RHIC POLARIZED PROTON OPERATION*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) operation as the polarized proton collider presents unique challenges since both luminosity(L) and spin polarization(P) are important. With longitudinally polarized beams at the experiments, the figure of merit is LP^4. A lot of upgrades and modifications have been made since last polarized proton operation. A 9 MHz rf system is installed to improve longitudinal match at injection and to increase luminosity. The beam dump was upgraded to increase bunch intensity. A vertical survey of RHIC was performed before the run to get better magnet alignment. The orbit control is also improved this year. Additional efforts are put in to improve source polarization and AGS polarization transfer efficiency. To preserve polarization on the ramp, a new working point is chosen such that the vertical tune is near a third order resonance. The overview of the changes and the operation results are presented in this paper.

INTRODUCTION

The spin physics program in the Relativistic Heavy Ion Collider (RHIC) calls for highly polarized proton beams with high luminosity. Acceleration of polarized proton beams to high energy in circular accelerators is difficult due to numerous depolarizing resonances. A Siberian snake [1], a device that rotates the spin by 180° around a horizontal direction, can eliminate the effects of strong depolarization resonances that occur in circular accelerators. The RHIC spin program utilizes two Siberian snakes and four spin rotators in each ring to accelerate polarized protons to various energies as high as 250 GeV. The significant amount RHIC running was at 100 GeV in the past. The first polarized proton run at 250 GeV in RHIC took place in 2009. This year operation aims at higher polarization and higher luminosity. Polarized proton beam have been accelerated to 250 GeV. They were stored and collided with a peak luminosity of about 1×10^{32} cm^{-2}s^{-1} and polarization above 45% measured by a polarized hydrogen jet [2].

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SPIN DYNAMICS

In the presence of magnetic fields, the spin is governed by the Thomas-BMT (Bargmann, Michel, and Telegdi) Equation [3],

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left(G\gamma\vec{B}_\perp + (1+G)\vec{B}_\parallel\right), \tag{1}$$

where $\vec{S}$ is the spin vector of a particle in the frame that moves with the particle's velocity, $\vec{B}_\perp$ and $\vec{B}_\parallel$ are defined in the laboratory rest frame with respect to the particle's velocity. $G = \frac{g-2}{2}$ is the gyromagnetic anomaly of the proton, and γ is the Lorentz factor.

In a perfect planar synchrotron with a vertically oriented guiding magnetic field, the spin vector of a proton beam precesses around the vertical axis $G\gamma$ times per orbital revolution. The number of precessions per revolution is called the spin tune ν_{sp} and is equal to $G\gamma$ in this case. In a real circular accelerator, the horizontal magnetic field that arises from various sources, such as the vertical closed orbit and the vertical betatron oscillation, kicks the spin vector away from the precessing around the vertical axis. Normally, this perturbation is small. However, when the spin precession frequency coincides with the frequency at which the spin vector gets kicked by the horizontal magnetic field, the spin vector is kicked away coherently and a spin depolarizing resonance is encountered.

In general, a spin resonance is located at

$$\nu_{sp} = G\gamma = k \pm l\nu_y \pm m\nu_x \pm n\nu_{syn}, \tag{2}$$

where k, l, m and n are integers, ν_x and ν_y are horizontal and vertical betatron tunes, and ν_{syn} is the tune of the synchrotron oscillation. There are three main types of depolarizing resonances: imperfection resonances at $\nu_{sp} = k$, intrinsic resonances at $\nu_{sp} = l \pm \nu_y$, and coupling resonances at $\nu_{sp} = n \pm \nu_x$. The imperfection resonance is due to the vertical closed orbit error, and its strength is proportional to the size of the closed orbit distortion. The intrinsic resonance comes from the vertical betatron motion and is determined by the size of the vertical betatron oscillation. The larger the betatron oscillation, the stronger the resonance.

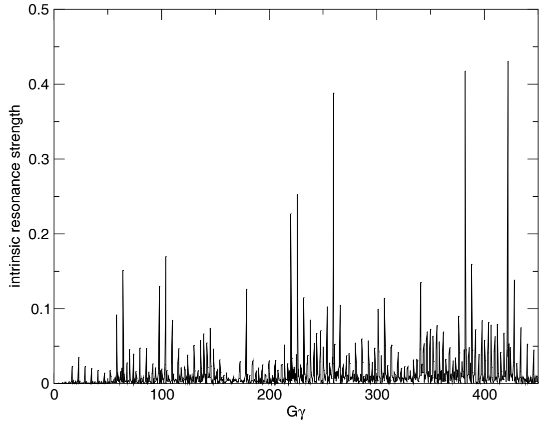

Figure 1: RHIC depolarizing intrinsic resonance spectrum.

The coupling resonance is caused by the vertical motion with horizontal betatron frequency due to linear coupling. The strength of coupling resonance is proportional to the coupling coefficient in addition to the beam emittance.

The acceleration of polarized proton beam in RHIC from 25 GeV to 250 GeV crosses numerous spin resonances. Fig. 1 shows the intrinsic spin resonance strength as a function of $G\gamma$. In general, the strength of an intrinsic resonance is proportional to the square root of beam vertical emittance; the strength of an imperfection resonance is proportional to the rms closed orbit error.

With snakes in the ring, the spin tune is always 1/2 and energy independent. Thus, all imperfection, intrinsic and coupling resonance conditions can be avoided. However, when the spin resonance strength is large, a new class of spin-depolarizing resonances can occur. These resonances, due to coherent higher-order spin-perturbing kicks, are called snake resonances [4] and located at

$$\Delta\nu_y = \frac{k \pm \nu_{sp}}{n}, \tag{3}$$

where $\Delta\nu_y$ is the fractional part of vertical betatron tune, n and k are integers, and n is called the Snake resonance order. The snake resonances can be divided into two categories, even order resonances (when n is even integer) and odd order resonances (when n is odd integer). With the two snakes configuration in RHIC, the even order snake resonances are suppressed with no closed orbit errors, but will appear when the intrinsic resonance overlaps an imperfection resonance. For these two reasons, the orbit and tune control are very important to suppress the resonance strength and to stay away from the resonance conditions.

RHIC ACCELERATOR CHAIN

The Brookhaven polarized proton facility complex is shown schematically in Fig.2. The polarized H$^-$ beam from the optically pumped polarized ion source(OPPIS) [5] was accelerated through a radio frequency quadrupole and the 200 MeV LINAC. During the run, the polarization measured by the 200 MeV polarimeter was about 80%. The

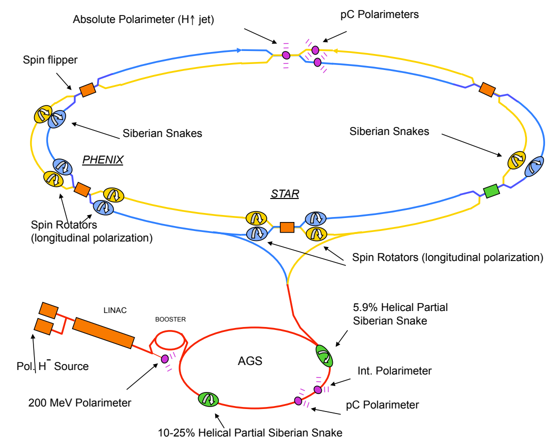

Figure 2: The Brookhaven polarized proton facility complex, which includes the OPPIS source, 200 MeV LINAC, the AGS Booster, the AGS, and RHIC. The clockwise ring is called Blue ring and the counter-clockwise ring is called Yellow ring. There are six IPs in RHIC. Two large detectors, STAR and PHENIX resides at six and eight o'clock IPs, respectively. Two polarimeters at straight section in 12 o'clock region from each ring provide fast relative polarization measurement. A polarized jet target at IP12 is used to measure absolute polarization. Two snakes are installed at three and nine o'clock sections in each ring.

beam was then strip-injected and accelerated in the Booster up to 2.4 GeV or $G\gamma = 4.5$. The vertical betatron tune of the Booster was chosen to be 4.9 in order to avoid crossing the intrinsic resonance $G\gamma = 0 + \nu_y$. The imperfection resonances at $G\gamma = 3, 4$ were corrected by harmonic orbit correctors.

The Alternative Gradient Synchrotron (AGS) has been running as RHIC polarized proton injector with two partial snakes [6] since 2006. One partial snake is a 1.53T normal conducting helical magnet (a.k.a. warm partial snake) [7] and the other is a 3T superconducting helical magnet (a.k.a cold partial snake). With the vertical tune set inside the spin tune gap generated by the two partial snakes, all vertical intrinsic and imperfection resonances are avoided [8]. In addition, a horizontal tune jump quadrupole system which can generate tune jump of 0.05 in 100μs for 82 times along the AGS ramp (0.5 sec) was also used to overcome the horizontal intrinsic resonances [9]. The horizontal tune jump system has been commissioned in past two years and has been used for RHIC operation this year. It provides about 3-5$\%$ polarization gain. The typical polarization out of AGS is about 70$\%$.

RHIC is equipped with two snakes located at 3 o'clock and 9 o'clock in each ring. The tune/oupling/orbit feedbacks are on for all ramps. To provide longitudinal polarization at experimental IPs, spin rotators are ramped in a separate ramp after energy ramp. All feedbacks are on for this ramp, too. The β^* of the two major experiments is set as 0.65m. The working point is around (0.685, 0.675) for both rings. Dynamic aperture simulation [10] shows better dynamic aperture for a working point below the ($\nu_y - \nu_x = 0$) diagonal line. The transition energy was lowered by 0.5 unit by using gamma jump quads such that the injection energy is further away from the transition energy.

Polarization are measured by the two fast relative p-carbon polarimeters [11] in each ring. Polarization profiles are associated with polarization losses. It is important to measure polarization profiles in both vertical and horizontal planes for spin dynamics. The two polarimeters in each ring provide such information (one for vertical and one for horizontal) in the fill by fill bases. These measurements are fast but relative. The absolute polarization is provided by the polarized hydrogen jet target [2].

Several factors prevented increasing bunch intensity in run9. First, we observed more frequent magnet quenches when dumping beam with bunch intensity above 1.1×10^{11}. The beam dump system has been upgraded to accommodate a bunch intensity above 1.4×10^{11}. Secondly, electron cloud effect will be stronger with more bunch intensity. The effect is strongest at injection.

RHIC OPERATION

The first 250 GeV polarized proton physics operation was in 2009. There were polarization losses on the energy ramp. There are several possible sources of the polarization losses. First, it was found during run10 that many of the RHIC BPM offsets were put in with wrong signs. These included all vertical and half of the horizontal BPMs. The rms values of these offsets are around 0.5mm in both horizontal and vertical planes. The vertical orbit on the ramp could be at 1.3-1.5mm due to this sign error instead of the face value of 0.3-0.5mm. The effect on spin tune from imperfection resonances might create problems above 100 GeV. The corresponding imperfection resonance strength reaches 0.16 in the Blue ring, which is twice as large as the tolerance value. The large vertical orbit on the ramp caused an interference between imperfection and snake resonances. Second, a detailed tune scan near the working point (0.69, 0.68) revealed that the 7/10 snake resonance had a wide width. The vertical tune needs to be pushed as far as possible away from 0.7. As 2/3 orbit resonance is nearby, the chromaticity and tune control has to be very good to push the vertical tune close to 2/3. To improve the polarization transmission efficiency, the betatron tunes are pushed down to (0.685, 0.675) between 100 GeV and 250 GeV this year. Third, it was demonstrated that the spin tune shift due to the snake orbit angles can generate polarization loss when the spin resonances is shifted towards the vertical betatron tune.

Orbit Related Effects

With two snakes installed in RHIC, the first order resonance conditions (imperfection and intrinsic) have been avoided, because the spin tune is a constant 1/2. In reality, many factors can lead to spin tune shift and spin tune spread. A possible polarization loss is due to high order snake resonances. The orbit error can have a significant effect on the snake resonances. First, the spin tune shift ($\delta\nu_s$) leads to a split and shift of the snake resonance locations. Second, the snake resonance width is also affected. The even order snake resonances will be excited in the presence of orbit errors. The odd order snake resonances will get enhanced by factor $\pi^2|\epsilon_{imp}|^2$. This is only important for very strong resonances, so it is important to maintain $|\epsilon_{imp}| \ll 1$.

The spin tune shift due to horizontal orbit angles in snakes are given by [12]

$$\delta\nu_{sp} = \frac{1+G\gamma}{\pi}\alpha_{sn}, \tag{4}$$

where

$$\alpha_{sn} = x'_{co\_sn9} - x'_{co\_sn3}. \tag{5}$$

As the 7/10 resonance shift is less than 0.001, we need to maintain the spin tune shift less than 0.005, which corresponds to $\alpha_{sn} < \pm 30\mu$rad. With orbit and tune feedback working well this year, the variation of the horizontal orbit angles at the snake locations are well within the limit.

The spin tune shift due to horizontal dispersion angles in the snakes are given by

$$\delta\nu_{sp} = \frac{1+G\gamma}{\pi}\delta D'_{sn}(\frac{\Delta p}{p})_{ave}, \tag{6}$$

where

$$\Delta D'_{sn} = D'_{sn9} - D'_{sn3}. \tag{7}$$

In the regular RHIC lattice, the design value of $\Delta D'$ is about 54 mrad, which can not be changed easily. The only meaningful way to reduce this effect is to reduce the momentum spread by using 9MHz cavity.

9MHz cavity

It is desired to have shorter bunches at store for higher luminosity within the vertex cuts of experiment detectors. However, short bunches during the ramp enhance the electron cloud effect, which results in lower luminosity because of transverse emittance growth and instability. In the past, the bunches were long because we blew up the longitudinal emittance at injection by a mismatch between the bunch (AGS) and bucket (RHIC, 28MHz). As the result, a longer bunch was obtained at the cost of a large bunch emittance. It reduced the effective luminosity within the vertex cuts. The objective of 9MHz cavity is to have long bunches on the ramp and short bunches during store. 9MHz cavity is a common cavity to both rings. With the special design, it can have much lower voltage to match the beam coming from AGS. With the 9MHz cavity, the bunch length remains long on the ramp without blowing up the longitudinal emittance at injection. A longer bunch helps mitigate the electron cloud effect on the ramp. At the same time, the longitudinal emittance is preserved so that rebucketing with 197MHz cavity at store is possible. The 9MHz cavity is operational and it provides smaller bunch length at store. The shorter bunches are shown in Figures 3-4.

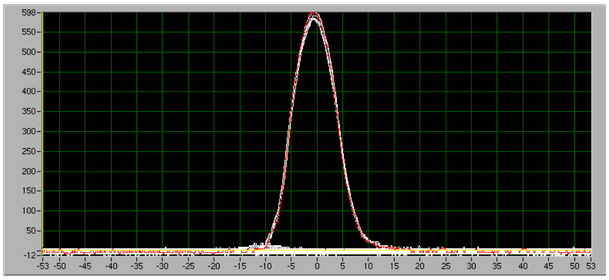

Figure 3: Bunches at store with 28MHz RF cavity on the ramp. The horizontal axis is in ns.

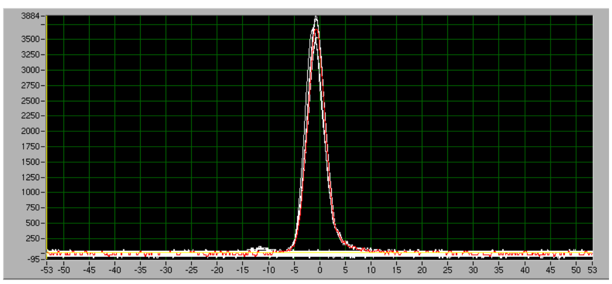

Figure 4: Bunches at store with 9MHz RF cavity on the ramp and rebucketing with 197MHz. The horizontal axis is in ns.

Orbit and Tune Control

The ramp efficiency has improved with high bunch intensity in this run: the ramp efficiency for both rings is around to 99%. This is the result of tune and orbit control on the ramp. The tune, couping and orbit feedbacks became a routine operation.With all feedback on, the reproducibility of a ramp is not an issue. With the orbit feedback, the vertical rms closed orbit error is less than 0.1mm (see Fig. 5), well within the specification value of 0.3 mm to maintain polarization on the energy ramp. The horizontal orbit angle at the snake locations can also be kept almost a straight line without much variation during the ramp. The tune feedback kept the betatron tune at the desired values, which make it possible to push the tune closer to 2/3 resonance [13]. Between 100 and 240sec, there are three strong intrinsic resonances. The vertical tune is pushed down to be away from the 7/10 and 11/16 snake resonances (see Fig. 6).

A new vertical survey was done before the run and the misalignments as large as 2mm were eliminated. With the reversal of the BPM offsets, both RHIC rings are flatter than before. With large errors, the effect on spin tune from imperfection resonances leads to polarization loss above 100 GeV. However, it is worth of note that the effect on snake angles is small.

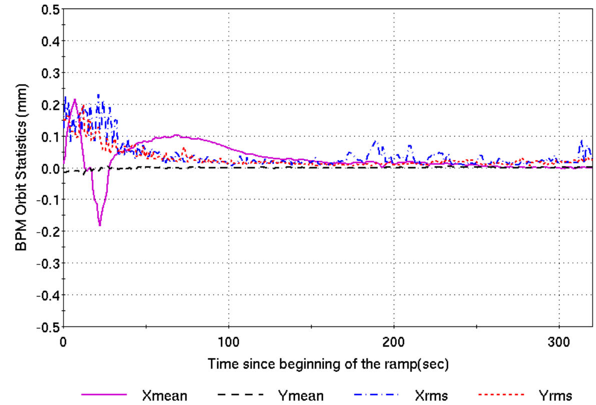

Figure 5: An example of yellow orbit on the ramp. Both rms closed orbit errors of horizontal and vertical are close to zero.

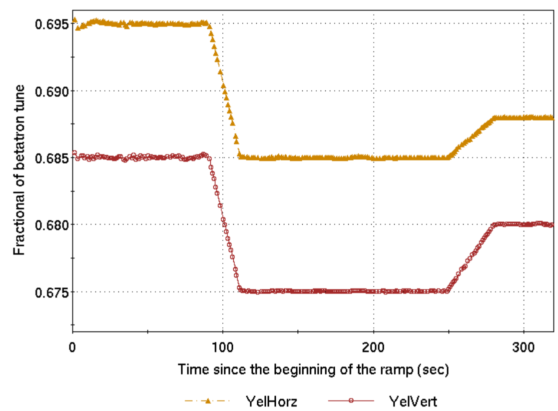

Figure 6: An example of measured yellow betatron tunes on the energy ramp. The tune swings on the ramp are necessary to push tune closer to 2/3 so that effect on polarization can be minimized.

10Hz Orbit Feedback

Vibration of the cryogenic triplet magnets are suspected to be the cause of the closed orbit oscillations at frequencies close to 10 Hz (7800 turn periodicity). They reach several millimeters in the focusing triplets ($\beta^* \sim 1$ m). This gives rise to modulated beam-beam jitter at the interaction point (IP) which can lead to emittance growth and luminosity loss for sufficiently large beam-beam offsets. Several solutions to counteract the effect have been considered in the past, including reinforcing the magnet base support assembly, a mechanical servo feedback system, and a local beam feedback system at each of the two experimental IPs. However, the mechanical solution is very expensive and the local one does not really solve problems outside the experiment IPs. The global orbit feedback is the better solution in both expense and performance. As shown in

Fig. 7, the 10Hz orbit oscillations are greatly reduced and the oscillations in the luminosity are also eliminated [14].

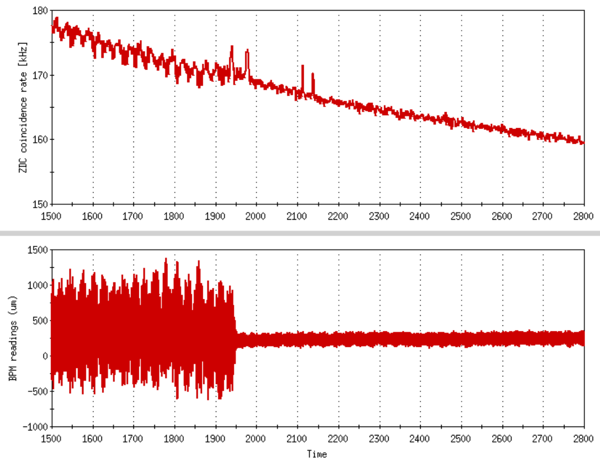

Figure 7: Luminosity with and without 10Hz orbit feedback. Top: luminosity. A few spikes are due to polarization measurements. Bottom: BPM signals with feedback off(early) and on(later).

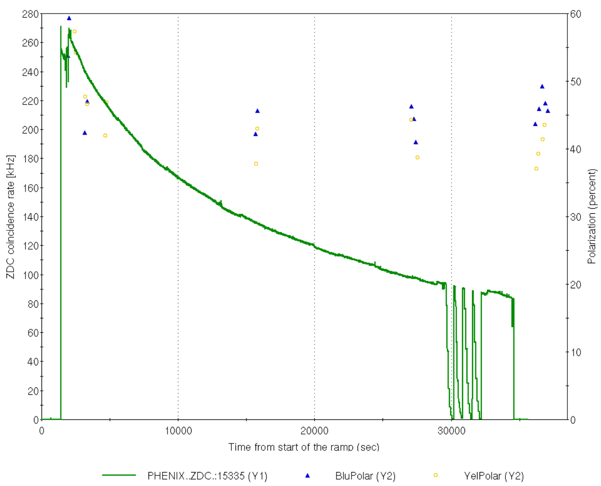

Figure 8: Luminosity at PHENIX and polarization of a typical store. Vernier scan was done near the end of this store.

CONCLUSION

Siberian snakes are essential tools to preserve polarization when accelerating polarized beams to higher energy. At the same time, the higher order resonances still can cause polarization loss. As seen in RHIC, the betatron tune has to be carefully set and maintained on the ramp and during the store to avoid polarization loss. In addition, the orbit control is also critical to preserve polarization.

The higher polarization during this run comes from several improvements over last run. First we have a much better orbit on the ramp. The orbit feedback brings down the vertical rms orbit error to 0.1mm, much better than the 0.5mm last run. With correct BPM offset and vertical realignment, this rms orbit error is indeed small. Second, the jump quads in the AGS improved input polarization for RHIC. Third, the vertical tune was pushed further away from 7/10 snake resonance. The tune feedback maintained the tune at the desired value through the ramp.

To calibrate the analyzing power of RHIC polarimeters at any energy above injection, the polarized hydrogen jet target runs for every fill with both beams [2]. Based on the known analyzing power, there is very little polarization loss between injection and 100 GeV. An alternative way is to measure the asymmetry at 100 GeV followed by ramping up to 250 GeV and back down to 100 GeV and then to measure the asymmetry again at 100 GeV. If the asymmetry after the down ramp is similar to the measurement before the up ramp, polarization was also preserved during the ramp to 250 GeV. The analyzing power at storage energy can then be extracted from the asymmetries measured at 100 GeV and 250 GeV. The tune and orbit feedbacks are essential for the down ramp to be possible.

The polarized proton operation is still going on. We will push bunch intensity higher until reaching the beam-beam limit. The even higher intensity will have to wait for the electron lenses to compensate the beam-beam effect. To understand the details of spin dynamics in RHIC with two snakes, spin simulation with the real magnet fields have been developed recently [15]. The study will provide guidance for possible polarization loss schemes. Further polarization gain will requires a polarized source upgrade; more careful setup jump quads in the AGS to get full benefit; and control emittance in the whole accelerator chain.

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