RHIC SPIN FLIPPER*

M. Bai, A. Luccio, P. Pile, Y. Makdisi, T. Roser
Brookhaven National Laboratory, Upton, NY 11720, U.S.A

Abstract

This paper proposes a new design of spin flipper for RHIC to obtain full spin flip with the spin tune staying at half integer. The traditional technique of using an rf dipole or solenoid as spin flipper to achieve full spin flip in the presence of full Siberian snake requires one to change the snake configuration to move the spin tune away from half integer [1, 2, 3]. This is not practical for an operational high energy polarized proton collider like RHIC where beam lifetime is sensitive to small betatron tune change. The design of the new spin flipper as well as numerical simulations are presented.

INTRODUCTION

RHIC as a high energy polarized proton collider employs full Siberian snakes to avoid the polarization loss during the acceleration and store. Two pairs of Siberian snakes of helical dipoles were installed in the two accelerators of RHIC, respectively. In each accelerator, the two snakes are located 180° apart from each other with their spin precession axes perpendicular to each other. With this configuration, the spin tune in RHIC is $Q_s = \frac{1}{2}$ [4].

In order to cancel the systematic errors for the RHIC spin physics experiments, one would like to reverse the spin directions of the two colliding beams multiple times during the store when data are taken. The traditional technique of obtaining full spin flip is to use an rf dipole or solenoid to adiabatically sweep the rf dipole frequency through the spin precession frequency. However, this requires the spin precession frequency stays away from half of the orbital revolution frequency to achieve full spin flip [5] because a single rf dipole induces not only spin resonance at $Q_s = Q_{osc}$ but also at $Q_s = -Q_{osc}$ as shown in the corresponding spinor equation Eq. 1

$$\frac{d\psi(\theta)}{d\theta} = -\frac{i}{2}[G\gamma\sigma_3 + (1+G\gamma)\frac{B_{\rm osc}L(\theta)}{B\rho} \frac{e^{i(Q_{\rm osc}\theta+\chi)\sigma_3} + e^{-i(Q_{\rm osc}\theta+\chi)\sigma_3}}{2}\sigma_1]\psi(\theta). \quad (1)$$

Here, $\psi(\theta)$ is the two-component spinor and $\sigma_{1,2,3}$ are the three 2×2 Pauli matrices. Q_s and Q_{osc} are the spin precession tune and rf dipole tune, i.e. the spin precession frequency and rf dipole frequency in unit of orbital revolution frequency. $B_{\rm osc}L(\theta)$ is the amplitude of the integrated strength of the rf dipole oscillating field, $\theta_{\rm osc}$ is the azimuthal angle where the rf dipole is located and

$$B_{\rm osc}L(\theta) = B_{\rm osc}L\delta(\theta-\theta_{\rm osc}) \quad (2)$$

* The work was performed under the auspices of the US Department of Energy.

and

$$\int_0^{2\pi}\delta(\theta-\theta_{\rm osc})d\theta = 1. \quad (3)$$

Fig. 1 shows the numerical simulation results of using a single rf dipole as spin flipper. The red line is the spin tracking of a single particle with $Q_s = 0.47$. The strength of this rf dipole induced resonance [6, 7, 8] is

$$\epsilon_k = \frac{1+G\gamma}{4\pi}\frac{\int B_{\rm osc}dl}{B\rho} \quad (4)$$

and a full spin flip is evident. The green line in Fig. 1 is the same spin tracking but with $Q_s = \frac{1}{2}$ and no full spin flip is achieved. Since in practice, RHIC is operated at its beam-beam limit to maximize the luminosity and leaves very limited space for spin tune and betatron tune changes, the luminosity lifetime and beam lifetime is therefore sensitive to any small tune shifts. Hence, it is necessary to look for a new design of spin flipper which allows one to achieve full spin flip at the operational spin tune of $\frac{1}{2}$.

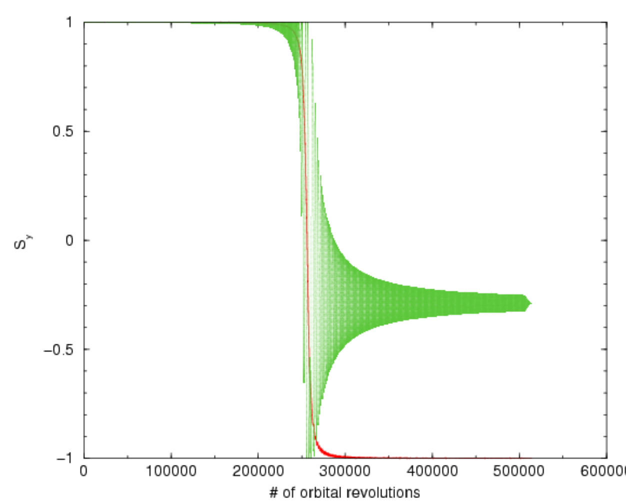

Figure 1: This plot shows the spin tracking results of spin flipping using an rf dipole. The amplitude of the rf dipole integrated oscillating field is adiabatically ramped from 0.0 Gauss-m to 40 Gauss-m in 6000 turns at a fixed tune of $Q_s - 0.01$. The rf dipole tune was then adiabatically sweeping from $Q_s - 0.01$ to $Q_s + 0.01$ in 500000 turns. It was then adiabatically ramped down to zero in another 6000 turns. The red line shows full spin flip when the spin precession tune is set to 0.47 and the green line shows depolarization for a spin tune at 0.5.

1-4244-0917-9/07/$25.00

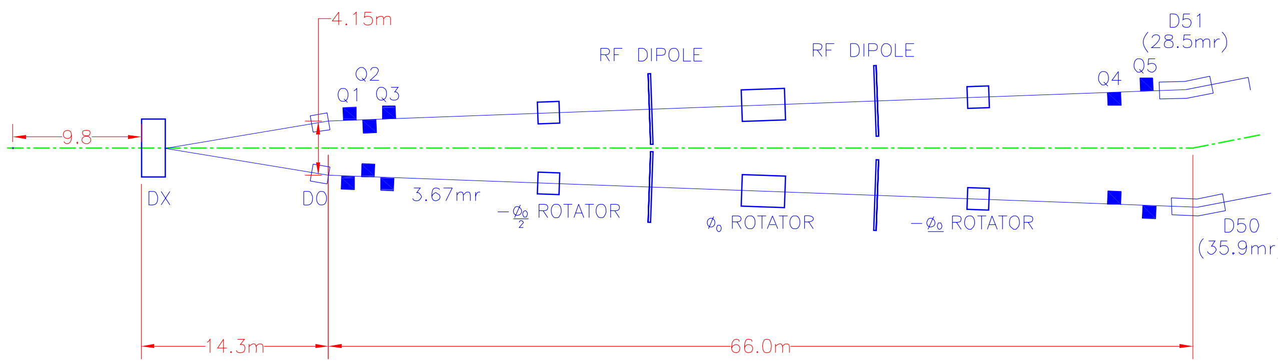

Figure 2: The schematic layout of RHIC spin flippers. The separate spin flippers in the two acclerators allows independent spin flipping in each ring.

RHIC SPIN FLIPPER

Comparing with the single rf dipole method of spin flipping, the new design of RHIC spin flipper employs two rf dipoles with a spin rotator in between to achieve a field with its axis rotating in the horizontal plane. As demonstrated in [5], this rotating field only induces one spin resonance at $Q_s = Q_{osc}$. Since the resonance at $Q_s = -Q_{osc}$ is eliminated, a full spin flip can be obtained with spin precession tune staying at half integer.

Fig. 2 shows the schematic drawing of spin flipper for RHIC with two rf dipoles and a spin rotator with the axis along the vertical direction in between The strength of the two spin rotators on either side of the two rf dipoles is half of the strength of the center spin rotator but the opposite polarity to cancel the spin rotation by the center spin rotator and keep the spin tune unchanged. This arrangement also localizes the horizontal orbit deflection by the 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

$$OTM = (-i\sigma_2)e^{-\frac{i}{2}G\gamma\pi\sigma_3}(-i\sigma_1)e^{-\frac{i}{2}G\gamma(\pi-\phi_0)\sigma_3} e^{-\frac{i}{2}\frac{\pi}{4}\sigma_3}M_{sflip}e^{-\frac{i}{2}\frac{\pi}{4}\sigma_3}e^{\frac{i}{2}G\gamma\phi_0\sigma_3} \quad (5)$$

where

$$M_{sflip} = e^{\frac{i}{4}\phi_0\sigma_3}e^{-\frac{i}{2}\phi_{\rm osc}\cos(Q_{\rm osc}\theta+\chi_2)\sigma_1}e^{-\frac{i}{2}\phi_0\sigma_3} e^{-\frac{i}{2}\phi_{\rm osc}\cos(Q_{\rm osc}\theta+\chi_1)\sigma_1}e^{\frac{i}{4}\phi_0\sigma_3} \quad (6)$$

where ϕ_0 is the amount of spin rotation from the center spin rotator and $\chi_{1,2}$ is the initial phase of the two rf dipoles, respectively. One can prove that for a small $\phi_{\rm osc}$ and $\chi_1 - \chi_2 = 180^\circ + \phi_0$, M_{sflip} in Eq. 6 is equal to

$$M_{sflip} = e^{-\frac{i}{2}\phi_{\rm osc}\sin\phi_0[\sin(Q_{\rm osc}\theta+\chi_2)\sigma_1-\cos(Q_{\rm osc}\theta+\chi_2)\sigma_2]}. \quad (7)$$

which is the spin transfer matrix for a rotating field [5]. Fig. 3 shows the numerical simulation result with the RHIC lattice using the spin tracking code SPINK [11] which does the full tracking of both orbital motion and spin motion.

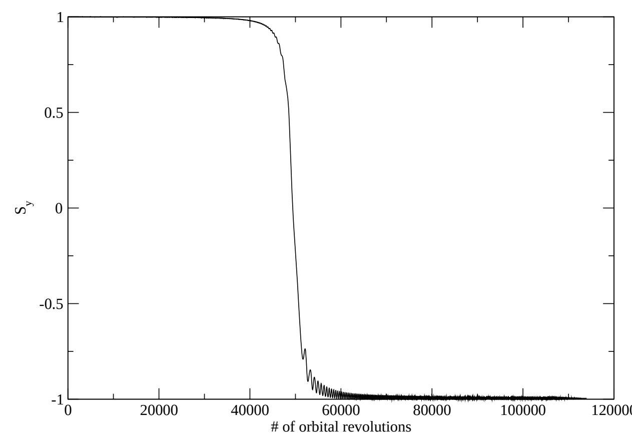

Figure 3: This plot is the spin tracking results of a spin flipper setup as shown in Fig. 2 with the RHIC lattice. The amplitude of two rf dipole oscillating field is set to 100 Gauss-m. The initial phase between the two rf dipoles is 30°.

The spin tracking is done for a single particle with a spin tune of $\frac{1}{2}$ and the spin flipper tune being swept from 0.49 to 0.51. The amount spin rotation from the spin rotator between the two rf dipoles is 30° and the amplitude of the two rf dipoles is 100 Gauss-m. Since SPINK not only tracks the spin vector but also tracks both transverse and longitudinal orbital motion, the tracking result also includes the spin motion from the focusing quadrupole fields due to the rf dipole induced coherent betatron oscillation [8, 9]. In general, the polarized proton beam is stored at an energy far away from strong intrinsic spin resonances, the effect of the driven coherent betatron oscillation on spin motion is insignificant [5] and full spin flip can still be achieved as shown in Fig. 3.

For RHIC, to achieve 30° rotation angle at 100 GeV and 250 GeV, the spin rotator needs a dipole field of 0.9 Tesla-m. This corresponds to an orbital deflection of 2.73 mrad for 100 GeV and 1.07 mrad for 250 GeV.

OTHER APPLICATION OF RHIC SPIN FLIPPER

Another application of this rotating field spin flipper is to measure the spin precession tune. Instead of sweeping the rf dipole tune, one can adiabatically induce a coherent spin precession around the vertical direction by driving the rf dipole at a tune near the spin precession tune. In this case, the spin vector gets adiabatically kicked away from the vertical direction with a constant projection on the vertical direction as shown in Eq. 8 [10].

$$P_y = \frac{Q_s - Q_{\rm osc}}{\sqrt{\epsilon_k^2 + (Q_s - Q_{\rm osc})^2}}. \tag{8}$$

The projection of the spin vector on the horizontal direction on the other hand oscillates at the spin flipper tune and the amplitude of this coherent oscillation is given by

$$P_x = \frac{\epsilon_k}{\sqrt{\epsilon_k^2 + (Q_s - Q_{\rm osc})^2}}. \tag{9}$$

The ratio of Eq. 8 and Eq. 9 directly measures the distance of the spin precession tune and the spin flipper tune and it vanishes at $Q_s = Q_{\rm osc}$. The advantage of this technique is that this is an adiabatic spin manipulation and can preserve the beam polarization. Hence, this technique is ideal for measuring the spin precession tune at store energy of high energy accelerators.

CONCLUSION

This paper presents the new design of RHIC spin flipper. the spin tune is $\frac{1}{2}$. It demonstrates through theoretical derivation as well as numerical simulations that a full spin flip can be achieved without moving the spin tune away from $\frac{1}{2}$. This design can also be used to measure the spin precession tune in a high energy polarized proton accelerators.

ACKNOWLEDGMENT

The authors would like to thank Jim Alduino and Laura Taddonio from the BNL Collider Accelerator department mechanical engineering group for helping to make the schematic drawing of the RHIC spin flipper as shown in Fig. 2. The authors would also like to thank Charles Pearson for helping in locating the spin rotators.

REFERENCES

[1] B. B. Blinov, V. A. Anferov and *et al.*, *Spin Flipping in the Presence of a Full Siberian Snake*, Phys. Rev. Lett. Vol. 81, Number 14, 2906, 1998.

[2] B. B. Blinov, Z. B. Etienne and *et al.*, *99.6% Spin-Flip Efficiency in the Presence of a Strong Siberian Snake*, Phys. Rev. Lett. Vol. 88, Number 1, 014801-1, 2002.

[3] V. S. Morozov, A. D. Krisch and *et al.*, *Spin manipulation of 1.94 GeV/c polarized protons stored in the COSY cooler synchrotron*, Phys. Rev. ST Accel. Beams 7, 024002, 2004.

[4] RHIC Spin Design Manual, (1998).

[5] M. Bai and T. Roser *Full Spin Flipping in the Presence of Full Siberian Snake*, Phys. Rev. ST AB, submitted.

[6] The private discussions that authors had with A. Kondratenko and A. Chao suggest the coefficient $(1 + G\gamma)$ in Eq. 4 should be $G\gamma$ since it is evaluated in the particle's frame. However, for high energy polarized proton accelerators like RHIC, the difference is negligible.

[7] M. Bai and *et al.*, *comment on "Spin manipulation of 1.94 GeV/c polarized protons stored in the COSY cooler synchrotron"*, Phys. Rev. ST Accel. Beams, Issue 9, 099001, 2005.

[8] S. Y. Lee *Spin Resonance Strength of a Localized rf magnetic field*, Phys. Rev. ST Accel. Beams 9, 074001, 2006

[9] M. Bai and et al *Experimental test of coherence betatron excitations*, Phys. Rev. E56, 6002, 1997

[10] S. Y. Lee *Spin Dynamics and Snakes in Synchrotrons*, World Scientific, Singapore, 1997.

[11] A. U. Luccio *Spin Tracking in RHIC (Code Spink)*, proceedings of Trends on Collider Spin Physics, ICTP, Trieste, Italy, 1995.

