ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL012

NON-DESTRUCTIVE SPIN TUNE MEASUREMENT OF POLARIZED PROTONS IN A STORAGE RING*

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

Abstract

To maintain polarization in a polarized proton collider, it is important to know the spin tune of the polarized proton beam, which is defined as the number of full spin precessions per revolution. A nine-magnet spin flipper has demonstrated high spin-flip efficiency in the presence of two Siberian snakes. The spin flipper drives a spin resonance with a given frequency (or tune) and strength. When the drive tune is close to the spin tune, the proton spin precession direction is not vertical anymore, but precesses around the vertical direction. By measuring the precession frequency of the horizontal component, the spin tune can be precisely measured. A driven coherent spin motion and fast turn-by-turn polarization measurement are keys to the measurement. The vertical spin direction is restored after turning the spin flipper off slowly enough. The fact that this manipulation preserves the polarization makes it possible to measure the spin tune during the operation of a polarized collider such as RHIC and EIC.

INTRODUCTION

To avoid polarization loss from depolarizing resonances during acceleration and at store, high energy polarized proton colliders require full Siberian snakes, which are specially arranged magnets to rotate the spin by 180° around an axis in the horizontal plane [1]. For the Relativistic Heavy Ion Collider (RHIC), a pair of Siberian snakes are installed in each ring. This configuration yields a spin tune ν_s of $\frac{1}{2}$ [2], defined as the number of spin precessions per turn. A spin tune of $\frac{1}{2}$ avoids all depolarizing resonances as long as the vertical betatron tune ν_y is not also $\frac{1}{2}$. However, the higher-order resonances (snake resonances) [3] still can lead to polarization loss. The resonance condition is

$$\nu_s = k + m\nu_y, \tag{1}$$

where k and m are integers. Snake imperfections and closed orbit errors can also shift the spin tune away from $\frac{1}{2}$. This shift leads to a shift of snake resonance locations and limits the possible operating parameters of the accelerator [4].

To avoid these higher order resonance conditions, knowing both the vertical betatron tune and the spin tune accurately is important. Betatron tune measurements have been done with various methods in synchrotrons [5]. It is typically measured with coherent turn-by-turn beam oscillations in response to a beam excitation. The spin tune measurement is much harder. A nine-magnet spin flipper has been used in RHIC to flip spin [6]. This is accomplished by sweeping the drive tune of the spin flipper ac dipole across the spin tune with the proper crossing speed. The spin flipper can also be used to drive an artificial spin resonance at a fixed tune. When the drive tune is near the spin tune, the polarization direction is moved away from vertical and is precessing around the vertical direction. The vertical polarization measurement as a function of drive tune in the vicinity of the expected spin tune can give a direct measurement of the spin tune. Examples are shown in Fig. 2 of Ref. [6]. However, such a measurement often results in decoherence of the spin motion and loss of polarization, so it requires several fills of freshly polarized proton beams. It becomes very time consuming if acceleration to higher energy is needed.

In principle, the spin tune can be measured with a similar idea as the betatron tune measurement: measuring the spin response to a driven spin coherence. Such a method can also be non-destructive. A coherent spin precession around the vertical direction can be adiabatically induced by driving the ac spin rotator at a drive tune near the spin tune.

If the undisturbed stable spin direction is vertical, the vertical component of polarization P in the neighborhood of an isolated spin resonance is given by [7]:

$$P_y = \frac{\nu_s - \nu_{osc}}{\sqrt{|\nu_s - \nu_{osc}|^2 + |\epsilon|^2}}, \tag{2}$$

where ϵ is the strength of the driven spin resonance and ν_{osc} is the drive tune. The horizontal component oscillates with ν_{osc}:

$$P_x = \frac{|\epsilon|}{\sqrt{|\nu_s - \nu_{osc}|^2 + |\epsilon|^2}} \cos(2\pi\nu_{osc} i - \Psi), \tag{3}$$

where i is the ith orbital revolution and Ψ is the initial phase offset. The ratio of the amplitude part of Eq. (3) $\hat{P}_x$ and P_y gives the difference between ν_s and ν_{osc}:

$$\tan\theta_0 = \frac{\hat{P}_x}{P_y} = \frac{|\epsilon|}{\nu_s - \nu_{osc}}, \tag{4}$$

where θ_0 is the opening angle of the polarization vector. With known resonance strength ϵ from the spin flipper and the drive tune ν_{osc}, the spin tune ν_s can be derived from the measured quantity $\tan\theta_0$.

There are two advantages to this technique. First, it is an adiabatic spin manipulation and can preserve the beam polarization. Second, this is a relatively fast measurement. Hence, this technique is ideal for measuring the spin tune at the store energy of a high-energy polarized synchrotron, such as RHIC or a future polarized electron ion collider [8].

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

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For the success of a spin tune measurement using driven coherent spin motion, several conditions have to be met. First, a large enough oscillation amplitude needs to be generated. This requires a strong enough driven spin resonance and a small enough separation between the drive tune and the spin tune. Second, the spin tune spread needs to be small. This allows a drive tune close to the resonance and significantly enhances the signals. Third, the measurement requires a large data sample from the polarimeter and the polarization must be measured as a function of the oscillation phase. Although the vertical component is constant, the horizontal component is changing from turn to turn. To measure such an oscillation accurately, the polarimeter needs to measure the polarization over many turns as a function of the oscillation phase.

The RHIC spin flipper can induce a spin resonance with a strength of $\epsilon = 0.00057$. At injection energy, the strength is limited to 0.00024 due to the larger beam size. For this method to work, the separation between ν_s and ν_{osc} should be similar to the strength to generate a sizable horizontal polarization component.

POLARIMETER SETUP

The RHIC p-carbon (pC) polarimeters measure recoil carbon asymmetries [9] in the Coulomb-Nuclear Interference (CNI) region [10–12]. Carbon nuclei are scattered in the plane transverse to the polarized proton direction with an azimuthal angle θ distribution

$$dN/d\theta \propto 1 + a\sin(\theta - \theta_s)\,. \qquad (5)$$

Here $a = A_N P$, where A_N is the CNI asymmetry for 100% polarization, which has values $\sim 10^{-2}$, and P at RHIC has values ~ 0.5-0.8. θ_s is the azimuthal angle of the spin direction in the plane transverse to the beam direction. The small value of the oscillatory term, $a \sim$ few$\times 10^{-3}$, dictates that a large statistical sample is necessary to accurately measure it on top of the flat underlying component.

In operation RHIC is filled with approximately equal numbers of spin up and spin down proton bunches. The carbon hits are recorded with a unique bunch crossing identifier, and hits for up and down bunches are counted separately. A change from spin up to spin down amounts to a shift $\theta_s \to \theta_s + \pi$ in Eq. (5). The asymmetry of carbon hits, i.e. the relative difference of up and down bunch hits, normalized by the number of protons on target for each case, as a function of azimuthal angle is then

$$\mathrm{Aymmetry}|_\theta = a\sin(\theta - \theta_s)\,. \qquad (6)$$

During normal RHIC operation, the main result from the polarimeters is a, which determines the magnitude of the beam polarization. In the present study we focus on θ_s, the azimuthal angle of the spin vector in the plane transverse to the beam direction, and how it is influenced by the coherent spin motion. To measure the driven coherent spin motion, recoil carbon events need to be recorded on a turn-by-turn

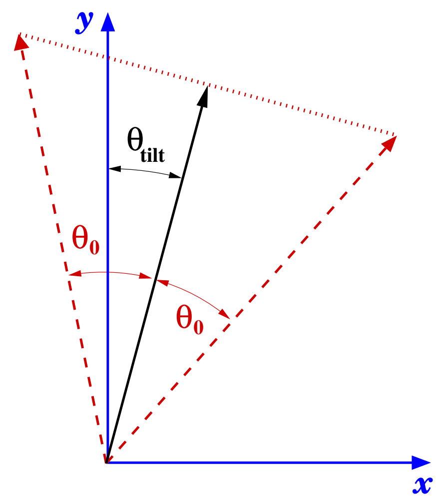

Figure 1: Projection of the spin vector into the transverse plane when the spin tune is near a spin resonance. The spin oscillates around the stable spin direction (solid arrow) between the two boundaries (dashed arrows) over many orbit turns.

base. Figure 1 shows the spin precession projected onto the $x - y$ plane transverse to the beam direction. The pC polarimeter measures the spin vector projection in this plane. With driven coherent spin motion the spin vector in this plane oscillates over the range shown by the two dashed arrows, with a period equal to that of the driven resonance. The amplitude of the precession is θ_0 from Eq. (4); θ_{tilt} is an arbitrary offset between vertical and the stable spin direction. From P_x/P_y the spin azimuthal angle θ_s measured by the pC polarimeter with a possible tilt angle θ_{tilt} will follow the precession

$$\frac{P_x}{P_y} = \tan(\theta_s - \theta_{tilt}) = \tan\theta_0 \cdot \cos(2\pi\nu_{osc} i - \Psi)\,. \qquad (7)$$

Note that only the two transverse components of the polarization can be measured. If the spin direction has a significant longitudinal component in addition to the angle θ_{tilt}, the simple form of Eq. (7) should be modified.

SPIN TUNE MEASUREMENTS

The experiment was carried out at injection at 24 GeV and store at 255 GeV. The bunch pattern was 120 bunches in the ring and RHIC bunch crossings were used as a clock signal for the analysis. For these measurements, a signal from the resonance drive was provided to the polarimeter readout, which allowed alignment of the phase of carbon hits within one period of the resonance drive. The drive signal was read with an accuracy of two bunch crossings, whereas the typical period of the drive was ~ 240 bunch crossings (for a drive tune near 0.5), so the phase of carbon hits was known to within 1% of a period.

In the experiment, the spin tune was first roughly located by sweeping the drive tune. If the polarization sign flips, the spin tune is covered by the sweep range. This method

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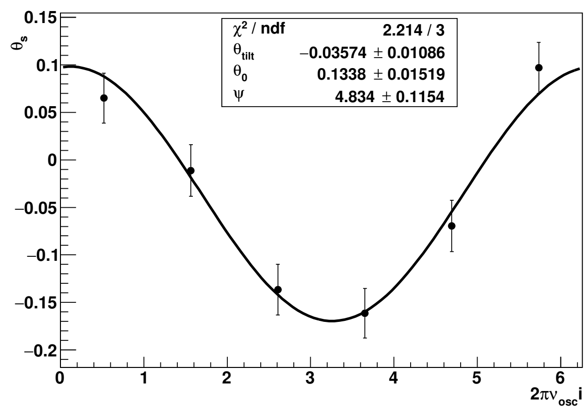

Figure 2: Measured spin azimuthal angle as a function of driven oscillation phase at 24 GeV with drive tune as 0.498, about 0.002 away from the spin tune. All angles ($\theta_s, \theta_{tilt}, \theta_0, \Psi$) are in the unit of radian. The non-zero θ_{tilt} means there is a small tilt angle in the stable spin direction away from vertical.

successively divides the drive tune sweep range in half over the intervals that exhibit a spin-flip. The progressively narrowing tune sweep ranges caused increased polarization loss and eventually converges on a range, which causes complete polarization loss. This typically gives a narrow range for the spin tune location. Then, with fresh beam, the drive was turned on adiabatically at fixed tune and the driven coherent spin motion was measured with the polarimeter. After the measurement, the drive was turned off adiabatically and the original spin direction was restored.

Figure 2 shows θ_s versus one cycle of drive phase for one drive setting. For statistical accuracy, the carbon hits were grouped in 6 bins of 40 bunch crossings, spanning nearly one entire drive cycle; the mean spin azimuthal angle θ_s was measured in each bin. The curve is fit to the function, from rearrangement of Eq. (7):

$$\theta_s(i) = \theta_{tilt} + \tan^{-1}\left(\tan\theta_0 \cdot \cos(2\pi\nu_{osc} i - \Psi)\right) \ . \qquad (8)$$

The arbitrary phase offset Ψ depends on the propagation time of proton bunches from the drive to the polarimeter, and the cable delay of the signal from the drive to the polarimeter readout.

The measured θ_0 and derived spin tune for 7 sets of measurements are shown in Table 1. The separation of the drive tune and the spin tune varies from 0.001 to 0.004. For each of the three pairs of measurements done under the same conditions, the results are consistent with each other within the statistical errors. Within statistical errors, the spin tune from the driven spin coherence (column 3) agrees with the range obtained from the spin-flip method (column 4).

Among the seven spin tune measurements, five are at injection. The first pair of spin tune measurements were done with two different drive tunes. The experimental data and fit from the second set are shown in Fig. 2. The spin

Table 1: Spin tune measurement results. The first five cases are at 24 GeV and the last two cases are at 255 GeV. The precession amplitude angle θ_0 is in the 1st column. The 2nd column is the drive tune of the ac dipoles. The derived spin tune from driven coherence is given in the 3rd column. Last column is the spin tune range from spin flipper operation.

θ_0 (rad)	ν_{osc}	ν_s measured	ν_s from flip
0.273±0.059	0.499	0.4999±0.0002	0.4975-0.5
0.134±0.015	0.498	0.4998±0.0002	0.4975-0.5
0.109±0.015	0.5004	0.5026±0.0003	0.5022-0.5025
0.132±0.021	0.5009	0.5027±0.0003	0.5022-0.5025
0.062±0.015	0.499	0.4951±0.0010	0.491-0.495
0.263±0.033	0.494	0.4961±0.0003	0.495-0.4965
0.174±0.024	0.493	0.4962±0.0005	0.495-0.4965

tune was above 0.5 for the next pair of spin tune measurements (sets 3 and 4 in Table 1). Although the spin tune range determined with spin-flip method was fairly small (0.5022-0.5025), the spin tune from coherent spin motion measurements of the pair are self-consistent with each other and they are in agreement with the results from the spin-flip method within statistical errors.

In the 5th set of measurement, the Siberian snakes were tuned to move the spin tune far away from 0.5, and the spin-flip method gave the spin tune between 0.491-0.495. The drive tune for the spin coherence measurement was 0.499. Due to larger tune separation, the asymmetry oscillation amplitude was smaller and the relative statistical uncertainty was larger.

The last pair of spin coherence measurements were done at 255 GeV. The spin tune was also determined as between 0.496 and 0.4965 by a fixed drive tune scan (see Fig. 2 of Ref. [6]). Note that there is a quite large tilt angle of the spin of 0.25 rad at the store energy [13]. The spin tune measured from coherent spin motion is in agreement with the results from the spin-flip and fixed drive tune methods. This implies that Eq.(7) is valid for RHIC and there is no significant longitudinal component of the stable spin direction.

CONCLUSION

Driven coherent spin motion has been used to measure the spin tune in RHIC at 24 GeV and 255 GeV. The results show that the spin tune can be measured by driven spin coherence when the tune separation is small enough. For it to work, the drive tune needs to be close to the spin tune, which requires a small spin tune spread. In RHIC, where a pair of Siberian snakes are used, the small spin tune spread was achieved by the reduction of dispersion slope difference at the two Siberian snakes [14, 15]. These experimental results prove that it is possible to routinely measure the spin tune of polarized proton beams—the most important polarized beam parameter—which will lead to more stable and optimized operation of a high-energy polarized collider, such as RHIC or a future polarized electron ion collider.

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