Recent Spin Manipulation Experiments in RHIC

Haixin Huang

1. Spin Dynamics
2. Spin Flipping Experiment
3. Spin Tune Measurement

BROOKHAVEN
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

January 29, 2021

MSU Colloquium

Introduction to Spin Dynamics

Protons Have a Magnetic Moment (Spin)

- Protons behave in magnetic fields as if they were tiny magnetic dipoles
  - Analogous to tiny loops of current in B field
  - Or a gyroscope in a gravitational field

The 'spin' vector (direction of angular or magnetic moment), *precesses* around the local field (gravitational or magnetic)
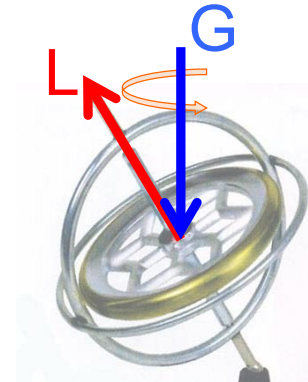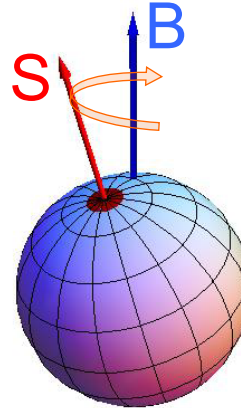
Motivation of Spin Experiments

- To understand the mysteries of the universe.
- We want to know where the spin of a proton comes from

So

- We need to study reactions that are sensitive to the spin direction

So

- We need to know the direction of the spin going into each reaction (collision) with some certainty→Beam with spin aligned to the same direction= polarized beam

1980s   now
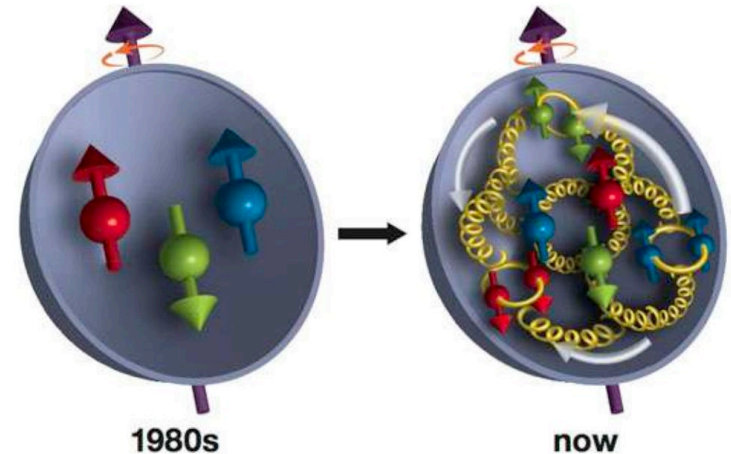
Physicists expected that the quarks carry all the proton spin. However, not only was the total proton spin carried by quarks far smaller than 100%, but these results were also consistent with almost zero (4–24%) proton spin being carried by quarks. -> "proton spin crisis".

Spin vs. Polarization

Spin is a fundamental property of the particle

Polarization is a property of a given set of particles

Polarization is the projection of all the spin vectors in a group of particles onto some axis (often vertical).

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

Example: 80 out of 100 particles with spin up, 20 out 100 particles with spin down. The polarization P is 60%.

Spin Dynamics

Precession Equation in Laboratory Frame:
(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$$dP/dt = - (e/\gamma m) [G\gamma B_\perp + (1+G) B_L] \times P$$

Lorentz Force equation:

$$dv/dt = - (e/\gamma m) [\quad B_\perp \quad\quad\quad] \times v$$

- For pure vertical field:
  Spin rotates $G\gamma$ times faster than orbital motion, $\nu_s = G\gamma$
- For spin manipulation:
  At low energy, use longitudinal fields
  At high energy, use transverse fields
- G = 'anomalous gyromagnetic ratio', $G_{proton} = 1.7928$

Depolarizing Resonances in RHIC

Spin tune: Number of 360 degree spin rotations per turn, ν_s
It is similar to betatron tune.

Depolarizing resonance condition:
Number of spin rotations per turn = Number of spin kicks per turn

Imperfection Resonances

arise from sampling of error fields, fields due to closed orbit errors, etc.

$\nu_s = G\gamma = n$ (integer)

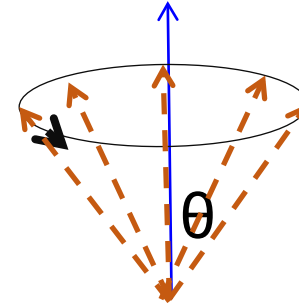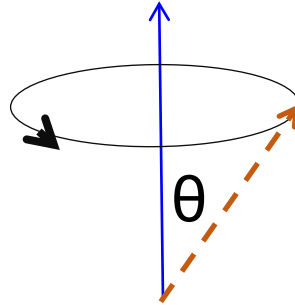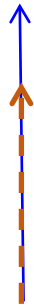**Intrinsic Resonances**

arise from sampling of focusing fields due to finite beam emittance.

$\nu_s = G\gamma = kP \pm \nu_y$ P: Superperiodicity [RHIC: 3]

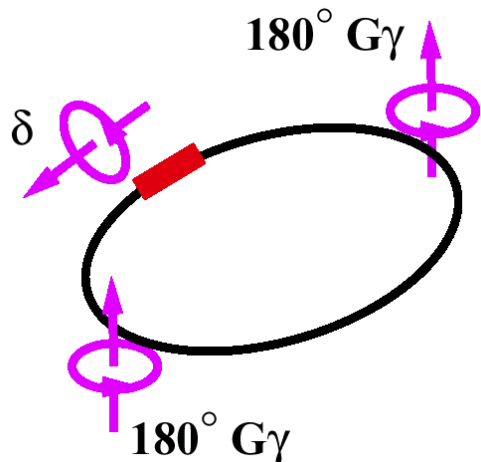ν_y: Vertical betatron tune [RHIC: ~29.23]

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

Depolarization Mechanism

Spin vectors (red) of many particles	ALL spin vectors kicked away from vertical by a single horizontal B field	Small energy spread in the beam means the precession rates are slightly different
All initially aligned with a B field		
No precesssion	Initially they all precess together	The spin motion 'decoheres'
Average projection onto vertical is 1	Average projection onto vertical is cos θ (<1)	Average projection onto vertical still cos θ (<1)
100% polarized	< 100% polarized But *in principle* could be kicked back if corrected soon	Polarization loss happens here (like emittance dilution from injection mismatch)

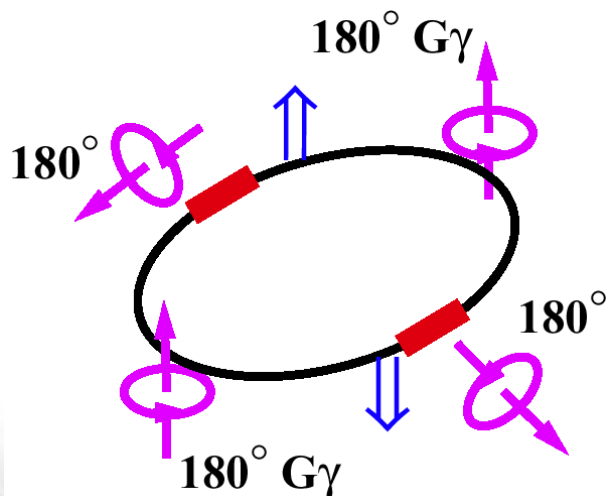# Siberian Snakes (Local Spin Rotators)

$$\cos(180^\circ\,\nu_s) = \cos(\delta/2) \cdot \cos(180^\circ\,G\gamma)$$

$\delta \neq 0^\circ \rightarrow \nu_s \neq n$

<u>No</u> imperfection resonances
Partial Siberian snake (AGS)

$\delta = 180^\circ \rightarrow \nu_s = \frac{1}{2}$

<u>No</u> imperfection resonances <u>and</u>
<u>No</u> Intrinsic resonances
Full Siberian Snake

Two Siberian Snakes in RHIC

Siberian Snake
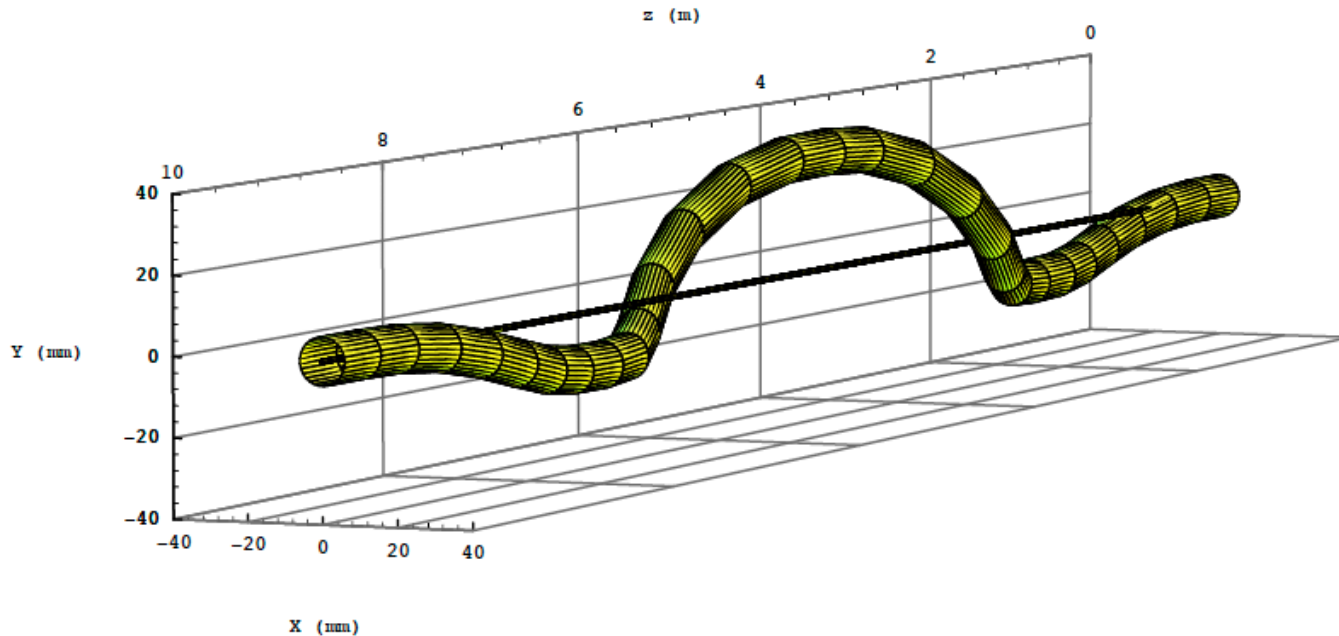
Three-dimensional view of the trajectory through a RHIC Snake. It was first introduced by physicists in Siberia and the trajectory inside the magnet is like snake. It was named Siberian snake by Ernest Courant.

Polarized Proton Collisions in RHIC

M. Bai, *et al.,* PRL 96, 174801(2006)
H. Huang, *et al.,* PRL 99, 154801(2007)
H. Huang, *et al.,* PR-AB 17, 081001(2014)

Polarization Passing through Resonance

Resonance conditions depend on energy (γ) so during acceleration we pass through (cross) many resonances
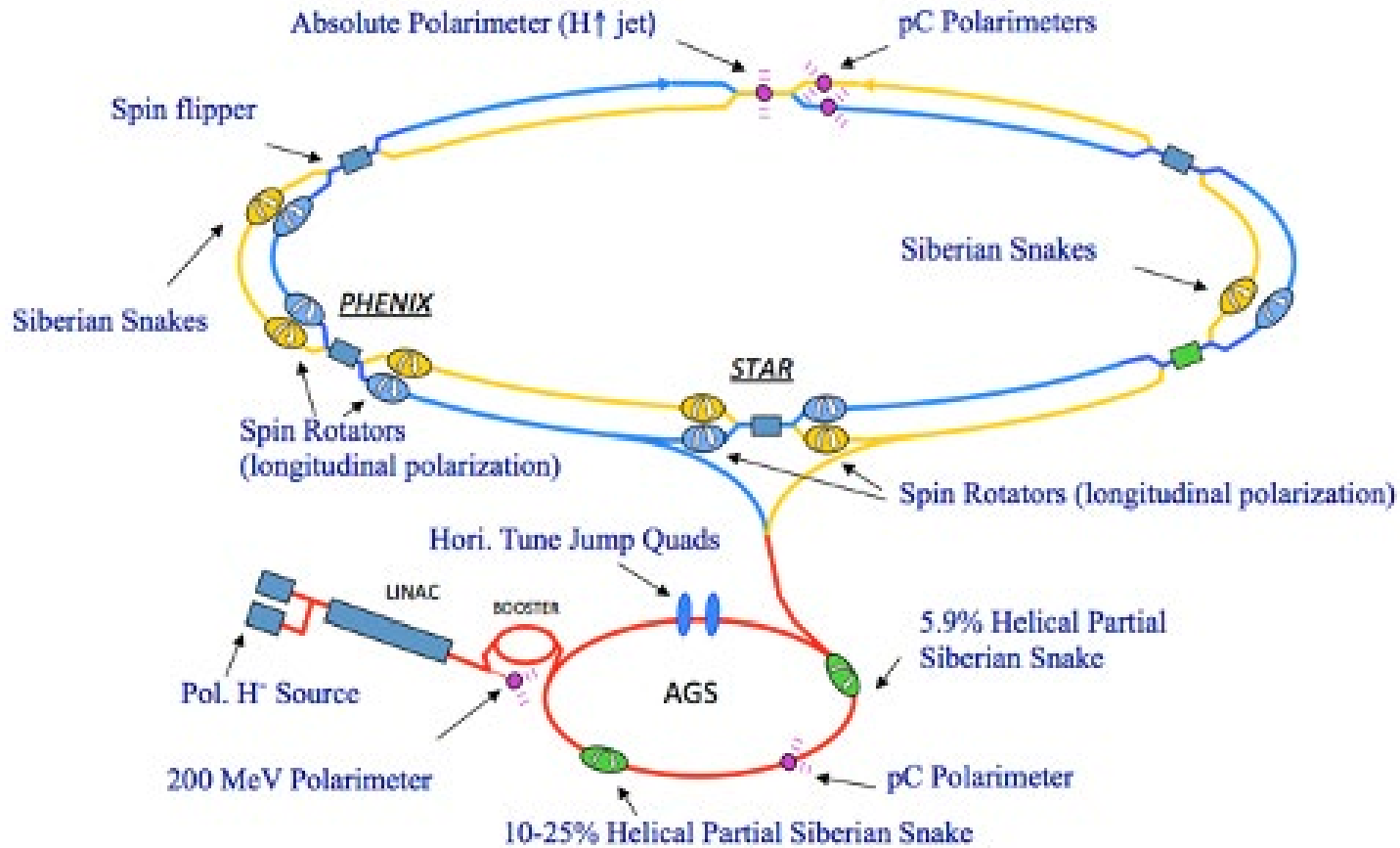
What happens to the spin of a particle passing through a resonance of strength ε at a crossing rate $\alpha = (dG\gamma/d\theta)$

Initial spin->Final spin:

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

P_f/P_i = final and initial polarization ratio
α = crossing rate
$|\varepsilon|$ = resonance strength

No. of Orbit Turns

With adiabatic condition satisfied, Spin flip!
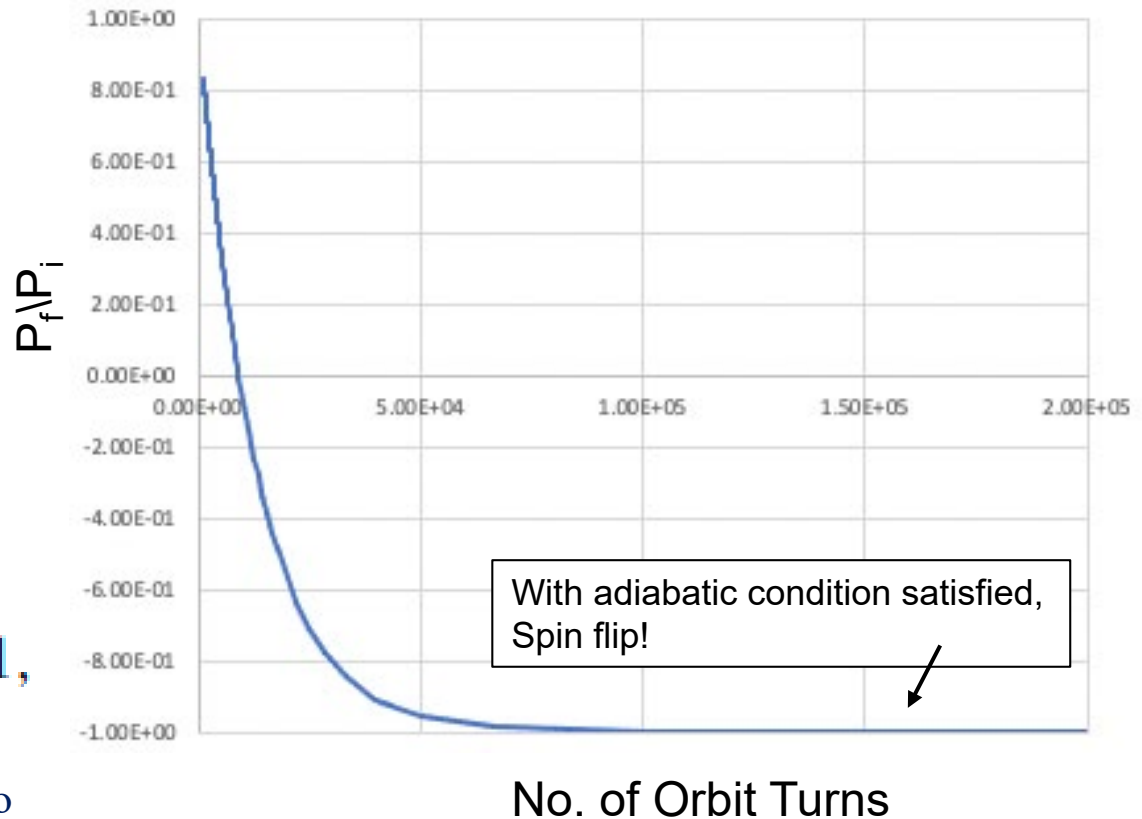
Unlike betatron resonance: when adiabatic condition is satisfied, $\dfrac{|\epsilon|^2}{\alpha} \gg 1$, polarization amplitude can be preserved, by a full spin flip

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

Spin Flip Experiment

Why Spin Flipper Is Needed?
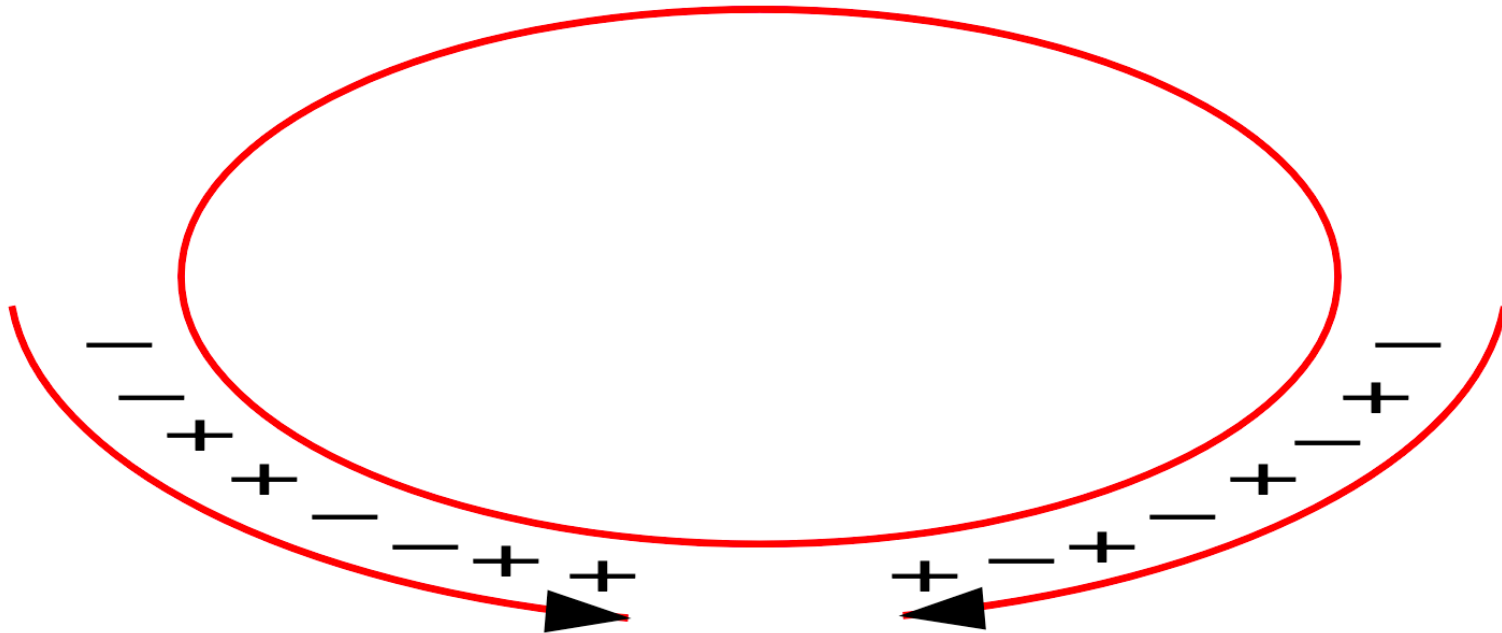
To reduce systematic error, collisions are arranged with various collision pattern (++, +-, -+,--). Because the same bunches collide for a given IP, periodically reversing the spin will reduce systematic errors for asymmetry measurements even further.

Spin Flipper

- The spin flip can be achieved by an artificial resonance generated by an dipole running with certain rf frequency. It is done as following: ramping the frequency or the spin rotator tune ν_{osc} across the spin tune ν_s adiabatically and the spin can be flipped following the Froissart-Stora formula:

$$\frac{P_f}{P_i} = 2\exp^{-\frac{\pi}{2}\frac{|\epsilon|^2}{\alpha}} - 1, \qquad \alpha = \frac{\Delta\nu_{osc}}{2\pi N}$$
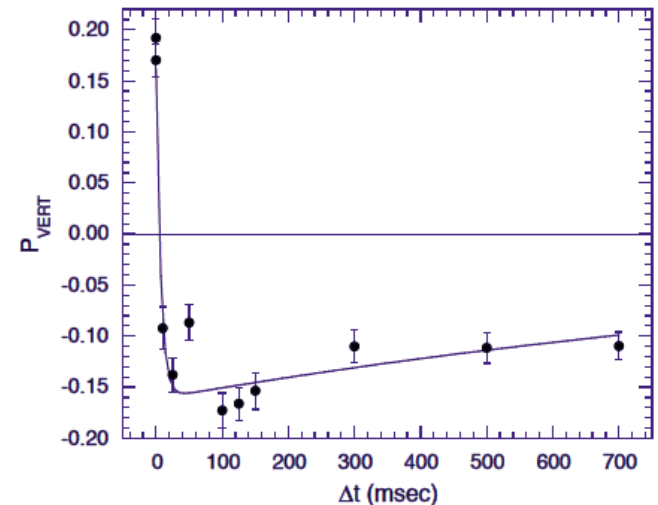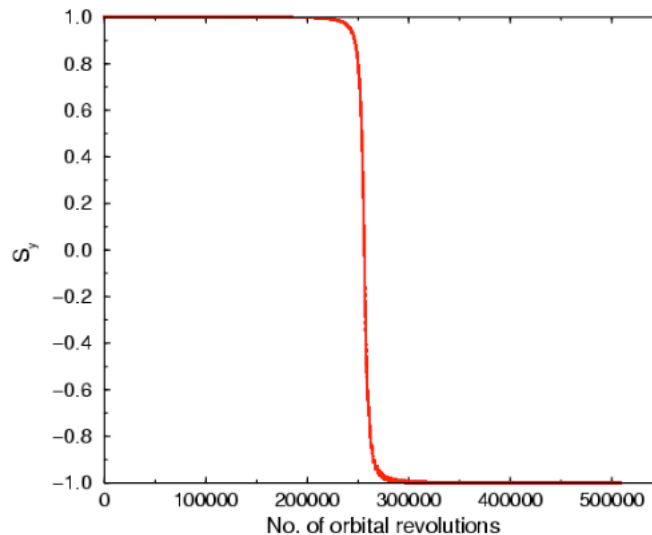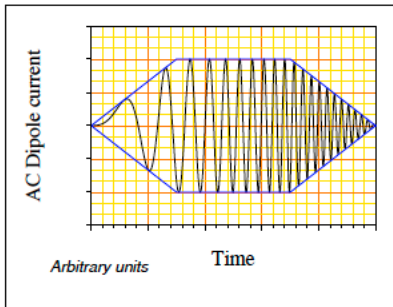
V.A. Anferov, *et al.*, PR-AB Vol. 3, 041001(2000).
Spin flip results at 202.7MeV with single AC dipole.

Haixin Huang

Spin Flipper Challenges at RHIC

- The simple device can't be applied to high energy colliders such as RHIC where spin tune is ½.

- First, a single AC dipole generate two resonances located at $\nu_s = \nu_{osc}$ and $\nu_s = 1 - \nu_{osc}$, the so-called mirror resonance. When ν_s is adiabatically sweeping across $\nu_s = 1/2$, the polarized beam simultaneously crosses the spin resonance $\nu_s = \nu_{osc}$ from one side and the spin resonance $\nu_s = 1 - \nu_{osc}$ from the opposite side. The contributions from both can cancel each other or interfere. No full spin flip can be achieved.

- Second, the orbit distortion due to the spin flipper has to be zeroed outside the spin flipper.

- Third, there is a spin tune spread related to the slope of dispersion function in the snake. Spin tune of a ring with two snakes is given by

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

There is a spin tune spread related to the synchrotron motion and the resulting momentum spread:

$$\Delta\nu_s = \frac{(1 + G\gamma)}{\pi}(D'_1 - D'_2)\frac{\Delta p}{p}$$

M. Bai and T. Roser, PR-AB 11, 091001(2008).
S.R. Mane, PR-AB 12, 099001(2009).

Haixin Huang

RHIC Spin Flipper

In summary, these are the key requirements for the spin flippers in the presence of snakes:

1. The mirror resonance has to be eliminated.
2. The vertical orbit distortion has to be zeroed.
3. The spin tune spread has to be small. In the case of RHIC, the ΔD' of two snake locations has to be reduced.

There were several iterations of the spin flipper designs. It evolved from two AC dipoles to five magnets, and eventually nine magnets. The 9-magnet design satisfies the first two requirements. The ΔD' suppression lattice was achieved with γ_{tr} quads.
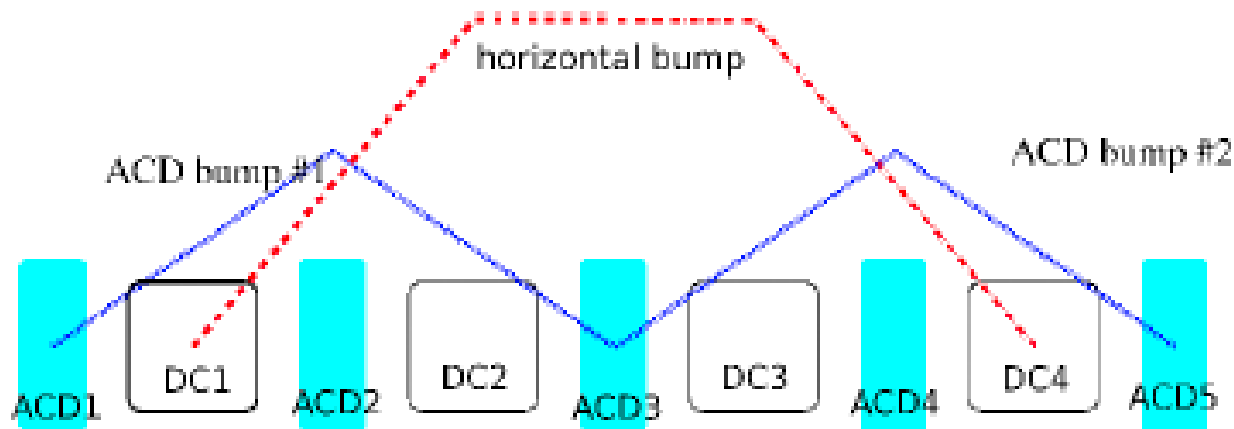
Spin Flipper Layout
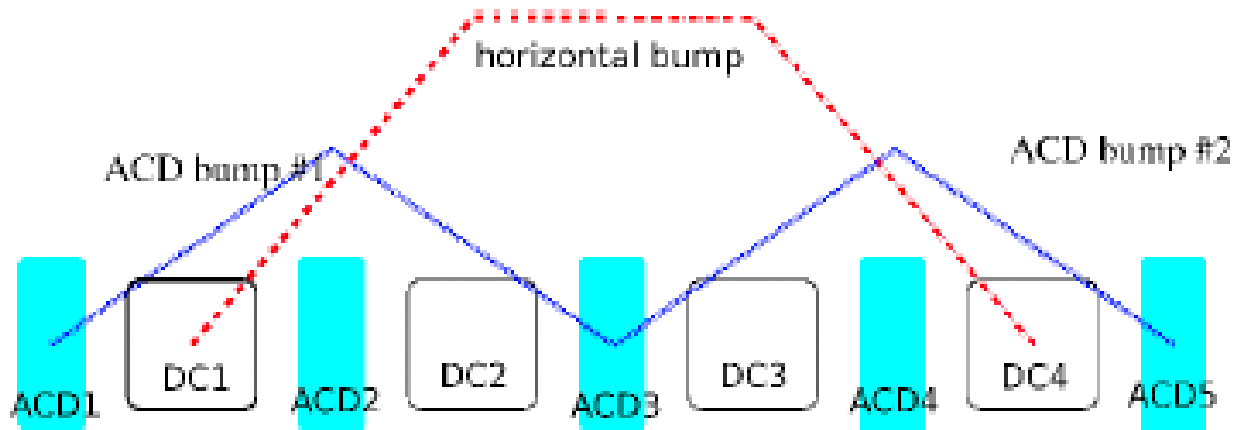
The four dc dipoles yield spin rotation angles of $+\psi_0/-\psi_0/-\psi_0/+\psi_0$.
The ac dipoles 1-3 and ac dipoles 3-5 create a local vertical orbit bump with a $+\phi_{osc}/-2\phi_{osc}/+\phi_{osc}$ spin rotation sequence.

The ac dipole currents satisfy these relations, where i is the ith orbital revolution.

$$I_2 = I_0 \sin(2\pi\nu_{osc}i + \chi_1),$$

$$I_4 = I_0 \sin(2\pi\nu_{osc}i + \chi_2),$$

$$I_1 = \frac{1}{2}I_0 \sin(2\pi\nu_{osc}i + \chi_1 + \pi),$$

$$I_5 = \frac{1}{2}I_0 \sin(2\pi\nu_{osc}i + \chi_2 + \pi),$$

$$I_3 = I_1 + I_5,$$

H. Huang, *et al.,* PRL 120, 264804(2018)

Spin Flipper Magnets in RHIC Tunnel

Mirror Resonance is Visible with Old Flipper

Driving tune is 0.49. The spin tune is changed by changing snake current, about 5A out of 320A for the two dips. The two colors correspond to 2 AC dipoles(black) and 1 AC dipole case(red).

The structure looks similar on both sides.
M. Bai *et al*. , IPAC10 Proc., p. 1224.

The spin tune spread was about ±0.005 from ZGOUBI model(blue lines).

Haixin Huang
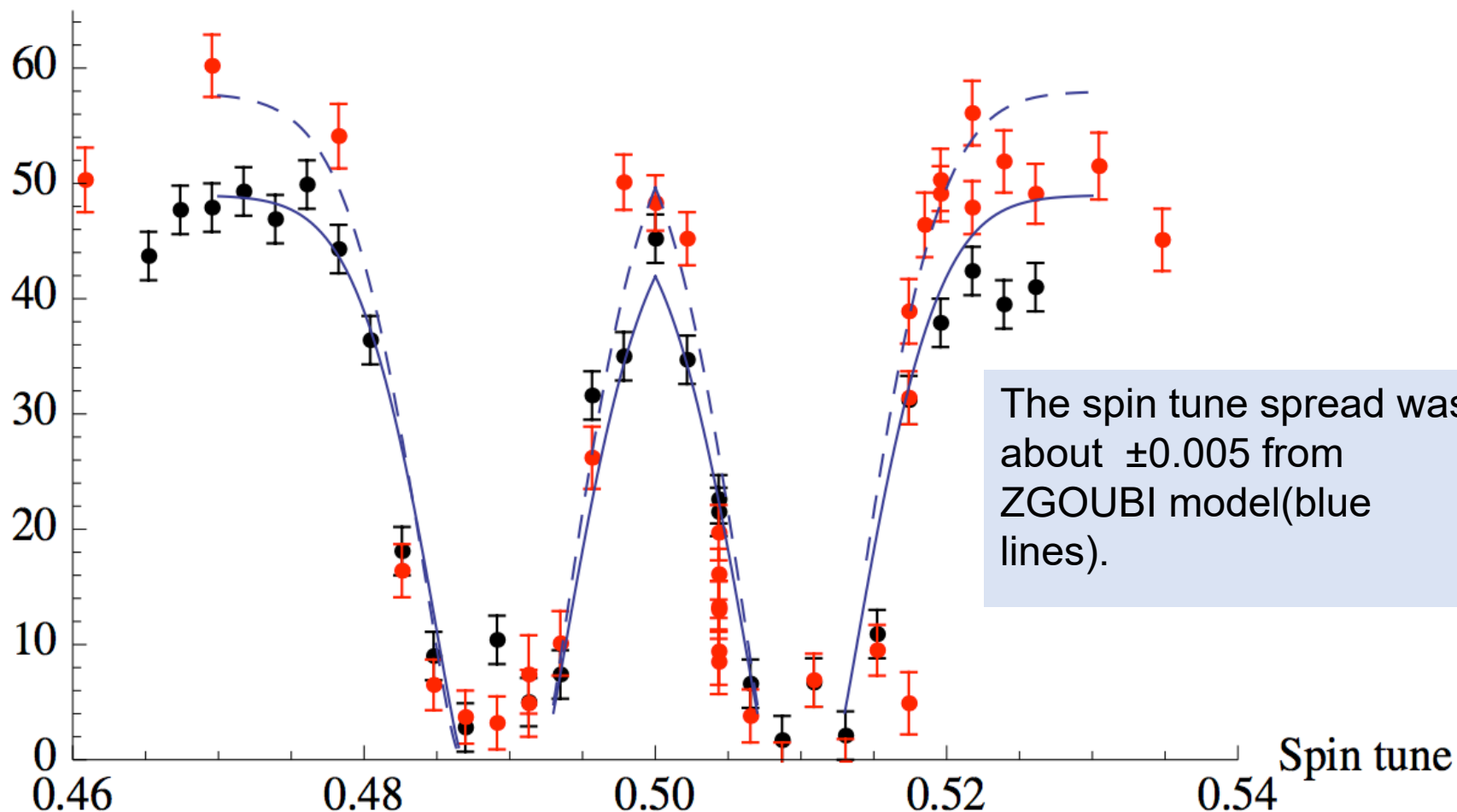
Fast or Slow Sweeping Speed?

No. of Orbit Turns
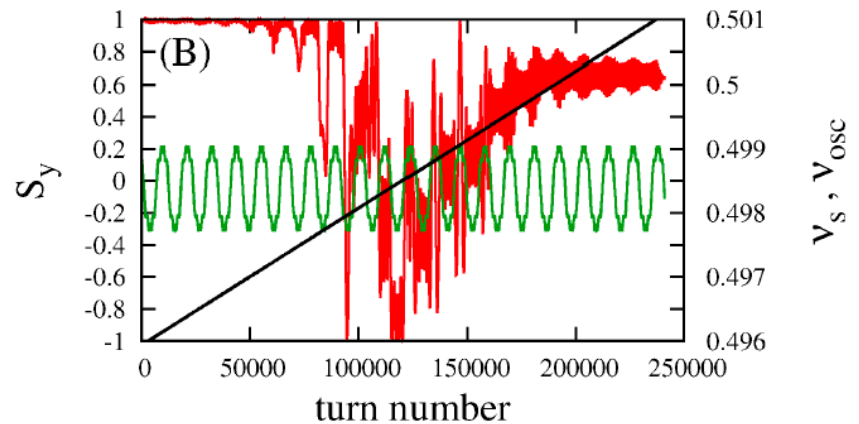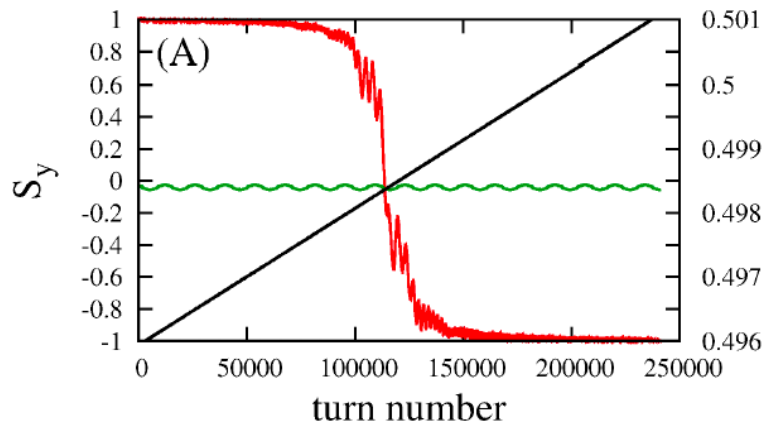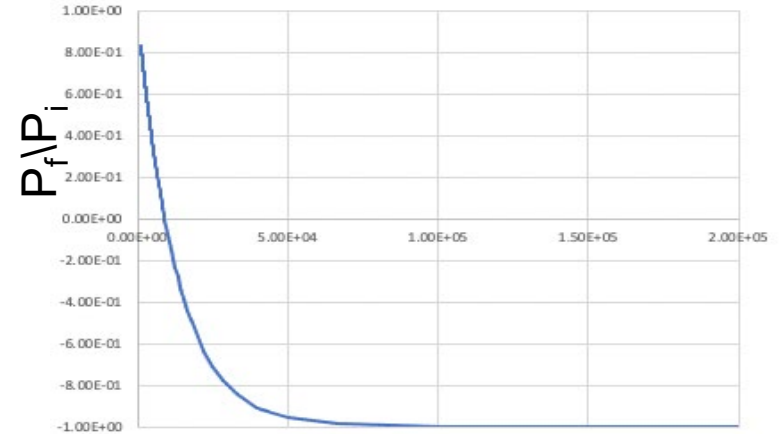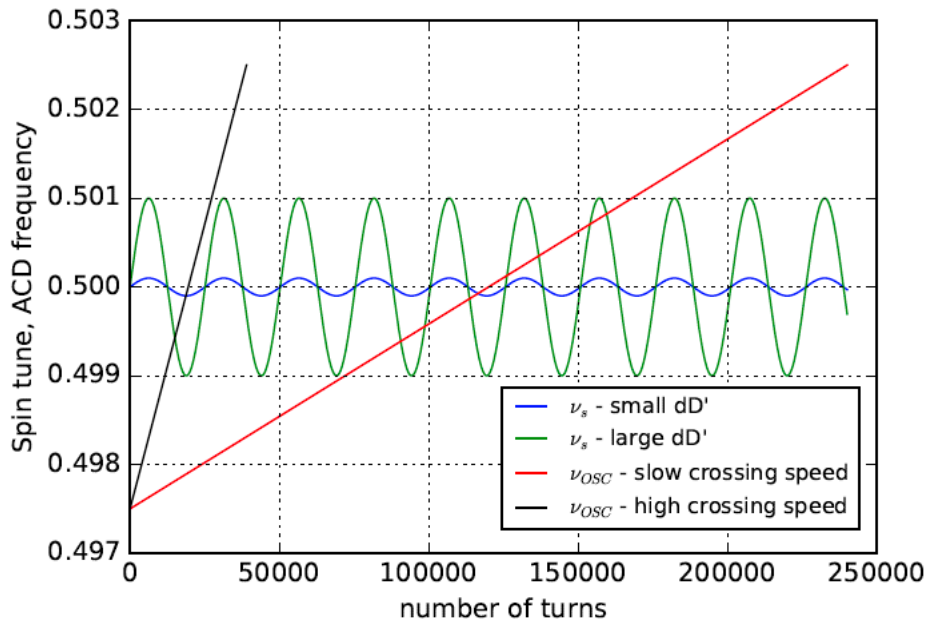
The choice is a compromise: as slow as possible but avoid multiple crossing.

Spin Tune from Driving Tune Scan @ Injection

$$S_y = \frac{P_0}{\sqrt{1 + \epsilon^2/\Delta^2}}$$

Use above formula, one can plot the vertical polarization as function of vicinity to the spin resonance. The data follow the curve very well.

Polarization was measured with spin flipper on at fixed tune for 3 sec.

No mirror resonance at 0.498.

$$\delta\nu_s = \frac{1 + G\gamma}{\pi}\Delta D'\frac{\Delta p}{p}$$

Polarization(%)

Driving Tune

Legend:
- $\Delta D'=0.044$, 24GeV
- $\Delta D'=0.003$, 24GeV
- model 24GeV

Haixin Huang

Spin Flip Efficiency vs. ΔD'

The spin flip efficiency for a 3sec sweep time at RHIC injection as function of ΔD'. The ΔD' suppression is critical for good spin flip efficiency.

$$\delta\nu_s = \frac{1 + G\gamma}{\pi} \Delta D' \frac{\Delta p}{p}$$

C. Liu, *et al.,* PR-AB 22, 061002(2019).

ΔD' between Two Siberan Snakes

Haixin Huang

Spin Flip Efficiency vs. Sweep Time @ Injection

The spin flip efficiency at RHIC injection as function of sweep time. The lower efficiency at slower ramp rate is due to multiple resonance crossings.

$$\delta\nu_s = \frac{1 + G\gamma}{\pi}\Delta D' \frac{\Delta p}{p}$$

Axis labels:
- Y-axis: Spin Flip Efficiency (%), values -0.6, -0.7, -0.8, -0.9, -1
- X-axis: Spin Flipper Sweep Time (sec), values 0, 1, 2, 3

Haixin Huang

Spin Tune from Driving Tune Scan @Store

$$\delta\nu_s = \frac{1+G\gamma}{\pi}\Delta D'\frac{\Delta p}{p}$$

The data shows wider spread than the model. There may be other sources of spin tune spread.

mirror resonance at 0.504.

▲—▲ ΔD'=0.0001 255GeV
- - - model 255GeV

Polarization(%)

Driving Tune

The polarization dip around 0.504 doesn't look like the mirror resonance.

Spin Flip Efficiency vs. Sweep Time @ Store

The spin flip efficiency at RHIC store as function of spin flipper sweep time. Similar to injection, the best efficiency was achieved with faster sweep time.

Haixin Huang

Spin Tune Measurement with Driven Spin Coherence

Polarization Measurements

Polarization is measured by polarimeter:

1) Insert a *very* thin carbon ribbon into the beam (2.5 cm long, 10 μm wide and 25-50 nm thick, ~100 atoms)
2) Proton causes a carbon to be recoiled off the target
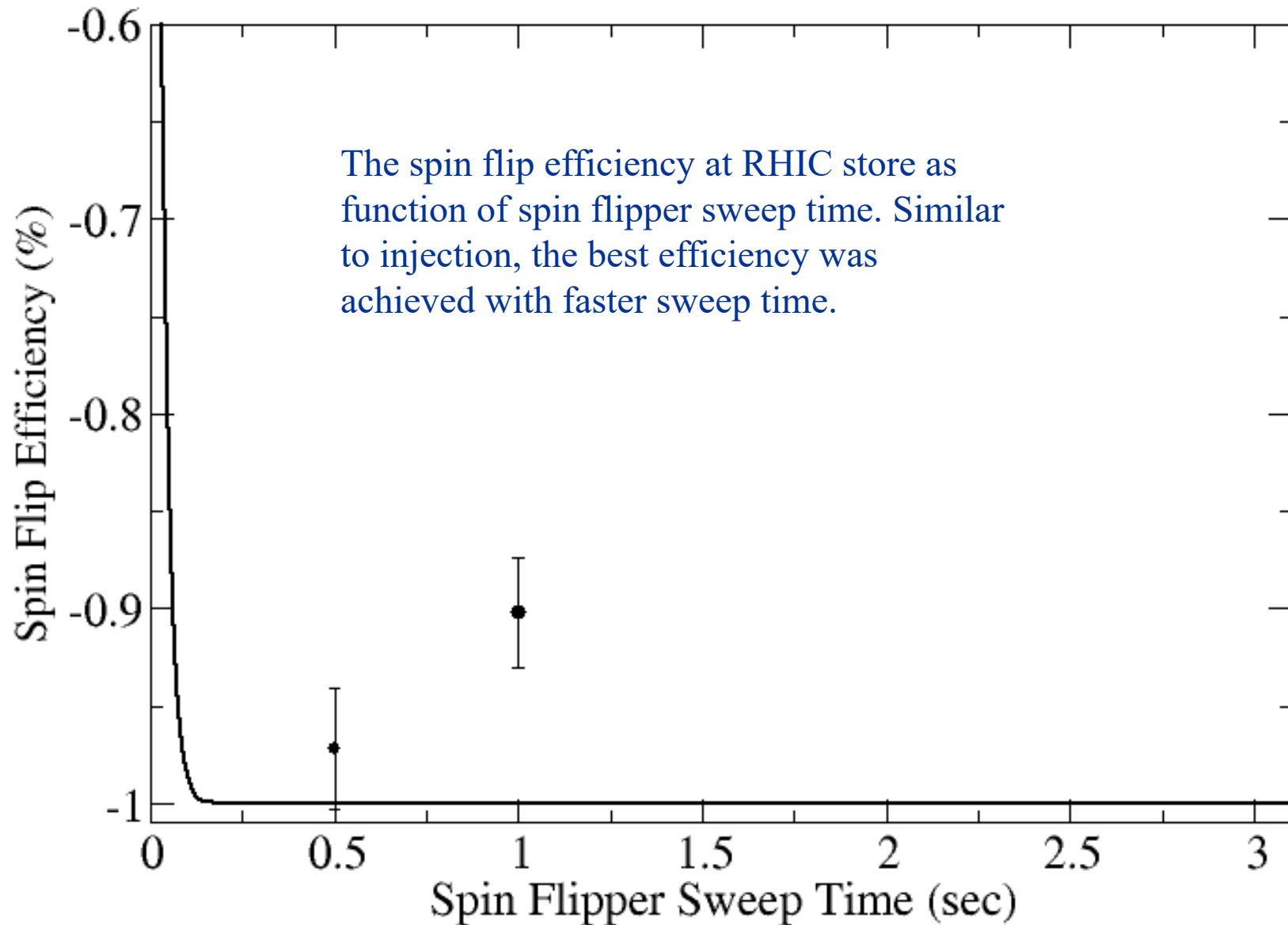   → The recoil events (right or left) depend on the spin direction (up or down) of the incident proton
3) Silicon detectors around the beam pipe detect the carbon, the left-right asymmetry is proportional to the vertical beam polarization; the up-down asymmetry is proportional to the horizontal beam polarization.

The asymmetry can be very small at high energy (<1% difference in left versus right for a highly polarized beam).

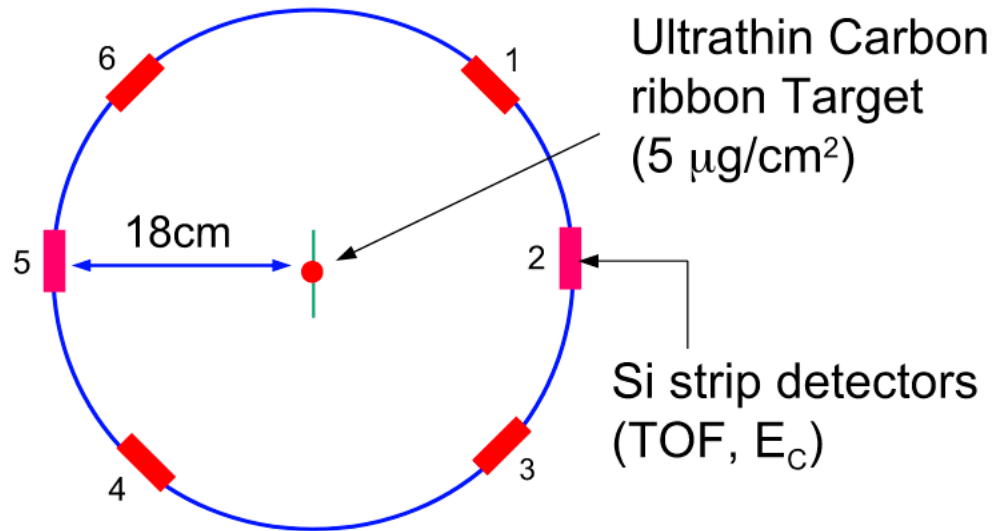Relationship between beam polarization and asymmetry is called the 'analyzing power'.

FIG. 1. Layout of a RHIC *p*-carbon polarimeter. The target and beam are represented by a vertical line and a dot, respectively.

Driven Spin Coherent Motion

In the neighborhood of an isolated spin resonance, the stable spin direction is given by

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

where ϵ is the resonance strength of the spin flipper, i is the orbit turn number.

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

The advantage of this method is that it is nondestructive. When the driving force is adiabatically removed, the spin will return to vertical.
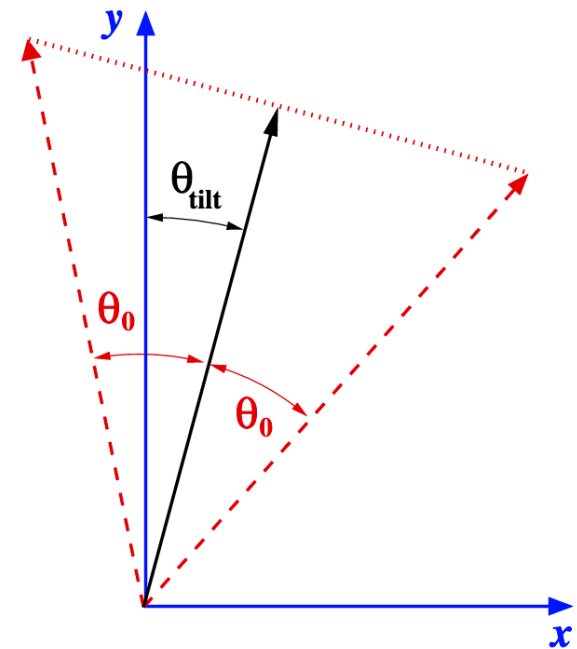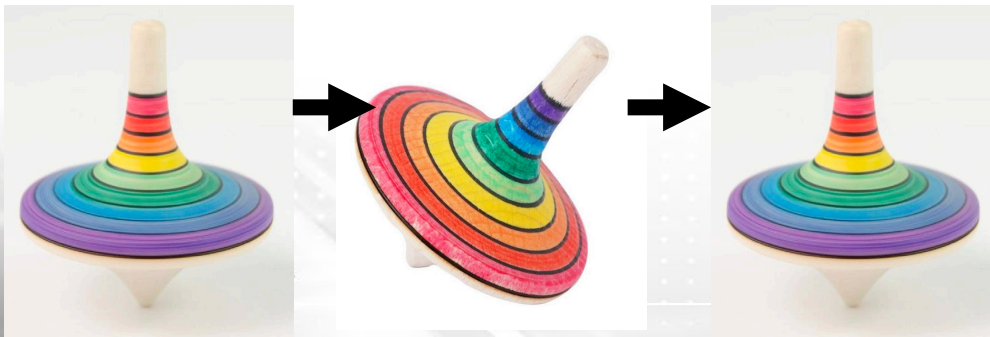

FIG. 2. Projection of the spin vector into the transverse plane when the spin tune is near a spin resonance. The spin oscillates around the stable spin direction (solid arrow) between the two boundaries (dashed arrows) over many orbit turns.

Keys for the Measurement

1. Generate large enough oscillation amplitude;

2. We need large amount of data from polarimeter, but the memory on the front end board is not larger enough. One has to align the TBT data properly to gain statistics. Align the data to the right phase is critical. This was done by align the events to spin flipper driving signal (see next page).

3. The small spin tune spread is also important. The large spin tune spread would smear out the oscillation.

If one can measure this spin coherent precession turn-by-turn, the spin tune can be measured.

$2\pi\nu_{res}i$

Haixin Huang
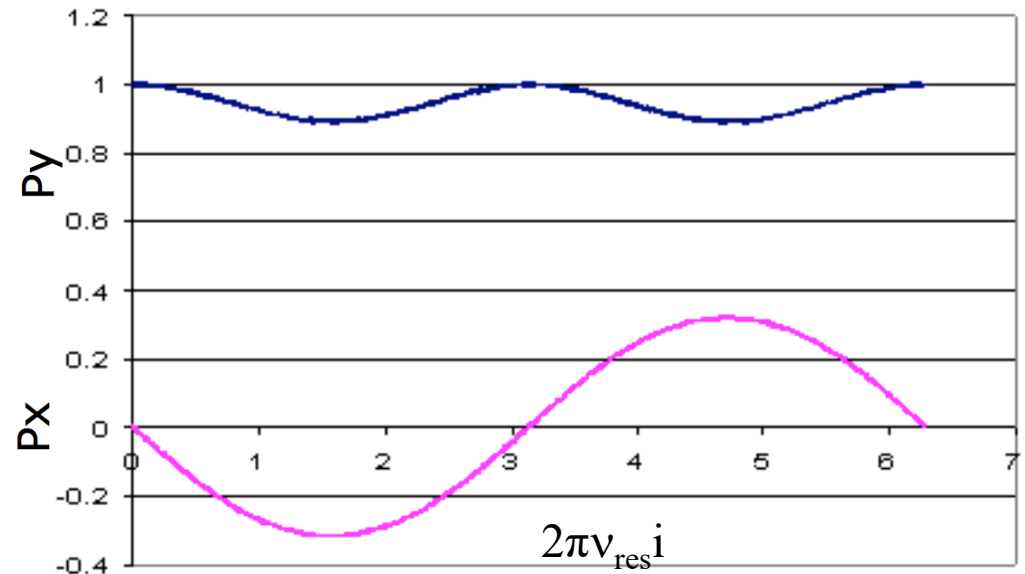
Spin Tune Measurement Data Flow

|<-~240 bunch crossing or 2 turns -> |
Divide it into 6 time bins

Spin flipper driving signals
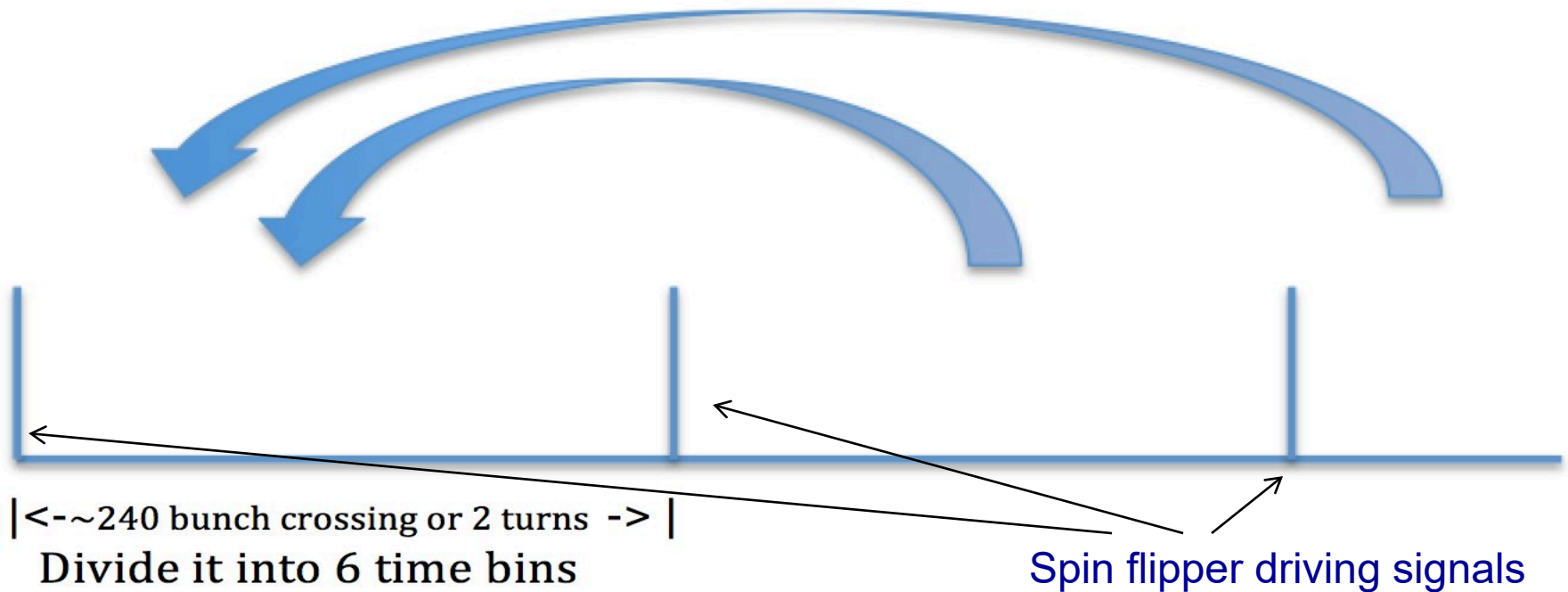
- We binned the carbon events in bins of bunches crossings since the most recent spin flipper signal, ~39kHz. We then grouped these bins into 6 big bins, 1-40, 41-80, 81-120, etc.
- The data in each of bin is then analyzed normally, to get the polarization and the tilt angle.

Haixin Huang

Driving Coherent Spin Precession at Injection
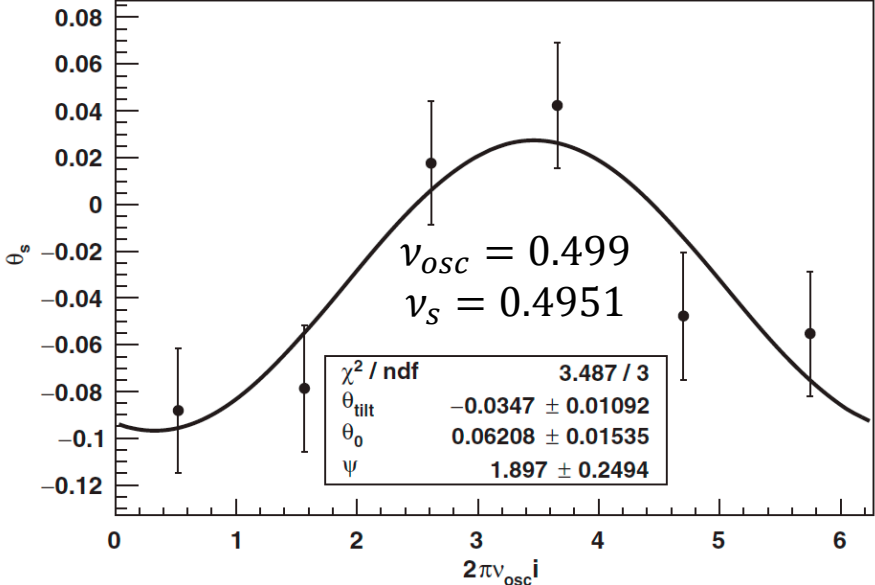
$$\frac{P_x}{P_y} = \tan(\theta_s - \theta_{\text{tilt}}) = \tan\theta_0 \cos(2\pi\nu_{\text{osc}}i - \Psi).$$

i is the No. of bins.

$$\theta_s(i) = \theta_{\text{tilt}} + \tan^{-1}\left[\tan\theta_0 \cos(2\pi\nu_{\text{osc}}i - \Psi)\right] \qquad \tan\theta_0 = \frac{\hat{P}_x}{P_y} = \frac{|\epsilon|}{\nu_s - \nu_{\text{osc}}}$$

Left plot fit parameters:

χ^2 / ndf	2.214 / 3
θ_{tilt}	-0.03574 ± 0.01086
θ_0	0.1338 ± 0.01519
Ψ	4.834 ± 0.1154

$$\nu_{osc} = 0.498$$
$$\nu_s = 0.4998$$

Right plot fit parameters:

χ^2 / ndf	3.487 / 3
θ_{tilt}	-0.0347 ± 0.01092
θ_0	0.06208 ± 0.01535
Ψ	1.897 ± 0.2494

$$\nu_{osc} = 0.499$$
$$\nu_s = 0.4951$$

The curve can tell if the driving tune is higher or lower than the spin tune. The left is with driving tune below spin tune. The right one is the opposite.
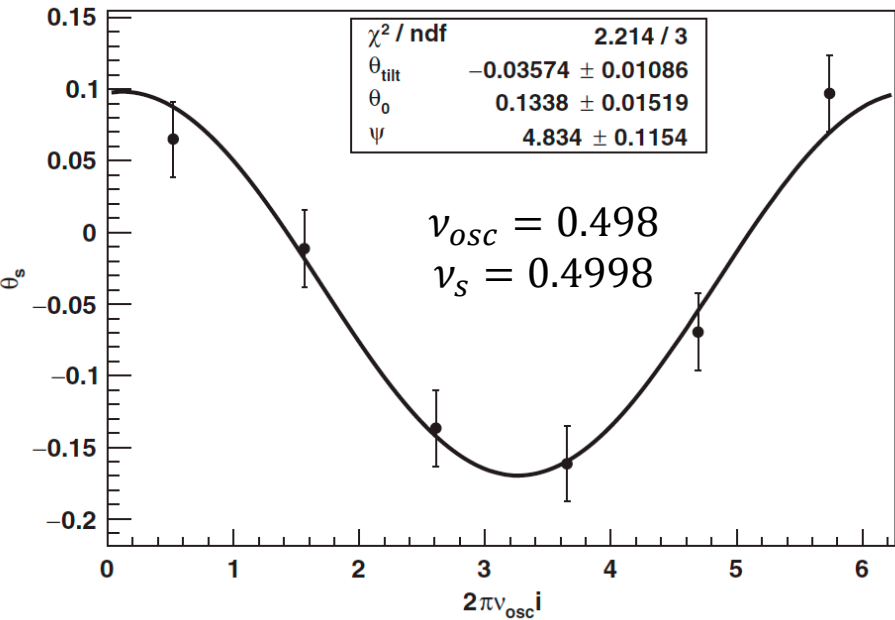
Haixin Huang

Driving Coherent Spin Precession at Store

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

i is the No. of bins.

$$\theta_s(i) = \theta_{tilt} + \tan^{-1}\left[\tan\theta_0 \cos(2\pi\nu_{osc} i - \Psi)\right]$$
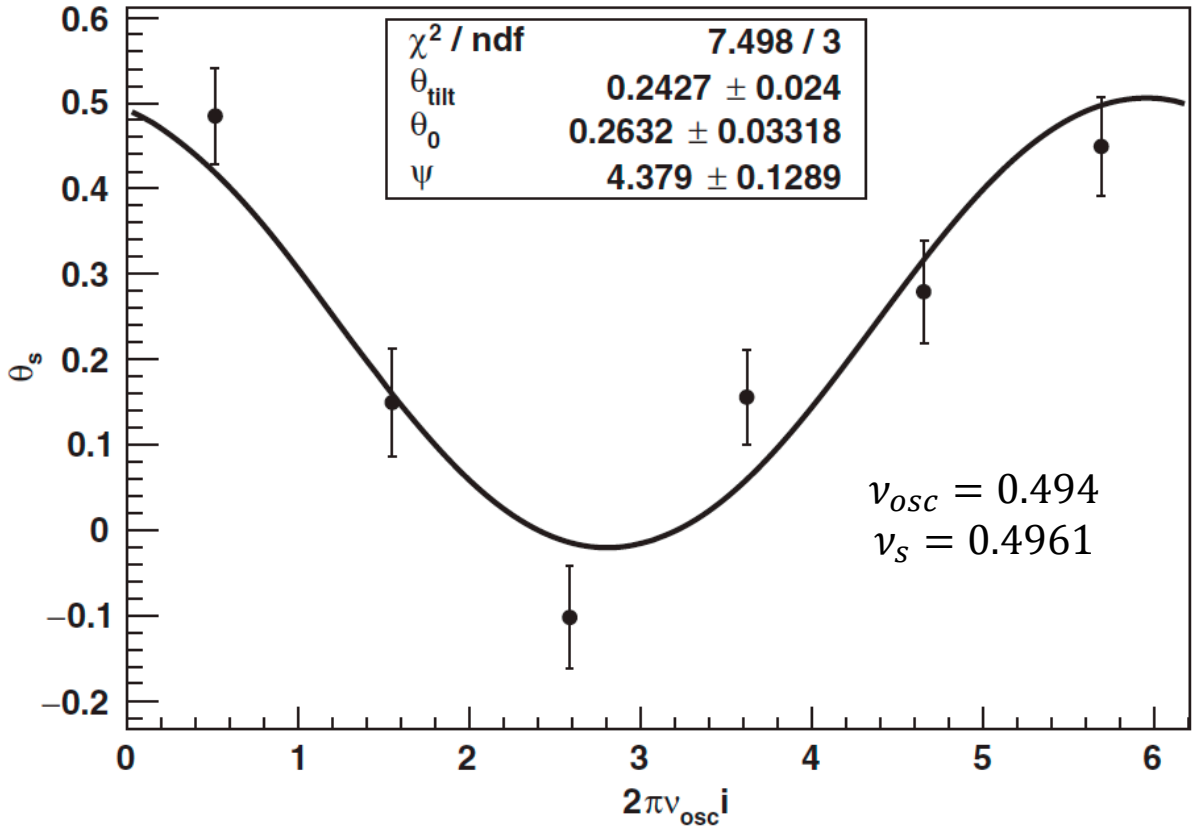
The driving tune is below spin tune.

Haixin Huang

Spin Tune Measurement Results

TABLE I. 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 second column. The third column is the drive tune of the ac dipoles. The derived spin tune from driven coherence is in the forth column. Last column is the spin tune range from spin flipper operation.

Set	θ_0 (rad)	ν_{osc}	ν_s from coherence	ν_s from flip
1	0.273 ± 0.059	0.499	0.4999 ± 0.0002	0.4975–0.5
2	0.134 ± 0.015	0.498	0.4998 ± 0.0002	0.4975–0.5
3	0.109 ± 0.015	0.5004	0.5026 ± 0.0003	0.5022–0.5025
4	0.132 ± 0.021	0.5009	0.5027 ± 0.0003	0.5022–0.5025
5	0.062 ± 0.015	0.499	0.4951 ± 0.0010	0.491–0.495
6	0.263 ± 0.033	0.494	0.4961 ± 0.0003	0.495–0.4965
7	0.174 ± 0.024	0.493	0.4962 ± 0.0005	0.495–0.4965

- With driven spin coherent precession, the transverse polarization components are measured. Take the ratio of the two components, the oscillation angle can be derived.
- The distance of driving tune to spin tune varied in above seven measurements, from 0.001 to 0.008. All of these measurements were done with small $\Delta D'$ lattice.

H. Huang *et al.,* PRL 122, 204803(2019).

BROOKHAVEN
NATIONAL LABORATORY

Summary

- The spin direction of proton beam aligns with the accelerator's magnetic field. But like a spinning top that starts to wobble, polarization axis sometimes starts to precess that deviates from perfect alignment due to external forces. If these external forces, such as small imperfections in the magnetic field, syncs up with the frequency of the precession, it can amplify the "wobble" of the proton spin and cause the beam to be depolarized. Siberian snakes are introduced to cancel the wobble effect.

- Polarization can be flipped by sweeping rf device frequency cross the spin precession frequency. At high energies, full spin flip has more constraints. The new spin flipper localizes the orbit distortion to within the spin flipper. This makes it possible to flip the spin without depolarization. In addition, new optics to suppress the spin tune spread is critical. 97% flip efficiency has been achieved.

- There are ways to measure the spin precession frequency, but techniques used to date effectively cause depolarization. A new way to measure the frequency of the precession *without* depolarizing the beam has been demonstrated. A controlled coherent spin precession (like top's wobble) can be introduced during the measurement and removed afterward. The key is to get close to the tipping frequency without destabilization. The techniques will lead to more stable and optimized operation at RHIC.

- Both techniques could also be used at future polarized Electron-Ion Collider.

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

Haixin Huang