# RHIC SPIN FLIPPER COMMISSIONING RESULTS*

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## *Abstract*

The five AC dipole RHIC spin flipper design in the RHIC Blue ring was first tested during the RHIC 2012 polarized proton operation. The advantage of this design is to eliminate the vertical coherent betatron oscillations outside the spin flipper [1]. The closure of each ac dipole vertical bump was measured with orbital response as well as spin. The effect of the rotating field on the spin motion by the spin flipper was also confirmed by measuring the suppressed resonance at $Q_s = 1 - Q_{osc}$.

## INTRODUCTION

RHIC spin flipper was designed to minimize the systematic errors of spin physics experiments by reversing the spin direction of the two colliding beams multiple times during a store. It also allows one to measure spin precession frequency by adiabatically exciting a coherent spin precession. Since the precession frequency is known, one can determine the spin precession frequency by carefully measuring the amplitude of the spin vector projection in the horizontal plane. For the desired spin manipulations at RHIC in the presence of a dual snake configuration, the design of the RHIC spin flipper is to achieve a rotating field, i.e. with the precession axis rotating in the horizontal plane [2]. Unlike the traditional technique of a single RF spin rotator, this rotating field only induces one spin resonance at $Q_s = Q_{osc}$, where $Q_s$ is the spin tune, the number of spin precessions in one orbital revolution, and $Q_{osc}$ is the spin flipper tune. Since the resonance at $Q_s = 1 - Q_{osc}$ is eliminated, a full spin flip can be obtained with the spin tune staying at half integer. The original design of two AC dipoles with a DC spin rotator in between showed that the global coherent betatron oscillation excited by the two AC dipoles broke the condition for a rotating field, and both resonances at $Q_s = Q_{osc}$ as well as $Q_s = 1 - Q_{osc}$ were measured [1].

Hence, the RHIC spin flipper design was modified by adding three more AC dipoles to form two closed vertical orbital bumps and eliminating the global coherent vertical oscillation outside spin flipper [1]. Fig. 1 shows the schematic drawing of the current RHIC spin flipper design where five AC dipoles are arranged with equal spacing between them. AC dipole #1, #2 and #3 can be powered to form a closed orbital bump by energizing AC dipole #1 and #3 with half of the current in AC dipole #2 but opposite polarity. Similarly, AC dipole #5, #4 and #3, can be powered to form another closed orbital bump. The phase between the currents in AC dipole #2 and #4 are chosen to satisfy

$$\chi_1 - \chi_2 = \psi_0, \tag{1}$$

where $\psi_0$ is the amount of spin rotation of each DC spin rotator, and $\chi_{1,2}$ is the initial phase of AC dipole #2 and #4, respectively . $\chi_{1,2}$ are also the initial phases of the two vertical bumps excited by AC dipoles. The effective spin resonance strength of this design $\epsilon_k$ then becomes

$$\epsilon_k = 2\phi_{osc} \sin\psi_0 \sin\frac{\psi_0}{2}, \tag{2}$$

where $\phi_{osc}$ is the amplitude of the spin rotation of AC dipole #2 or #4. The four DC spin rotators share the same power supply. The two DC spin rotators in the middle of the spin flipper have the same polarity, which is opposite to the polarity of the two outside DC spin rotators.

For this new design, the DC spin rotator power supply was also upgraded to reach a spin rotation of $45°$. A set of numerical spin simulations with RHIC polarized proton lattice were carried out, and confirmed that full spin flip can be achieved with the current RHIC spin flipper design. The spin tracking with off momentum particles also shows the impact of synchrotron oscillation on spin flipping. The spin tune spread due to the asymmetry of the dispersion slope at the two snakes can cause multiple resonance crossing during the spin flipping and result in polarization loss. Since it is extremely difficult to match the dispersion slope at the two snakes due to the intrinsic property of the RHIC lattice, one practical way to mitigate the problem is to use the 9MHz RF system which reduces synchrotron tune by a factor of 3 [3].

## EXPERIMENTAL RESULTS

The system was first tested during the latest RHIC polarized proton operation in 2012. The closure of the each AC dipole bump was first measured at injection energy. In this paper, AC dipole bump #1 is referred to the vertical bump by exciting AC dipole $\#1$, $\#2$ and $\#3$, AC dipole bump #2 is referred to the vertical bump with AC dipole $\#3$, $\#4$ and $\#5$.

To excite both AC dipole bumps, AC dipole #3 current is the linear composition of AC dipole #1 and #5 as shown in Eq. 7.

$$I_2 = I_0 sin(2\pi Q_{osc} i + \chi_1) \tag{3}$$

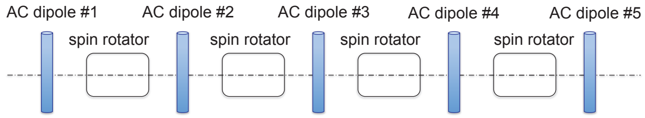

Figure 1: The schematic layout of RHIC spin flippers new design. This system is located in the insertion region up stream of IP10 in the Blue ring of RHIC.

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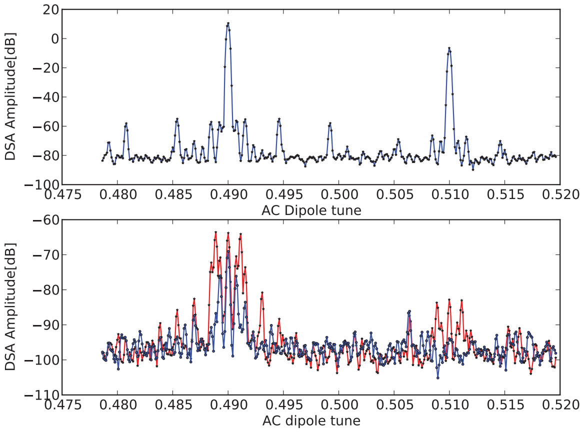

Figure 2: The top plot is the DSA beam motion spectrum when excited by a single AC dipole at a tune of 0.49 and current amplitude of 90 Amp. The peak at 0.49 is evident. The bottom plot shows the DSA beam motion spectrum when excited by AC dipole bump #1 and #2, respectively. The red curve corresponds to AC dipole bump #1 and the blue curve is the spectrum of AC dipole bump #2. Both bumps were excited by AC dipoles at a tune of 0.49 with the AC dipole #2 or #4 current amplitude at 90 Amp. The peak at 0.49 is suppressed by at least 50 dB in comparison to the the single AC dipole case.

$$I_4 = I_0 sin(2\pi Q_{osc} i + \chi_2) \tag{4}$$

$$I_1 = \frac{1}{2} I_0 sin(2\pi Q_{osc} i + +\chi_1 + \pi) \tag{5}$$

$$I_5 = \frac{1}{2} I_0 sin(2\pi Q_{osc} i + +\chi_2 + \pi) \tag{6}$$

$$I_3 = I_1 + I_5 \tag{7}$$

where $I_k$ is the current of AC dipole #$k$, $i$ is the $i^{th}$ orbital revolution. $\chi_{1,2}$ corresponds to the initial phase of AC dipole bump #1 or AC dipole bump #2, respectively. And $\chi_1 - \chi_2 = \psi_0$, where $\psi_0$ is the amount of spin rotation by each DC spin rotator, is the condition for exciting a single isolated resonance at $Q_s = Q_{osc}$ with spin flipper.

The closure of each AC dipole bump was monitored with Digital Spectrum Analyzer (DSA) located in the insertion region next to IP2, outside the spin flipper. For a perfect closure, the response of DSA at the AC dipole tune should be completely suppressed. Fig. 2 shows the DSA beam motion spectrum with a single AC dipole as well as with each AC dipole bump. For all the above measurements, the DC spin rotators remained off. The sidebands in the DSA beam motion spectrum were attributed to noise coupled into the AC dipole controls through cabling. This is responsible for the incomplete closure of the AC dipole bumps.

The effect of global coherent orbital oscillation from AC dipole was observed in the 2009 RHIC polarized proton run [1]. A detailed polarization measurement at injection as a function of spin tune by adjusting snake current showed both resonances at $Q_s = Q_{osc}$ as well as $Q_s = 1 - Q_{osc}$. During the latest RHIC polarized proton operations, the effect of a single AC dipole as well as each AC dipole bump on spin was measured with spin tune at 0.49, 0.5 and 0.51 at injection. The experimental result is shown in Table 1, and confirmed the measurement in 2009, i.e. the global vertical coherent oscillation is the direct cause of the excitation of resonance at $Q_s = 1 - Q_{osc}$. Here, Pol in Table 1 stands for measured polarization. All the above measurements were carried out without DC spin rotators. Most of the beam polarization measurements were done with Blue CNI polarimeter #1, except the two polarization measurements for single AC dipole with spin tune at 0.49 and 0.50. Those two measurements were done with Blue CNI polarimeter #2. Both polarimeters measure the relative polarization of the beam and have not yet been calibrated at RHIC injection energy.

Table 1: Effect of single AC dipole as well as closed AC dipole bump on the beam polarization at injection

| | **Pol[%]** $Q_s = 0.49$ | **Pol[%]** $Q_s = 0.502$ | **Pol[%]** $Q_s = 0.51$ |
|---|---|---|---|
| **baseline** | 59.79± 3.1 | 62.06± 1.57 | 61.63± 1.77 |
| **single ac dipole** | 4.18± 3.84 | 48.86±3.7 | 18.48± 2.10 |
| **ac dipole bump #1** | 61.05± 2.19 | – | 62.32± 2.10 |
| **ac dipole bump #2** | 59.7± 2.6 | 60.31± 1.8 | 63.0± 1.9 |

Limited by physical aperture, the DC spin rotator can only be excited to 894.33 Amps at injection. This corresponds to a spin rotation of $\psi_0 = 28.77°$ around vertical axis, based on the measured transfer function of DC dipoles. The five AC dipoles were then powered to excite two AC dipole bumps at a tune of 0.49 with a phase difference of $\Delta\chi = \chi_1 - \chi_2$. With this configuration, beam polarization at injection was measured as a function of spin tune as shown in Table 2. For all measurements, AC dipole #1, #3 and #5 currents were set according to Eq. 7. All polarization measurements in Table 2 were the

Table 2: Beam polarization as a function of spin tune for different spin flipper settings at injection

| | **Pol[%]** $Q_s =$ 0.49 | **Pol[%]** $Q_s =$ 0.50 | **Pol[%]** $Q_s =$ 0.51 | **ac di--pole** #2,#4[A] |
|---|---|---|---|---|
| **baseline** | 59.79 ± 3.1 | 62.06 ± 1.57 | 61.63 ± 1.77 | 0 |
| $\Delta\chi$ 28.79° | 23.85 ± 3.04 | –<br>– | 46.25 ± 3.04 | 90 |
| $\Delta\chi$ 29.1° | 23.85 ± 3.04 | 56.65 ± 2.69 | 52.45 ± 2.69 | 45 |
| $\Delta\chi$ −29.1° | 14.12 ± 3.03 | 59.25 ± 2.76 | 22.92 ± 2.86 | 90 |

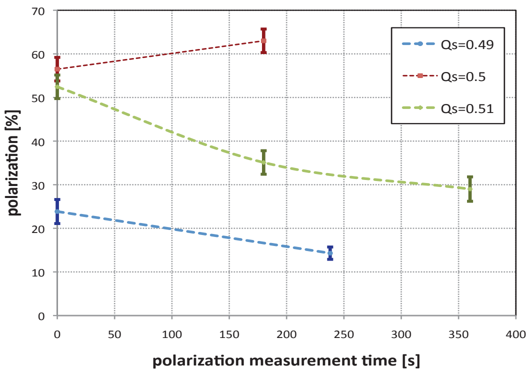

Figure 3: This plot shows the polarization measurement as a function of time in the presence of spin flipper at injection. The spin flipper was set to the condition corresponding to the case of $\Delta\chi = 29.1°$ in Table 2. The three data sets correspond to three different spin tunes achieved by different snake currents.

first polarization measurement right after the spin flipper was turned on. Resonance at $Q_s = Q_{osc} = 0.49$ was clearly observed. With $\chi_1 - \chi_2 \sim \psi_0 = 28.77°$, resonance at $Q_s = 1 - Q_{osc} = 0.51$ was significantly weakened, which indicated the existence of rotating field. However, depolarization was observed with beam stored in the presence of spin flipper. Fig. 3 shows the polarization as a function of time with $\Delta\chi = 29.1°$ in Table 2 for different spin tune. This shows that the resonance at $Q_s = 0.51$ was not perfectly cancelled. Since perfect cancellation of the resonance at $Q_s = 1 - Q_{osc}$ critically depends on whether the phase between the two AC dipole bumps is set properly, any deviation results in a residual resonance at this location and can cause depolarization if the spin flipper tune is fixed at 0.49. The strength of the residual resonance at $Q_s = 1 - Q_{osc}$ is proportional to how fast polarization gets lost. Fig. 4 shows the vertical component of proton spin vector in the presence of spin flipper as a function of orbital revolutions from spin tracking with RHIC polarized proton lattice. This demonstrates that complete cancellation of $Q_s = 1 - Q_{osc}$ is very sensitive to the phase between the two ac dipole bumps. Hence, a detailed scan of $\Delta\chi$ should be able to minimize the resonance at $Q_s = 1 - Q_{osc}$. The numerical spin tracking results in Fig. 4 were done with the RHIC polarized proton lattice using zgoubi [4].

## CONCLUSION

The new design of RHIC spin flipper was first tested at RHIC injection during the latest polarized proton operation in 2012. The experimental data confirmed that the excitation of the resonance at $Q_s = 1 - Q_{osc}$ is due to the global vertical coherent oscillation. The experimental data also demonstrated the significant weakening of resonance at $Q_s = 1 - Q_{osc}$ if the spin flipper is configured properly, which is the first experimental indication of a rotating spin field. Due to the limit of beam time, no detailed scan of phase between the two AC dipole bumps was carried out to minimize the resonance strength at $Q_s = 1 - Q_{osc}$.

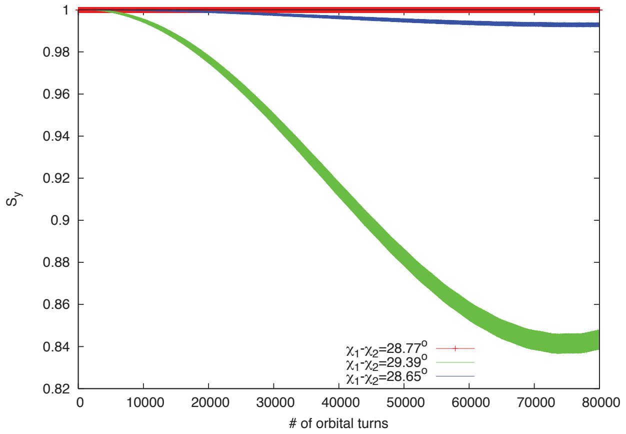

Figure 4: This plot shows the spin tracking of a single particle in the presence of spin flipper at RHIC injection energy. The DC spin rotators were set to a spin rotation of $\psi_0 = 28.77°$. The three data sets correspond to the phase between two AC dipole bumps at 28.77°, 28.65° and 29.39°, respectively. Evidently, the cancellation of resonance $Q_s = 1 - Q_{osc}$ is very sensitive to the phase between the two AC dipoles.

During the experiment, the closure of AC dipole bumps couldn't be optimized below -60dB due to the noise coupled into the AC dipole controls, which drove sidebands. This can also contribute to the incomplete cancellation of the resonance at $Q_s = 1 - Q_{osc}$. The noise source has been identified during the RHIC operation and will be fixed during the shut-down.

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