WCM profile is actually the particle population distribution in the longitudinal plane. For a given period, we can calculate the number of particles leaking out of the center bunch area. Figure 7 shows each bunch's particle leakage percentage out of [-5 ns, 5 ns] area during the first 0.5 hour in the Blue ring in Fill 15386, together with the actual particle loss percentage in the same period. The patterns of particle leakage and particle loss show a strong linear correlation, as shown in Figure 8.

The strong linear correlation between particle leakage and particle loss is also true for the rest of store. During the RHIC p-p runs, there was not de-bunched beam observed from the WCM profiles. Considering that particles in the bunch tail have larger off-momentum deviation, we conclude that the particles got lost in the transverse plane due to a small transverse off-momentum dynamic aperture with beam-beam interaction.

Off-momentum Dynamic Aperture

To achieve a short bunch length at physics store, 197 MHz RF cavities were used besides the acceleration RF cavities of 28 MHz. Figure 9 shows a typical longitudinal bunch profile. With 197 MHz cavities, the relative momentum spread for the center bucket between [-2.5 ns, 2.5 ns] increases to 5×10^{-4}. And for the tail particles out of [-6 ns, 6 ns] (full width), the relative momentum deviation is bigger than 6×10^{-4}.

Figure 10 shows the calculated off-momentum dynamic aperture without and with beam-beam interaction from a 10^6 turn particle tracking. The 2012 255 GeV Yellow ring lattice is used. The off-momentum dynamic aperture with beam-beam is much smaller than that without beam-beam when the relative off-momentum deviation $dp/p_0 > 4 \times 10^{-4}$. For the tail particles with $dp/p_0 > 6 \times 10^{-4}$, the dynamic aperture is less than 5 σ.

The large beam loss in the beginning of store was re-

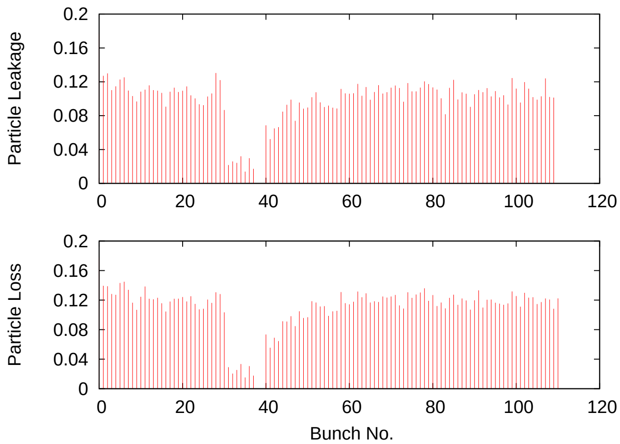

Figure 7: Particle leakage and particle loss of all bunches in Fill 15386.

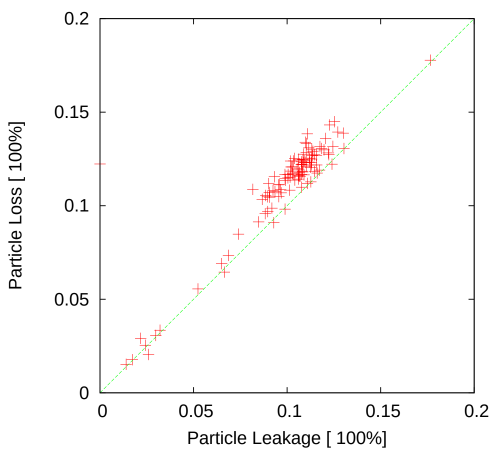

Figure 8: Correlation of particle leakage and particle loss of all bunches in Fill 15386.

lated to the initial large number of particles with large momentum deviation. Those particles were generated during RF re-bucketing and 197MHz RF cavity voltage ramp-up. From WCM profiles, large momentum particles were observed on both sides of the center bunch area after re-bucketing. We also observed beam loss shortly after RF re-bucketing without beam-beam. When beams were brought into collision, transverse off-momentum aperture was reduced. Those particles would get lost sooner or later in the first 1 hour depending on how close their $(dp/p_0)_{max}$ to the off-momentum aperture and the longitudinal diffusion rate.

Intra-beam Scattering Effects

The slow loss after first 1 hour into store was linked to slow diffusion processes. Here we calculate the effects of intra-beam scattering (IBS) on the proton beam emittance and bunch length growth. With a smooth ring approximation, the longitudinal and transverse IBS growth rates can

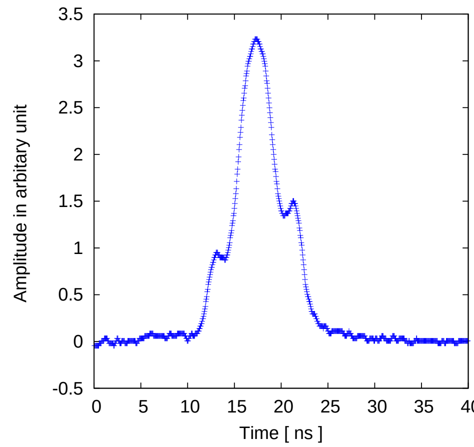

Figure 9: Longitudinal bunch profiles with RF re-bucketing and 197 MHz RF voltages.

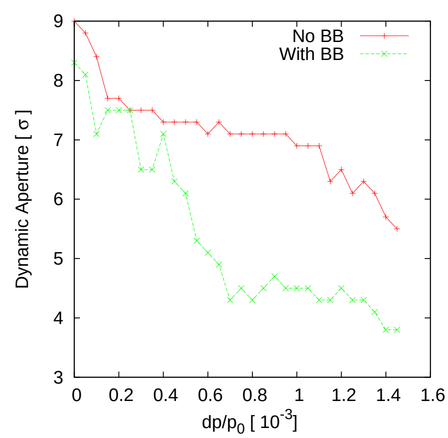

Figure 10: Calculated off-momentum apertures without and with beam-beam interaction.

be calculated as [12]

$$\tau_{||}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} \frac{r_i^2 c N_i \Lambda}{8\beta\gamma^3\epsilon_x^{3/2} < \beta_x^{1/2} > \sqrt{\pi/2}\sigma_l\sigma_p^2}, \quad (4)$$

$$\tau_{\perp} = \frac{\sigma_p^2}{\epsilon_x} < \frac{H_x}{\beta_x} > \tau_{||}^{-1}. \quad (5)$$

Here σ_l and σ_p are the rms bunch length and the rms relative momentum spread. $H_x = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$, $\alpha_x, \beta_x, \gamma_x$ are Twiss parameters. D_x, D_x' are horizontal dispersion and its derivative. Λ is the Coulomb logarithm.

Based on Eqs.(2) and (3), Figures 11 and 12 show an example of IBS contributions to the emittance and bunch length for Fill 16697. We took the bunch intensity evolution, the initial emittance and bunch length from the real measurements. Comparing the calculated IBS contributions to the luminosity derived emittance and WCM measured bunch length, the emittance and bunch length growth after 1.5 hours into the store are largely consistent with IBS.

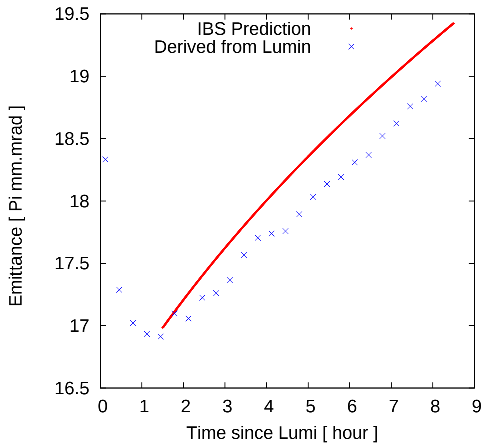

Figure 11: Emittance modeling with IBS for Fill 16697, compared to the emittance derived from luminosity.

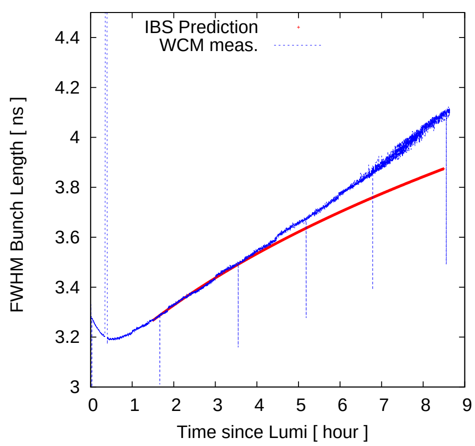

Figure 12: Bunch length modeling with IBS for fill 16697, compared to the WCM bunch length measurement.

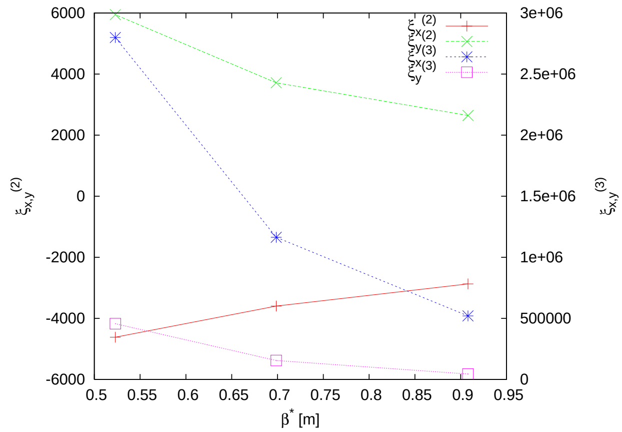

Figure 13: Calculated second and third order chromaticities vs. β^* in the p-p runs.

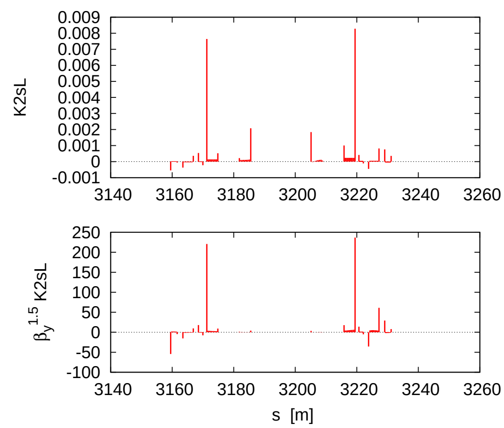

Figure 14: $K_{2s}L$ and $\beta_y^{1.5}K_{2s}L$ in IR8 in Yellow ring, based on the offline nonlinear IR model.

LIMITS

Low β^* Lattices

In order to further increase the luminosity, we can either increase the bunch intensity or reduce β^*. A low β^* lattice increases the β functions in the triplet quadrupoles and therefore the particles will sample large nonlinear magnetic field errors at these locations. As a result, the dynamic aperture will be reduced [13]. For example, in the 2009 100 GeV p-p run, we used a lattice with $\beta^* = 0.7$ m which gave a short beam lifetime [8]. At 250 GeV, we achieved $\beta^* = 0.65$ m. The reason is that the transverse beam size is smaller at 250 GeV than at 100 GeV [14].

A low β^* lattice also increases the nonlinear chromaticity and reduces the off-momentum dynamic aperture. Chromatic analysis shows that the nonlinear chromaticities are mostly originating from the low β insertions IR6 and IR8 [15]. The nonlinear chromaticities increase dramatically with the decreased β^*. Figure 13 shows the calculated second and third order chromaticities as functions of β^*. Large second order chromaticities push the particles with large momentum errors to the 3rd or 10th order resonances. Several correction techniques of nonlinear chromaticities have been tested and implemented in RHIC [16]. To further reduce β^*, we need to balance the hour-glass effect, beam lifetime reduction, and the luminosity increase.

$3Q_{x,y}$ Resonances

To mitigate the coupling between two beams, we would like to mirror the working points of the two RHIC rings on both sides of the diagonal in the tune space. However, in the operation we had to operate with both working points below the diagonal for better beam lifetimes. It was understood in the 2006 100 GeV p-p run that the strong $3Q_x$ resonances at $Q_x = 2/3$ prevented the working point above the diagonal [6]. At that time, the proton bunch intensity was 1.3×10^{11}.

In the 2012 100 GeV run, even with both working points below the diagonal, when the bunch intensity was higher than 1.7×10^{11}, we observed a larger beam loss due to

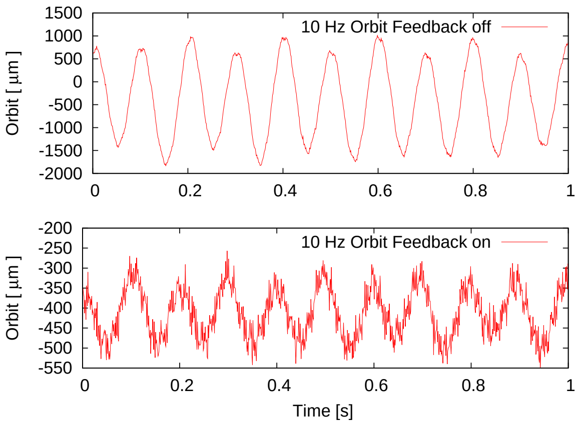

Figure 15: Orbit oscillation without and with 10 Hz orbit feedback. Fill No. is 15257.

the $3Q_y$ resonance which is located at $Q_y = 2/3$ [9]. The main contributions to the third order resonances are from the sextupole and skew sextupole components in the IR6 and IR8. As an example, Figure 14 shows $K_{2s}L$ and $\beta_y^{1.5}K_{2s}L$ in the IR8 in the Yellow ring. To reduce the resonance stop-bands, we routinely correct the local sextupole and skew sextuopole errors with IR orbit bumps by minimizing the feed-down tune shifts [17], which improved the beam losses experimentally. Measurement and correction of the global third order resonance driving terms with AC dipole excitation were also applied [18, 19].

10 Hz Orbit Oscillation

In the beginning of the 2008 100 GeV p-p run, we tested a near-integer working point (0.96, 0.95) in the Blue ring while keeping the working point in the Yellow ring at (0.695, 0.685). Weak-strong beam-beam simulation shows that there is a wider tune space with good dynamic apertures than the working point (0.695, 0.685) [20]. The spin simulation shows that there are weaker spin depolarization resonances in this region as well.

However, operating at near-integer tunes turned out very challenging [7]. With such tunes, we found that it was difficult to correct the closed orbit and to control the β-beat. Moreover, both detectors reported high background rates from the beam in the Blue ring when two beams were brought into collision. These backgrounds were caused by horizontal orbit vibrations around 10 Hz which originated from mechanical vibrations of the low-β triplets driven by the cryogenic flow [21].

To correct the 10 Hz orbit oscillations, we developed a local 10 Hz orbit feedback system and succeeded in the 2011 p-p run [22]. Figure 15 shows an example of horizontal BPM readings in the triplet without and with the 10 Hz orbit feedback. The peak-to-peak amplitude of the 10 Hz orbit oscillation was reduced by the feedback system from 2500 microns down to 250 microns. We plan to re-visit the near-integer working point in future beam experiment sessions.

SUMMARY

In this article we reviewed the beam-beam observations in the previous polarized proton runs in RHIC. Particle loss happened in the transverse plane, which was due to limited transverse off-momentum dynamic aperture. Beam-beam interaction, IR nonlinear multipole field errors, nonlinear chromaticities with low β^*s , and $3Q_{x,y}$ resonances reduce the transverse dynamic aperture. Measures had been implemented in RHIC to correct the nonlinear chromaticities and $3Q_{x,y}$ resonance driving terms. 10 Hz orbit modulation was reduced with a 10 Hz orbit feedback. To further increase the luminosity in the RHIC p-p operations, we plan to increase the bunch intensity and to reduce β^* at collisional IPs. To reduce the large beam-beam tune spread from high bunch intensities, head-on beam-beam compensation with electron lenses are being installed in RHIC.

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