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Relativistic Heavy Ion Collider spin flipper commissioning plan

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Abstract. The commissioning of the RHIC spin flipper in the RHIC Blue ring during the RHIC polarized proton run in 2009 showed the detrimental effects of global vertical coherent betatron oscillation induced by the 2-AC dipole plus 4-DC dipole configuration [1]. This global orbital coherent oscillation of the RHIC beam in the Blue ring in the presence of collision modulated the beam-beam interaction between the two RHIC beams and affected Yellow beam lifetime. The experimental data at injection with different spin tunes by changing the snake current also demonstrated that it was not possible to induce a single isolated spin resonance with the global vertical coherent betatron oscillation excited by the two AC dipoles. Hence, RHIC spin flipper was re-designed to eliminate the coherent vertical betatron oscillation outside the spin flipper by adding three additional AC dipoles. This paper presents the experimental results as well as the new design.

1. Introduction

In order to minimize the systematic errors for the RHIC spin physics experiments, a spin flipper was installed in the Blue ring of RHIC (Relativistic Heavy Ion Collider) at Brookhaven National Lab to reverse the spin direction of the two colliding beams multiple times during a regular physics store.

RHIC as a high energy polarized proton collider employs two pairs of full Siberian snakes to avoid polarization loss during the acceleration and store [2]. In each accelerator, the two snakes are located diametrically opposed with their spin precession axes perpendicular to each other, and the nominal spin precession tune [3] in RHIC is $Q_s = \frac{1}{2}$ [2]. This makes the traditional spin flipping technique of using a single AC spin rotator (a dipole or a solenoid) not possible because it induces a spin resonance not only at $Q_s = Q_{osc}$ but also $Q_s = 1 - Q_{osc}$ [1]. Here, Q_{osc} is the RF spin rotator oscillating frequency in unit of the orbital revolution frequency.

The first design of the RHIC spin flipper consists of two AC dipoles with a DC spin rotator in between to achieve a rotating field, i.e. with its axis rotating in the horizontal plane [4]. Unlike the traditional technique, this rotating field only induces one spin resonance at $Q_s = Q_{osc}$. Since the resonance at $Q_s = 1-Q_{osc}$ is eliminated, a full spin flip can be obtained with spin precession tune staying at half integer.

Fig. 1 shows the schematic layout of the spin flipper for RHIC with two AC dipoles, a two side-by-side DC spin rotators and two DC spin rotators on either side of the two AC dipoles. Each DC spin rotator rotates the spin vector around a vertical axis. All DC spin rotators are powered with the same current. But the DC spin rotators on either side of the two AC dipoles

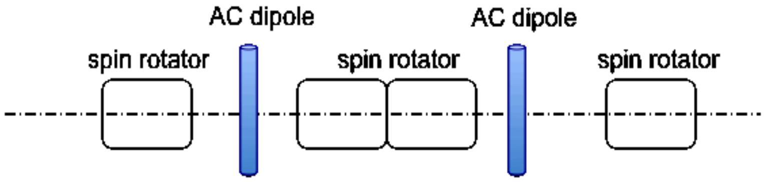

Figure 1. The schematic layout of RHIC spin flippers with two AC dipoles

and the DC spin rotators in the center of the spin flipper are configured with opposite polarity to cancel the spin rotation by the center DC spin rotators and keep the spin tune unchanged. This arrangement also localizes the horizontal orbit deflection by the DC spin rotators inside the spin flipper. With the two snakes in each ring, the spinor one turn map of RHIC in the presence of spin flipper becomes

$$OTM = (-i\sigma_2)e^{-\frac{i}{2}G\gamma\pi\sigma_3}(-i\sigma_1)e^{-\frac{i}{2}G\gamma\pi\sigma_3}M_{sflip} \tag{1}$$

where

$$\begin{aligned} M_{sflip} &= e^{\frac{i}{2}G\gamma\phi_0\sigma_3}e^{-\frac{i}{2}\phi_{\rm osc}\cos(Q_{\rm osc}\theta+\chi_2)\sigma_1}e^{-\frac{i}{2}2\phi_0\sigma_3} \\ & \quad e^{-\frac{i}{2}\phi_{\rm osc}\cos(Q_{\rm osc}\theta+\chi_1)\sigma_1}e^{\frac{i}{2}G\gamma\phi_0\sigma_3} \end{aligned} \tag{2}$$

where $\sigma_{1,2,3}$ are the 2×2 Pauli matrices, ϕ_0 is the amount of spin rotation from each spin rotator, ϕ_{osc} is the amplitude of the spin rotation of each AC dipole and $\chi_{1,2}$ is the initial phase of the two AC dipoles, respectively. One can prove that for a small $\phi_{\rm osc}$ and

$$\chi_1 - \chi_2 = 180^\circ + 2\phi_0, \tag{3}$$

M_{sflip} in Eq. 2 is equal to

$$M_{sflip} = e^{-\frac{i}{2}\phi_{\rm osc}\sin2\phi_0[\sin(Q_{\rm osc}\theta+\chi_2)\sigma_1-\cos(Q_{\rm osc}\theta+\chi_2)\sigma_2]} \tag{4}$$

which is the spin transfer matrix for a rotating field [4]. The strength of the spin flipper without the contribution from the coherent betatron oscillation driven by the AC dipoles is $\phi_{osc}\sin 2\psi_0$. For the first design of RHIC spin flipper, the DC spin rotators were designed to achieve 15° rotation angle at 100 GeV and 250 GeV, i.e. a dipole field of 0.45 Tesla-m. This corresponds to an orbital deflection of 2.73 mrad at the center of the spin flipper for 100 GeV and 1.07 mrad for 250 GeV.

2. Experimental results of RHIC spin flipper

In 2009, a set of measurements with the two AC dipole design of RHIC spin flipper was taken. The four DC spin rotators were first energied to their design currents to confirm that the horizontal orbital bump from the DC spin rotators was localized. The coherent betatron oscillation driven by the AC dipoles, however is global. This, in turn, drives a spin resonance at $Q_s = Q_{osc}$ as well as at $Q_s = 1 - Q_{osc}$. If this effect is not neglibible in comparison to the spin resonance due to the rotating field from the spin flipper, the condition of inducing a single isolated resonance can't be met and spin flipping can't be achieved in the presence of 1/2 spin tune [5].

In order to study the spin resonance strength due to the driven coherent betatron oscillation, the two AC dipoles were energied with the same oscillating amplitude but opposite phase.

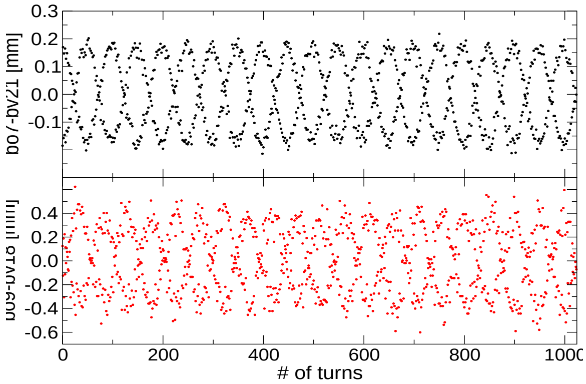

Figure 2. The top plot shows the turn by turn beam position data from one of the beam position monitors located in the middle of the arcs when the two AC dipoles were energized with opposite phase at RHIC injection. The bottom plot is the turn by turn beam position data in the arcs when a single AC dipole was on at injection, scaled from the measurement at a beam energy of 100 GeV. In both cases, a driven vertical coherent oscillation was evident.

In the absence of all the DC spin rotators, this configuration cancelles the amount of kicks on the spin vector from the two AC dipoles, while orbital effects aren't cancelled. With an amplitude of 10 Amp in both AC dipoles at 0.49 oscillating frequency in unit of orbital revolution frequency, the size of the residual driven coherent betatron oscillation in the middle of the arcs was about 0.15 mm at RHIC injection as shown in top plot of Fig. 2. Polarized protons were then injected with this configuration and polarization was measured with different spin tunes by adjusting the currents of the two snakes. The data in black dots in Fig. 3 shows the measured beam polarization as a function of spin tune. This data set confirmes that the global betatron oscillation is responsible for the excitation of the resonance at both $Q_s = Q_{osc}$ and $Q_s = 1 - Q_{osc}$.

Similar measurements were also done at injection for a single ac dipole with the same oscillating amplitude and frequency as the two ac dipoles case. In this case, the DC spin rotators were also on at a current corresponding to 15^o spin rotation. The spin resonance strength due to the oscillating field of the AC dipole along is $\frac{1+G\gamma}{4\pi}\frac{B_m L}{B\rho} \sim 8 \times 10^{-5}$ and the size of the driven coherent betatron oscillation in the middle of the arcs was about 0.5mm as shown in the bottom plot of Fig. 2.

The comparison of these two data sets shows that the width of the two induced spin resonances is independent of the size of the coherent drive osicllation, and indicates that this could be due to spin tune spread in the beam as well as the frequency spread in the AC dipoles. Detailed analysis was carried out using a model of two isolated spin resonances at $Q_s = Q_{osc}$ and $Q_s = 1 - Q_{osc}$ with non-zero spin tune spread as shown in Eq. 5.

$$P_f = P_i \int_{Q_{s0}}^{Q_{osc}} \frac{(Q_s - Q_{osc})^2}{(Q_s - Q_{osc})^2 + \epsilon^2} \frac{1}{\sqrt{2\pi} d} e^{-\frac{(Q_s - Q_{s0})^2}{2d^2}} dQ_s \tag{5}$$

where $P_{f,i}$ are the polarization measured with AC dipole(s) on and off, respectively. ϵ is the effective spin resonance strength for each case, and it was 0.0002 and 0.00006 for the case with a single AC dipole and two AC dipoles, respectively, obtained by a single particle using zgoubi [7]. The solid and dashed lines in Fig. 3 are calculations for the single AC dipole case and two AC dipole case, respectively. Both calculations assume a spin tune spread of 0.005 as well as ± 0.002 spread of the AC dipole frequency in units of orbital revolution frequency and full polarization loss for particles if the AC dipole tune is within the chromatic spin tune

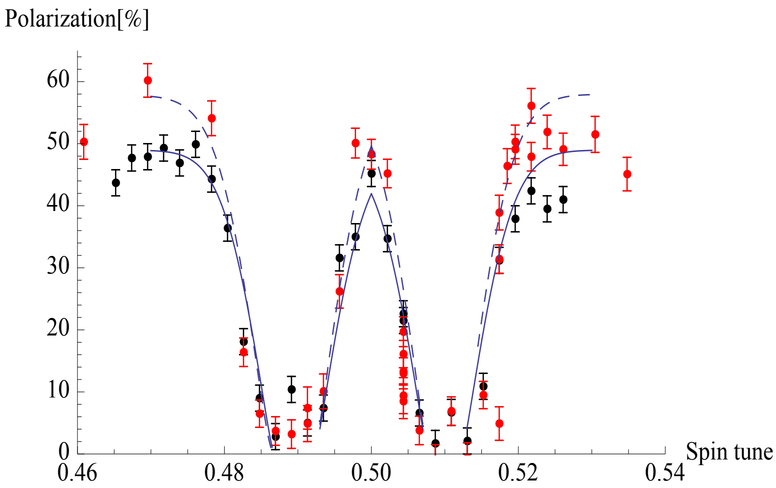

Figure 3. The two data sets in black and red dots correspond to the measured beam polarization for different spin tune with two AC dipoles on or a single AC dipole on, respectively. For both cases, the current amplitude of each AC dipole was 10 Amp and the frequency was set at 0.49 unit of the orbital revolution frequency. For the two dipole case, both AC dipoles were powered with opposite polarity and all DC spin rotators were kept off. And for the single AC dipole case, all the DC spin rotators were energized at a constant current corresponding to a spin rotation of 15^o.

variation of the particles. There is a reasonable match between calculations and experimental data. However, due to the lack of measurement of the dispersion derivative at the two snakes as well as the AC dipole current readback at the time of both measurements, it is hard to check these assumptions against the real beam conditions at the time.

The source of spin tune spread in an accelerator with two snakes is due to the asymmetry of the dispersion derivative at the two snakes,i.e. $\Delta D'$. In presence of the two snakes in RHIC, the non-zero horizontal orbital angle between the two snakes can cause an additional spin tune shift [6], and the spin tune of a particle is given by

$$Q_s = \frac{|\Delta\phi|}{\pi} - (1+G\gamma)\frac{\Delta\theta}{\pi}, \tag{6}$$

where $\Delta\phi$ is the angle between the rotation axes of the two snakes, $\Delta\theta$ is the horizontal angle between the two snakes. Hence, the asymmetry of the dispersion derivative at the two snakes can yield different spin tunes for particles with non-zero momentum offset, i.e. a spin tune spread of $\frac{1+G\gamma}{\pi}\Delta D'\frac{\Delta p}{p}$. Here, $\frac{\Delta p}{p}$ is the momentum spread of the beam. Since the maximum momentum spread at RHIC injection is about 0.001, in order to reduce to the spin tune spread to be less than 0.001, the dispersion derivative at the two snakes has to be matched to 0.07 rad or better.

3. Conclusion and Future Plan

The experimental data with the first RHIC spin flipper design in 2009 demonstrated that the two AC dipole design of the spin flipper failed to induce a single isolated spin resonance due to the global driven coherent oscillation. The data analysis also indicates a significant contribution from the spin tune spread due to the chromatic effect. Further spin tracking also shows that the spin flipping is also very sensitive to noise in the AC dipole spectrum. For the success of commissioning RHIC spin flipper in the coming polarized proton run, efforts in controlling the

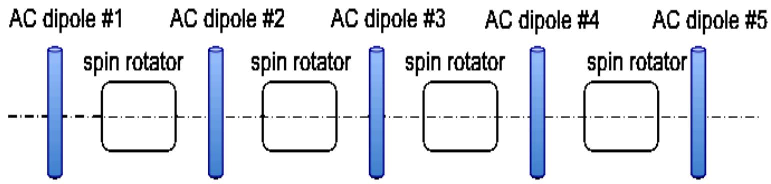

Figure 4. The schematic layout of RHIC spin flippers new design.

dispersion derivative at the two snakes as well as the quality of each AC dipole's spectrum are planned.

In order to eliminate the driven coherent oscillation contribution, the RHIC spin flipper design is modified to add three additional ac dipoles to localize the coherent driven oscillation inside spin flipper. Fig. 4 shows the schematic drawing of the current RHIC spin flipper design. The five AC dipoles are arranged with equal spacing between them. AC dipole #1, AC dipole #2 and AC dipole #3, the AC dipole in the middle can be powered to form a closed orbital bump by energizing AC dipole #1 and AC dipole #3 with half of the current in AC dipole #2 but opposite polarity. Similarly, AC dipole #5, AC dipole #4 and AC dipole #3, can be powered to form another closed orbital bump. The phases between the currents in AC diple #2 and AC dipole #4 are chosen to fullfill $180° - \phi_0$. The effective spin resonance strength of this design then becomes $2\phi_{osc} \sin\psi_0 \sin\frac{\psi_0}{2}$. With the DC spin rotator strength of the two AC dipole design, the effective spin resonance strength would only be 13.5% of the resonance strength of the spin flipper with two AC dipole. In order to increase the effective spin resonance strength, the amount of the spin rotation of each DC spin rotator is increased to 45^o for the new design.

An additional AC dipole was added to the current spin flipper with two AC dipoles during the RHIC summer shutdown in 2009 to allow us to verify the closure of the AC dipole orbital bump during the RHIC Au run in 2010. The direct measurement of the beam spectrum using DSA showed a factor of 100 reduction with the three AC dipoles configured in the closed bump mode in comparison to a single AC dipole case.

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