12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB014

FIRST HIGH SPIN-FLIP EFFICIENCY FOR HIGH ENERGY POLARIZED PROTONS*

H. Huang†, J. Kewisch, C. Liu, A. Marusic, W. Meng,
F. Méot, P. Oddo, V. Ptitsyn, V. Ranjbar, T. Roser
Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

In order to minimize the systematic errors for the Relativistic Heavy Ion Collider (RHIC) spin physics experiments, flipping the spin of each bunch of protons during the stores is needed. Experiments done with single RF magnet at energies less than 2 GeV have demonstrated a spin-flip efficiency over 99%. At high energy colliders with Siberian snakes, a single magnet spin flipper does not work because of the large spin tune spread and the generation of multiple, overlapping resonances. Over past decade, RHIC spin flipper design has evolved and a sophisticated spin flipper, constructed of nine-dipole magnets, was developed to flip the spin in RHIC. A special optics choice was also used to make the spin tune spread very small. In recent experiment, 97% spin-flip efficiency was measured at both 24 and 255 GeV for the first time. The results show that efficient spin flipping can be achieved at high energies.

INTRODUCTION

Experiments of polarized proton collisions in the Relativistic Heavy Ion Collider (RHIC) as well as a future polarized electron ion collider need to measure spin effect at the level of 10^{-3} to 10^{-4}. For such high precision measurements, frequent polarization sign reversal is imperative to avoid systematic errors from bunch spin pattern. A spin flipper in each ring is needed, which is capable of reversing the polarization sign of all bunches without changing other beam parameters.

To avoid polarization loss during acceleration and at store, high energy polarized proton colliders require full Siberian Snakes, which are specially arranged magnets to rotate the spin around an axis in horizontal plane by 180° [1]. For RHIC, a pair of Siberian Snakes are installed in each ring. The two Siberian Snakes are located in the opposite side of the ring (or separated by 180°)with their spin precession axes different by 90°. This configuration yields a spin tune ν_s as $\frac{1}{2}$, where the spin tune ν_s, defined as the number of spin precessions per turn, is given by $\nu_s = G\gamma$ in the absence of Siberian Snakes(γ is the Lorentz factor, G is the gyromagnetic anomaly and G=1.7928 for protons) [2]. The traditional spin flipping technique uses a single rf spin rotator that rotates the spin around an axis in the horizontal plane. The spin rotator can be implemented as an rf dipole or an rf solenoid. Experiments done at low energies(from 100 MeV to 2 GeV) have demonstrated a spin flip efficiency over 99% [3]. The spin flip is achieved by ramping the rf spin rotator tune ν_{osc} across the spin tune ν_s adiabatically. It should be noted that such a single spin rotator generates two spin resonances, one at $\nu_s = \nu_{osc}$, and one at $\nu_s = 1 - \nu_{osc}$ or so-called "mirror" resonance. As long as the spin tune is sufficiently far away from half integer, say at 0.47, then the two spin resonances are sufficiently far from each other and each one can be treated as an isolated resonance. This is the case for low energies when Siberian Snakes are not needed and the spin tune is not at or near half integer. In high energy polarized proton colliders such as RHIC, the spin tune is very close to half integer. The two spin resonances overlap and their interference makes the full spin flip impossible with such a single rf spin rotator. To reach full spin flip, the "mirror" resonance has to be eliminated [4].

* Work was supported by Brookhaven Science Associates, LLC, under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
† huanghai@bnl.gov

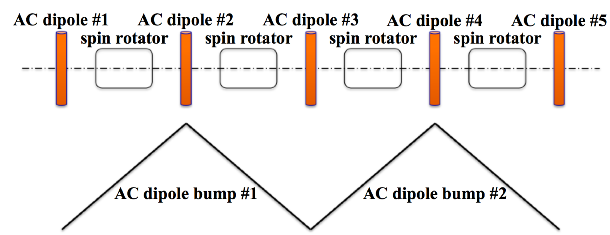

Figure 1: The schematics of the high energy spin flipper. It consists of five AC dipoles and four DC dipoles.

SPIN FLIPPER CONFIGURATION

Figure 1 shows the schematic drawing of the spin flipper design. The first three AC dipoles form the first closed orbital bump and the last three AC dipoles form the second closed orbital bump. The middle AC dipole (No. 3) is used twice. The four DC dipoles yield spin rotation angles of $+\psi_0$/-ψ_0/-ψ_0/+ψ_0. The rotation angle ψ_0 is given by

$$\psi_0 = (1 + G\gamma)\frac{B_{dc}L}{B\rho} \tag{1}$$

where $B\rho$ is the beam particle magnetic rigidity, $B_{dc}L$ is the integrated B field of each DC dipole. These DC dipoles create a closed local horizontal bump and leave the spin tune ν_s unchanged. The five AC dipoles are operated at the frequency about half of revolution frequency, so that the tune ν_{osc} is in the vicinity of ν_s. AC dipoles 1-3 and AC dipoles 3-5 create a local vertical orbit bump with a $+\phi_{osc}$/-2 ϕ_{osc}/+ϕ_{osc} spin rotation sequence. The rotation

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB014

angle ϕ_{osc} is given by

$$\phi_{osc} = (1 + G\gamma)\frac{B_{ac}l}{B\rho} \quad (2)$$

where $B_{ac}l$ is the integrated B field of AC dipole. This configuration induces a spin resonance at $\nu_{osc} = \nu_s$ while eliminating the "mirror" resonance at $1 - \nu_s$ and therefore ensuring a single resonance crossing during a ν_{osc} sweep through $\nu_s \approx \frac{1}{2}$ and producing full spin flip. In the presence of a "mirror" resonance, the isolated resonance crossing condition would otherwise require ν_s to be far enough away from $\frac{1}{2}$. The effective spin resonance strength of the spin flipper ϵ_k then becomes

$$\epsilon_k = 2\frac{\phi_{osc}}{\pi}\sin\psi_0 \sin\frac{\psi_0}{2} \quad (3)$$

Let ϵ represent the resonance strength induced by the spin flipper, and the crossing speed (rate of sweep of ν_{osc} through $\nu_s \approx \frac{1}{2}$) is given as

$$\alpha = \frac{\Delta\nu_{osc}}{2\pi N} \quad (4)$$

with $\Delta\nu_{osc}$ as the AC dipole frequency span and N as the number of turns of the sweep. The ratio of the final polarization (P_f) to the initial polarization (P_i) after crossing the single spin resonance generated by the spin flipper is given by the Froissart-Stora formula [5]:

$$\frac{P_f}{P_i} = 2\exp^{-\frac{\pi}{2}\frac{|\epsilon|^2}{\alpha}} - 1, \quad (5)$$

To reach full spin flip, α has to be small enough or N large enough for beam particles to adiabatically follow the flip of the spin precession axis.

SPIN TUNE SPREAD REDUCTION

Besides eliminating the "mirror" resonance and any global vertical betatron oscillation driven by AC dipoles, the reduction of the spin tune spread is also critical for achieving full spin flip. The spin tune of a synchrotron with two Siberian Snakes installed at opposite sides of the ring is given by

$$\nu_s = \frac{1}{2} + \frac{(1 + G\gamma)(\theta_1 - \theta_2)}{2\pi}, \quad (6)$$

where θ_1 and θ_2 are the integrated bending angles of the first half arc and second half arc, respectively. For the on-energy and on-axis protons both θ_1 and θ_2 are equal (π) and the design-orbit spin tune is $\frac{1}{2}$ independent of the beam energy. This changes with synchrotron motion and the resulting momentum spread $\frac{\Delta p}{p}$ [6]. The change in the bending angles are $\Delta\theta_1 = (x_1' - x_2')$ and $\Delta\theta_2 = (x_2' - x_1')$ respectively, where x_1' and x_2' are the slopes of the beam trajectory at the first and the second Siberian Snake. The spin tune then becomes $\frac{1}{2} + (1 + G\gamma)(x_2' - x_1')/\pi$. To the first order, x' can be expressed as $x' = D'\frac{\Delta p}{p}$, where D' is the slope of the dispersion function D, which measures orbit difference due to momentum offset, and $\frac{\Delta p}{p}$ is the momentum spread of beam particles. The momentum spread causes a spin tune spread when the dispersion slopes are different at the two Siberian Snakes:

$$\Delta\nu_s = \frac{(1 + G\gamma)}{\pi}(D_1' - D_2')\frac{\Delta p}{p} \quad (7)$$

In RHIC, this local dispersion slope difference between the two Siberian Snakes is about 0.045 at 255 GeV, which corresponds to 0.007 spin tune spread for a beam with a momentum spread of 0.001. This is comparable to the proposed spin tune sweep range of 0.02. Hence, successful full spin flipping requires to match the dispersion slopes. Since the $G\gamma$ values of 24 GeV($G\gamma = 45.5$) and 255 GeV($G\gamma = 487$) differ by a factor of ten, the required $\Delta D' = (D_1' - D_2')$ is ten times smaller at 255 GeV than at 24 GeV to maintain the same spin tune spread $\Delta\nu_s$.

The transition tune jump quadrupoles in the arcs were identified as effective elements for matching the dispersion slopes at the two Siberian Snakes [7]. Four trim quadrupoles in each of the six RHIC arcs were adjusted so that the dispersion slope difference is very small and the distortion of beta functions and tunes would be minimal [8].

EXPERIMENTAL RESULTS

The spin flipper experiment was carried out at two different energies, 24 GeV and 255 GeV. The 9MHz RF cavity is the major RF system for beam operation both at injection and during acceleration. The bunch intensity was 1.5×10^{11} protons with 111 bunches filled in one ring. The polarization was measured with the RHIC polarimeter [9].

In the measurement, the driving tune was swept for typically 0.005 tune range over certain time (such as 1 sec). The polarization was measured before and after each sweep. At injection, the final to initial polarization ratio was measured with $\Delta D'$ as low as 0.003. The spin flipper was set to sweep from 0.4995 to 0.5045 and the spin tune was 0.5025. The final to initial polarization ratio was measured as function of $\Delta D'$ and the results are shown in Fig. 2. The spin flipper sweep time was fixed as 3 sec during these measurements. It clearly demonstrates that the $\Delta D'$ suppression is critical to achieve high spin flip efficiency. With normal lattice where the $\Delta D'$ was large, the polarization was lost just with a single spin flipper sweep.

With the 0.005 tune sweep range and the given spin flipper strength, a 99% spin flip efficiency is predicted for a sweep time of 0.6 sec or slower at 24 GeV from Eq. (5) and numerical simulations [10]. The final to initial polarization ratio from Eq. (5) for the given spin flipper strength at injection is plotted in Fig. 3 as solid line. But this is an over-simplified model. In reality, the synchrotron motion and residual spin tune spread can have an impact on the final spin flip efficiency. The measured spin flip efficiencies for three different sweep times are also shown in Fig. 3. Each efficiency is the average of 10 to 12 spin flips. The best final to initial polarization ratio was obtained with a 1 sec sweep

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB014

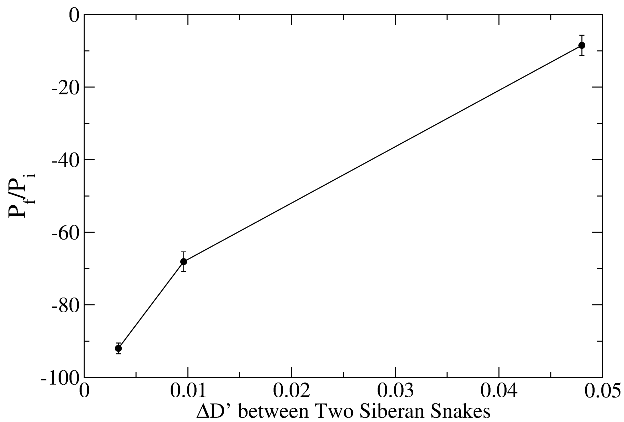

Figure 2: The average final to initial polarization ratio for 3 sec sweep time at injection as function of ΔD' at the two Siberian Snakes. The small $\Delta D'$ is critical for full spin flip.

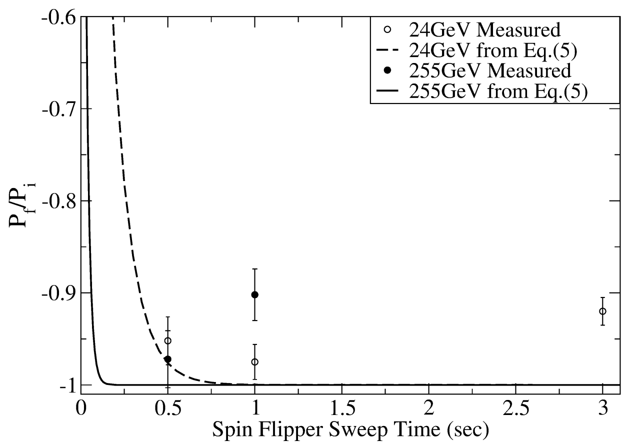

Figure 3: The average final to initial polarization ratio at 24 GeV and 255 GeV. The solid line is the polarization flip ratio from Eq.(5) for the resonance strength 0.00024 and the filled points are the averaged spin flip efficiencies for three different sweep times at 24 GeV. The dashed line and open points are for 255 GeV and the resonance strength 0.00057.

time: $-97.5 \pm 1.9\%$. This is close to the simple model prediction of -99%. At 0.5 sec, the final to initial polarization ratio is expected to be slightly worse due to faster crossing speed, and the measured value $-95 \pm 2.6\%$ is indeed slightly smaller. For the slowest sweep time, 3 sec, the final to initial polarization ratio is only $-92.0 \pm 1.5\%$. There are several reasons for this. First, with a slower sweep speed, multiple spin resonance crossings with different resonance crossing speeds can happen due to synchrotron oscillation. This would result in a worse final to initial polarization ratio. Second, the polarization loss from weak higher order depolarizing resonances would be larger with a slower sweep speed.

The final to initial polarization ratio from the given spin flipper strength at 255 GeV is plotted in Fig. 3 as dashed line. The spin flip efficiencies for the two different sweep times are also shown in Fig. 3. As before each efficiency is the average of 10 to 12 spin flips. The better final to initial polarization ratio is at the 0.5 sec sweep time: $-97.2 \pm 3.1\%$. This is close to the simple model prediction of -99%. For the slower sweep time of 1 sec the final to initial polarization ratio is $-90.2 \pm 2.8\%$. Similar to the 24 GeV case, the final to initial polarization ratio is worse with slower sweep speed, as seen in the results of numerical simulations as well.

CONCLUSIONS

It has been shown that the 9-magnet spin flipper eliminated the "mirror" resonance. With the lattice for which the dispersion slope difference at the two Siberian Snakes is greatly suppressed, a spin flip efficiency of over 97% has been achieved for polarized proton beam at 24 GeV and 255 GeV in the presence of two full Siberian Snakes. The dispersion slope difference at the location of the two Siberian Snakes as 0.003 at 24 GeV and 0.0001 at 255 GeV.

REFERENCES

[1] Ya. S. Derbenev *et al.*, "Radiative polarization: obtaining, control, using", *Part. Accel.*, vol. 8, p. 115, 1978.

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

[3] D. D. Caussyn *et al.*, "Spin flipping a stored polarized proton beam", *Phys. Rev. Lett.*, vol. 73, p. 2857, 1994. doi:10.1103/PhysRevLett.73.2857

[4] M. Bai and T. Roser, "Full spin flipping in the presence of full Siberian Snake", *Phys. Rev. ST AB*, vol. 11, p. 091001, 2008. doi:10.1103/PhysRevSTAB.11.091001

[5] M. Froissart and R. Stora, "Depolarisation d'un faisceau de protons polarises dans un synchrotron", *Nucl. Inst. and Meth. Phys. Res.*, vol. 7, p. 297, 1960. doi:10.1016/0029-554X(60)90033-1

[6] V. Ptitsyn, M. Bai, and T. Roser, "Spin Tune Dependence on Closed Orbit in RHIC", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper THPE054, pp. 4641–4643.

[7] J. Kewisch, M. Bai, D. Bruno, F. Méot, and T. Roser, "Correction of the spin chromaticity in RHIC", BNL C-AD Tech Notes AP 478, Feb. 2013. unpublished.

[8] C. Liu, J. Kewisch, H. Huang, and M. Minty, "Minimization of spin tune spread for preservation of spin polarization at RHIC", *Phys. Rev. Accel. Beams*, vol. 22, p. 061002, 2019. doi:10.1103/PhysRevAccelBeams.22.061002

[9] H. Huang and K. Kurita, "Fiddling Carbon String with Polarized Proton Beam", *AIP Proc.*, vol. 868, pp. 3-21, 2006. doi:10.1063/1.2401392

[10] F. Méot *et al.*, "RHIC Spin flipper, fast-sweep efficiency simulations", BNL C-AD Tech Notes AP 589, Sep. 2017, unpublished.