Existing Spin Manipulators at RHIC

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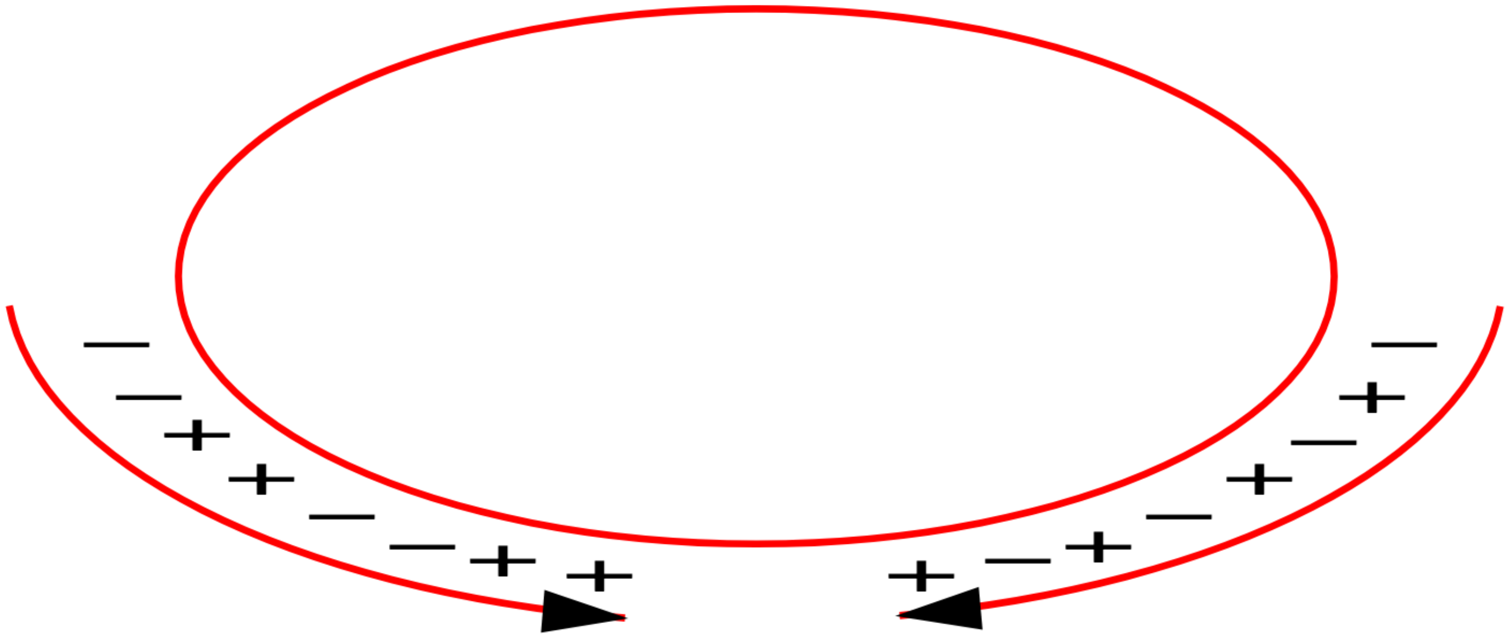
Workshop on Polarized Ion Sources and Beams at EIC
Stony Brook University

Outline

- RHIC spin flipper design consideration
- RHIC spin flipper experiment results
- Measure spin tune with spin flipper.
- Measure spin tune with AC dipole only
- Summary

Why Is Spin Flipper 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.

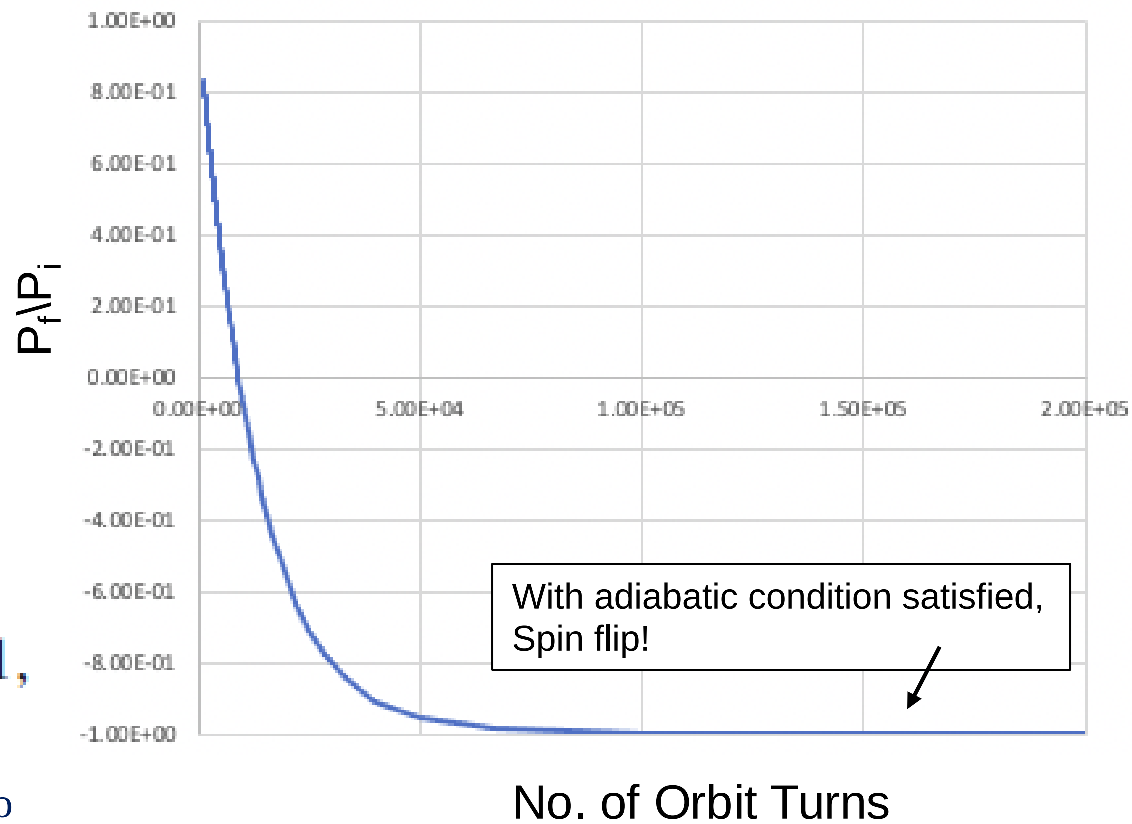
Polarization Passing through Resonance

Resonance conditions depend on energy (γ). During acceleration many resonances are crossed

What happens to the spin of a particle passing through a resonance of strength $|\epsilon|$ at a crossing rate $\alpha = (dG\gamma/d\theta)$ is given by the Froissart-Stora Formula:

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

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

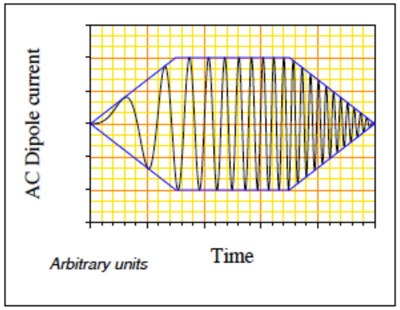


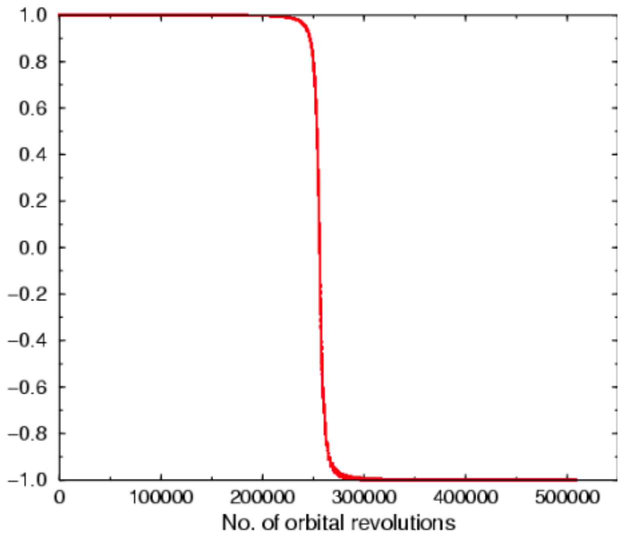
When adiabatic condition is satisfied, $\frac{|\epsilon|^2}{\alpha} \gg 1$, polarization amplitude can be preserved, by a full spin flip

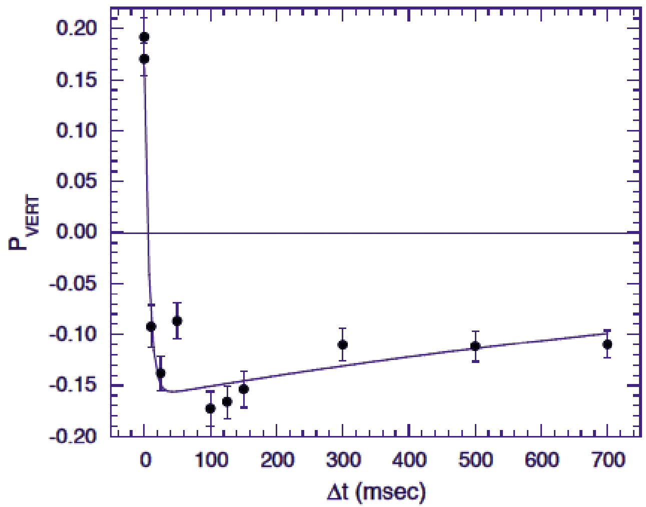
Spin Flipper

The spin flip can be achieved by an artificial resonance generated by a dipole running with certain rf frequency. It is done as following: ramping the frequency of the spin flipper 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*., Phys. Rev. Accel. & Beams **3**, 041001(2000). Spin flip results at 202.7MeV with single AC dipole.

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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 ν_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:

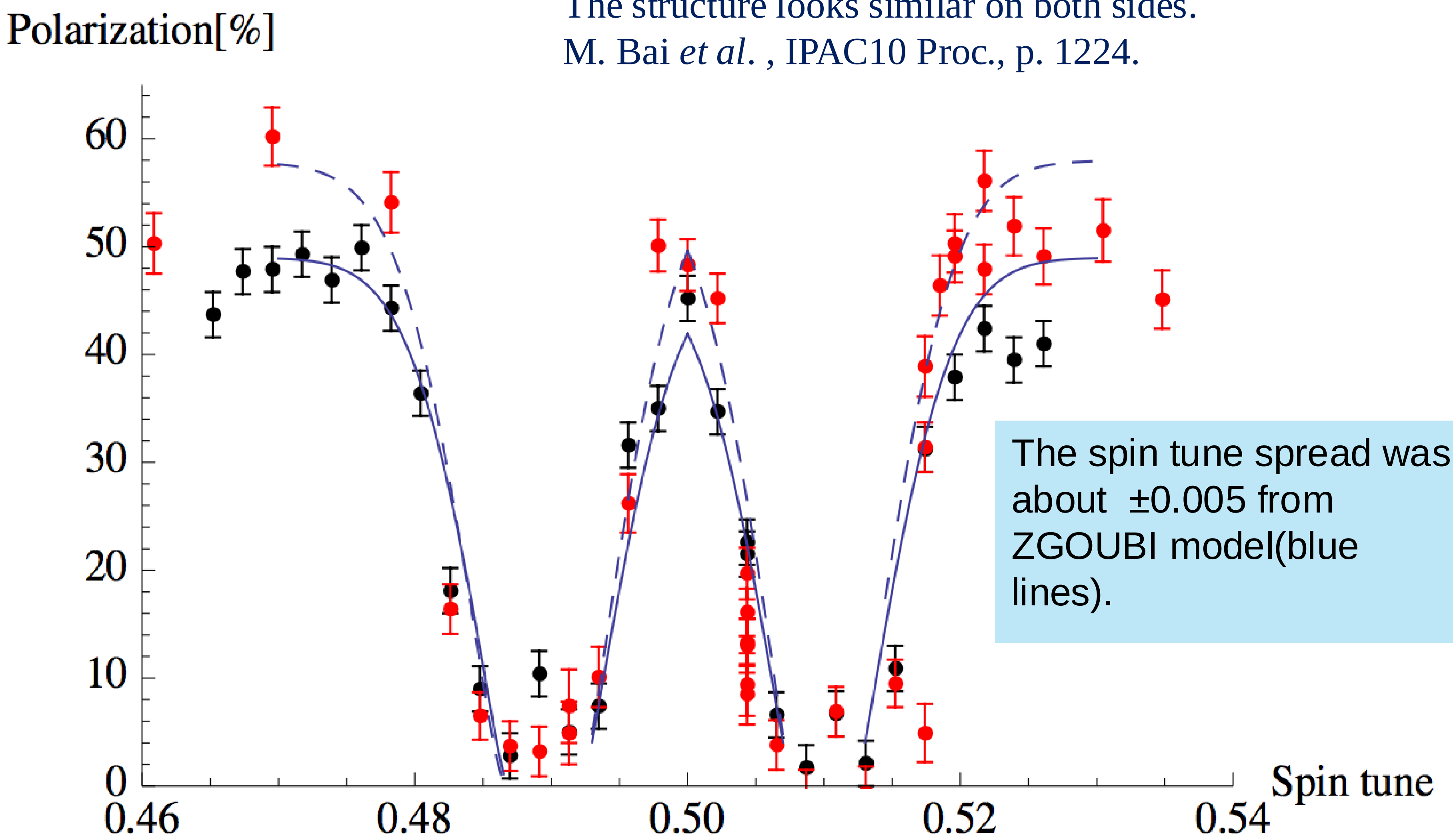
$$\Delta\nu_s = \frac{(1+G\gamma)}{\pi}(D_1' - D_2')\frac{\Delta p}{p}$$

M. Bai and T. Roser, Phys. Rev. Accel. & Beams **11**, 091001(2008).
S.R. Mane, Phys. Rev. Accel. & Beams **12**, 099001(2009).

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).

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Eliminating the Mirror Resonance

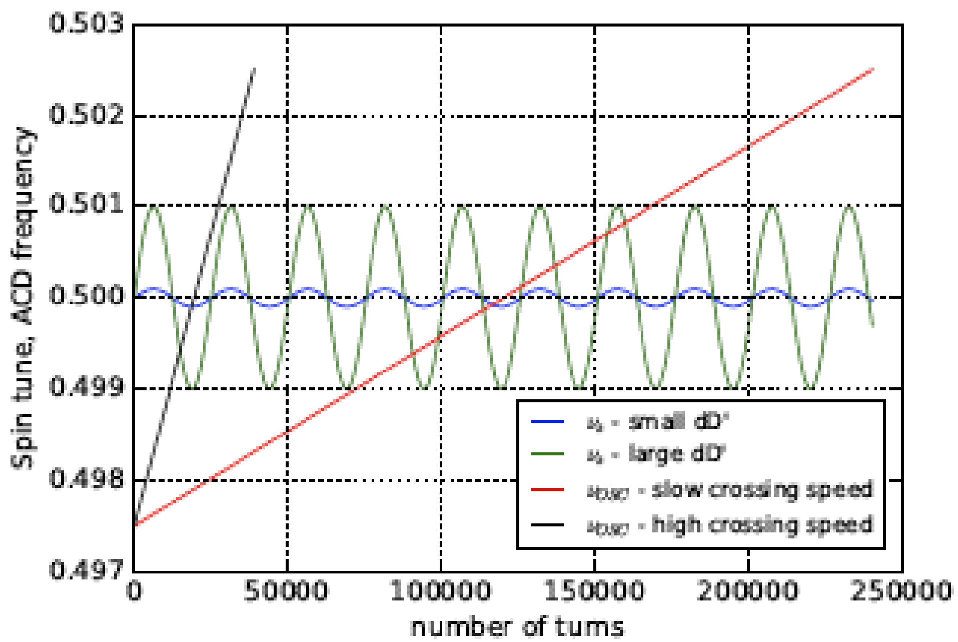
- Use 2 closed bumps to avoid spin rotations in quadrupoles and multipoles.
- Phase difference between the bumps must be equal to the spin rotation of one DC dipole.
- Phase difference accuracy better than ½ degree.
- Careful closure of the bumps.

The Effect of Spin Chromaticity

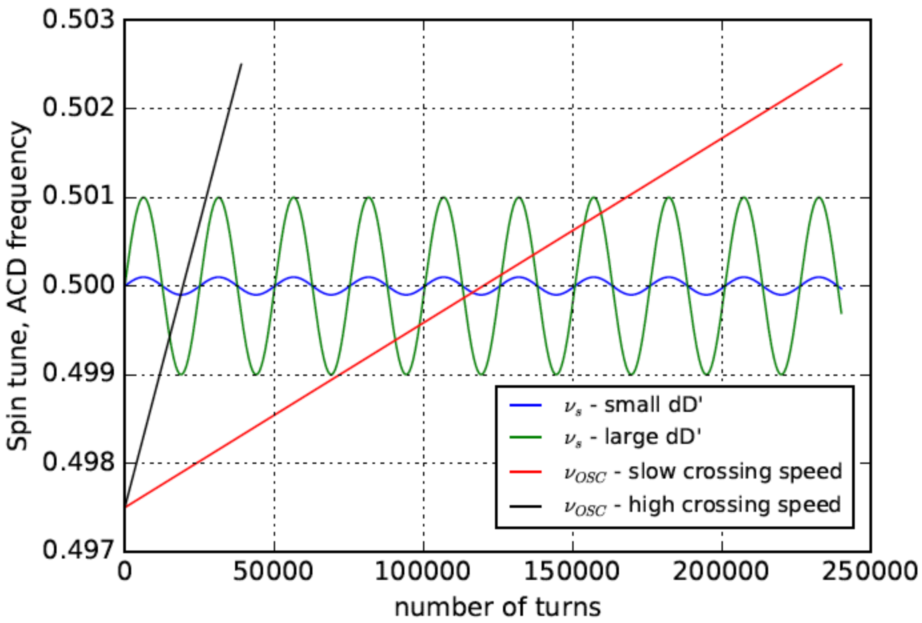
- The spin tune is $\nu = \frac{1}{2} + \gamma G(\theta_1 - \theta_2)$
- θ_1 and θ_2 are the total horizontal deflections angles in the two half rings between the snakes
- For an off-momentum particle the spin tune change is

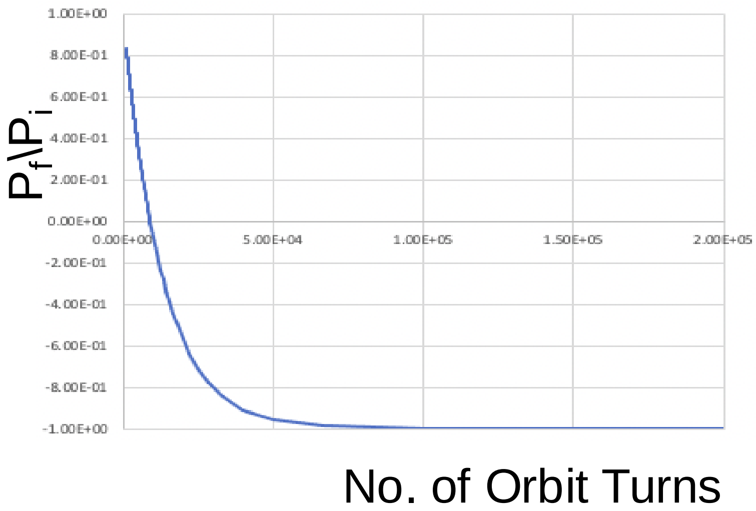
$$\Delta\nu = \frac{\gamma G}{\pi}\left[(D_2' - D_1')\frac{\Delta p}{p} + higher \quad order\right]$$

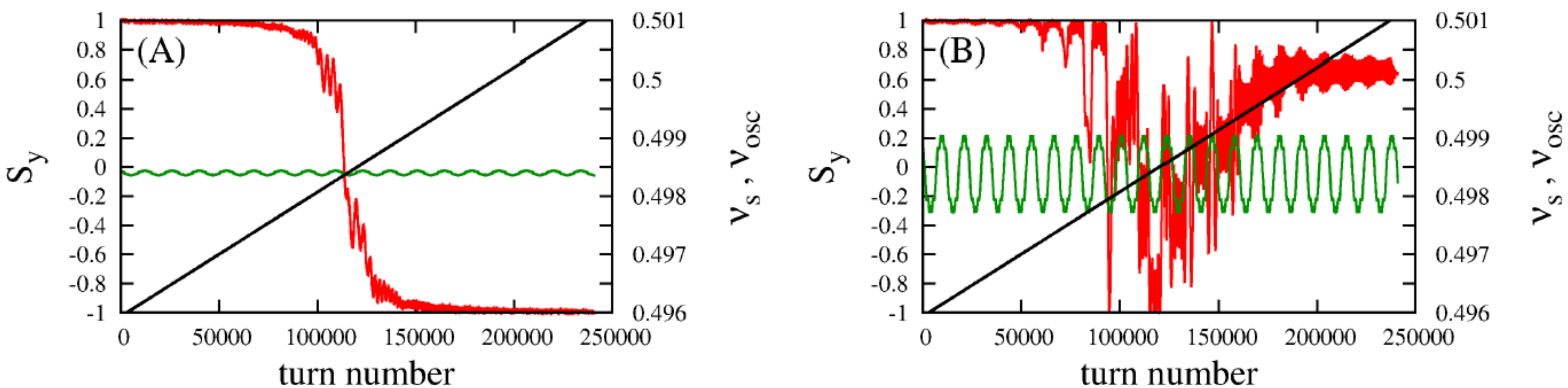
- The lattice needs to have small $\Delta D'$ between the two snakes.



Fast or Slow Sweeping Speed?







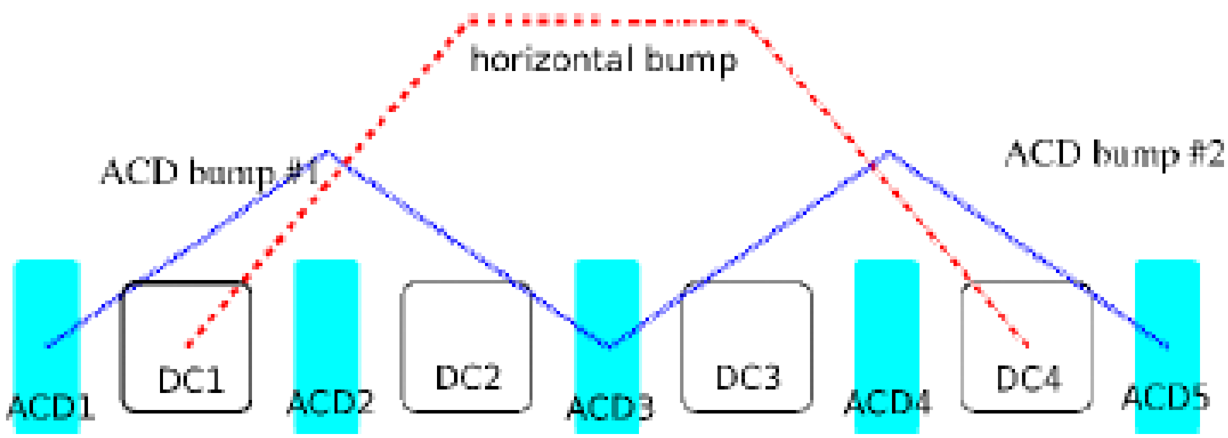
The choice is a compromise: as slow as possible (adiabatic) but avoid multiple crossing.

RHIC Spin Flipper

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

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

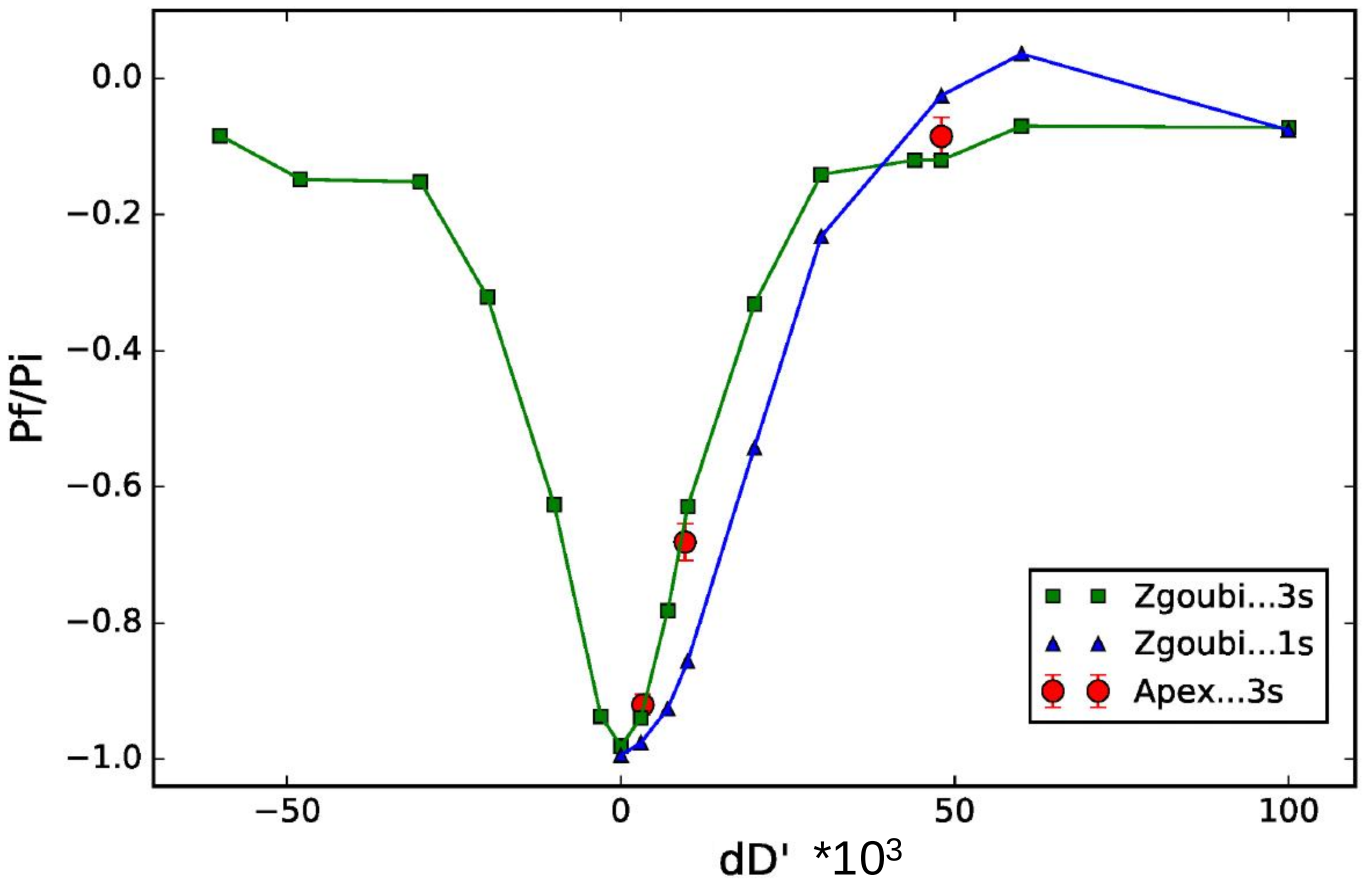
There were several iterations of the spin flipper designs. It evolved from two AC dipoles to five magnets, and eventually nine magnets. The 9-magnet design satisfies the first two requirements.



H. Huang, J. Kewisch, C. Liu, A. Marusic, W. Meng, F. Meot, P. Oddo, V. Ptitsyn, V. Ranjbar, and T. Roser, Phys. Rev. Lett. 120, 264804 (2018).

Spin Flip Efficiency vs. ΔD’

The spin flip efficiency at RHIC injection as function of D’ difference. The D’ difference reduction is critical for good spin flip efficiency.



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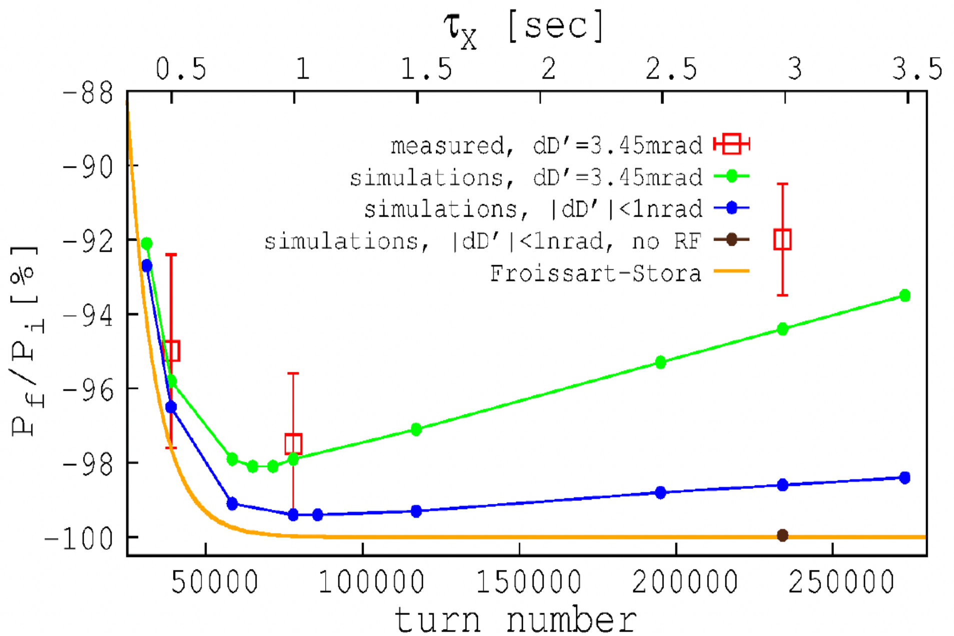
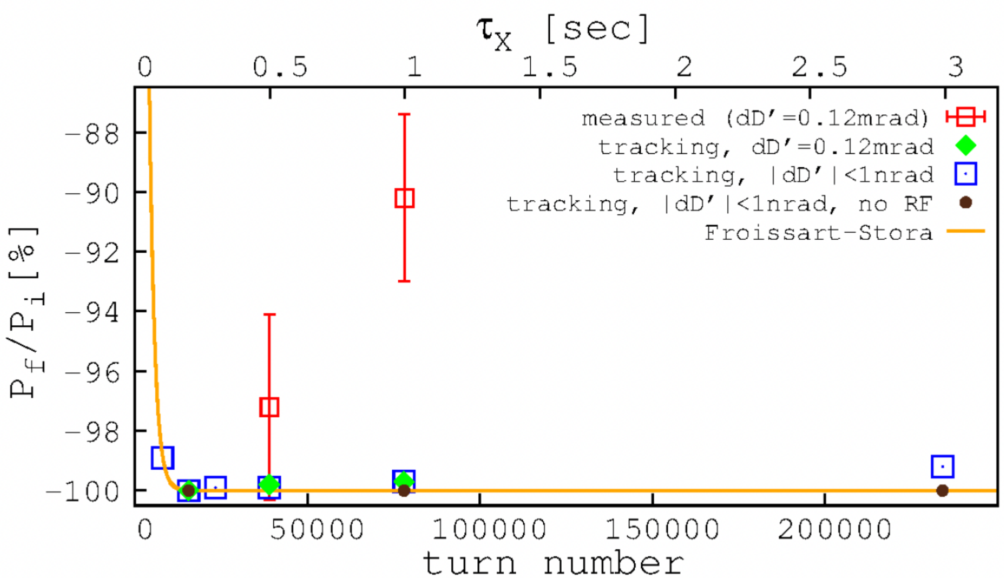
Spin Flip Efficiency vs. Sweep Time (Turns)

At longer sweep time, the multiple crossing is the main reason for less spin flip efficiency.



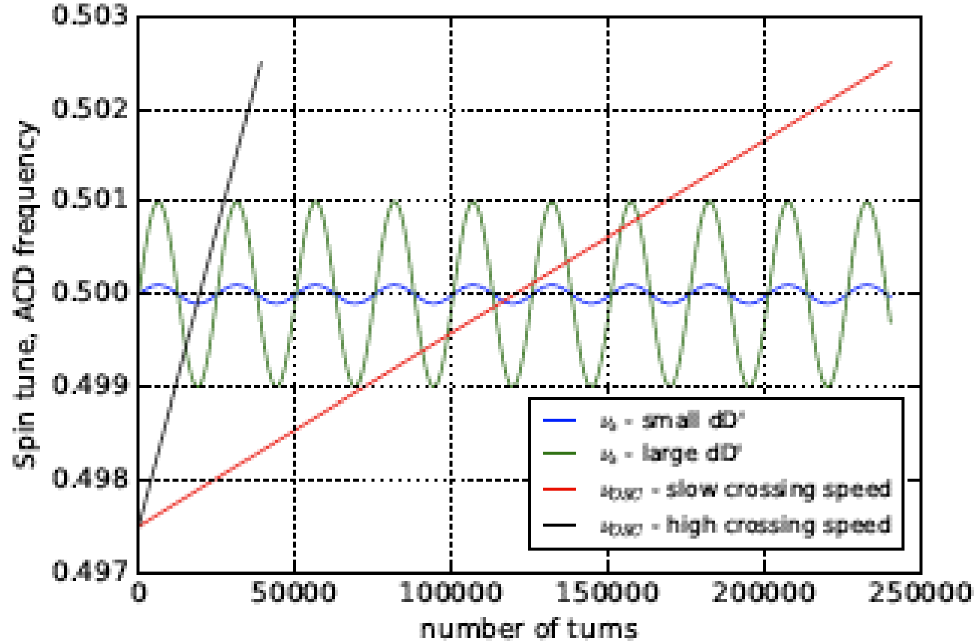


F. Meot , P. Adams, H. Huang, J. Kewisch, P. Oddo, and T. Roser, Phys. Rev. Accel. & Beams, 27, 071002 (2024)

Spin Flipper for EIC

For EIC, the main RF cavity will be 28MHz. The synchrotron frequency is increased from 6Hz to 60Hz. To avoid multiple crossing, the number of turns for the spin flipper operation must be reduced even further. To get $\frac{|\epsilon|^2}{\alpha} \gg 1$, $|\epsilon|$ must be increased.

$$\frac{P_f}{P_i} = 2\exp^{-\frac{\pi}{2}\frac{|\epsilon|^2}{\alpha}} - 1, \qquad \alpha = \frac{\Delta\nu_{osc}}{2\pi N}$$



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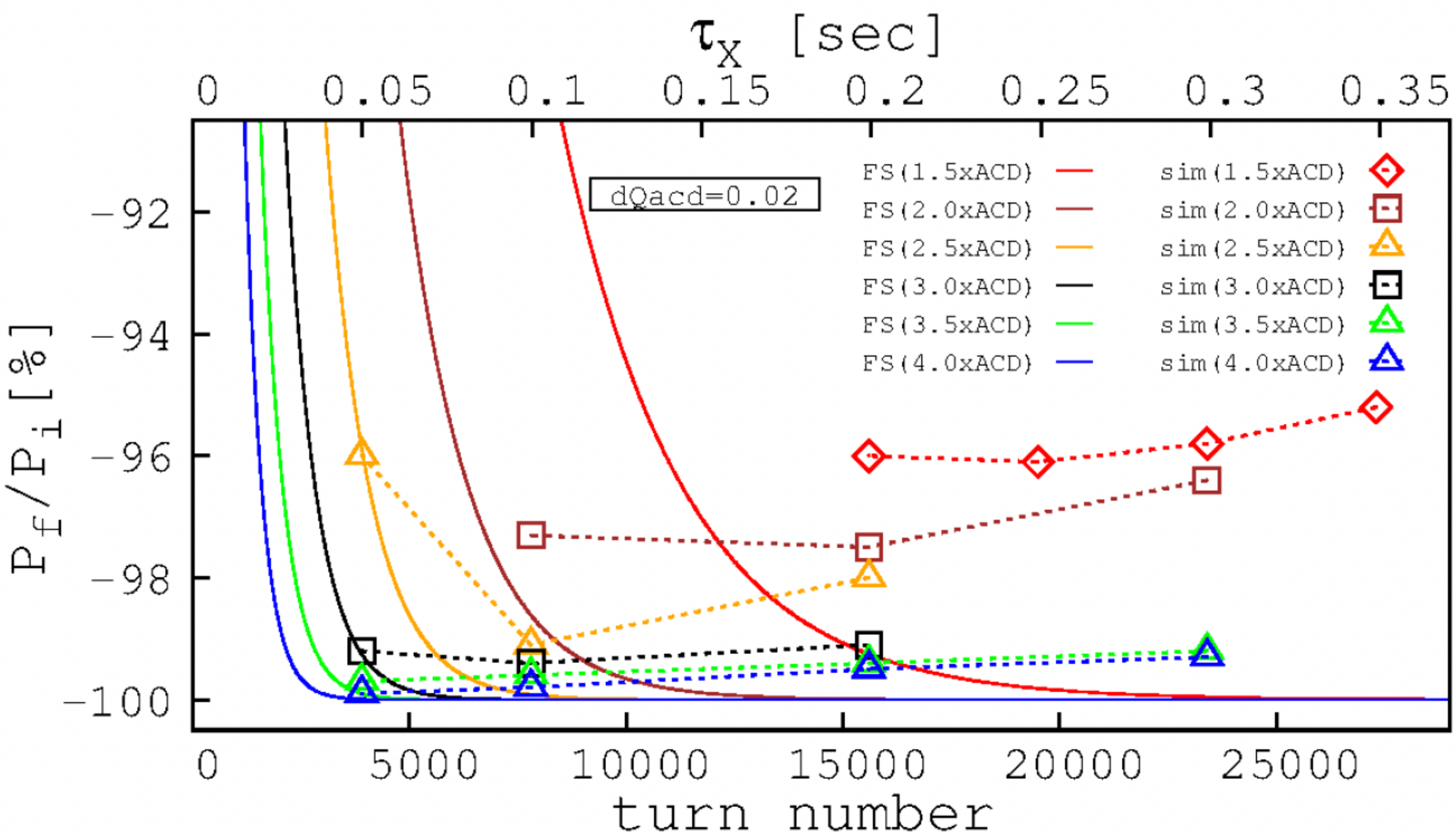
Simulations for Spin Flipper for EIC

- Spin Flip efficiency for different ACD strengths. Simulations are done with 28MHz at 255GeV with ν_{osc} = 0.02 (namely ν_{osc} = [0.48, 0.50] with ν_s = 0.4962). Froissart-Stora formula is plotted as well.
- To reach 99% spin flip efficiency, AC dipoles need to be ~4 times stronger.



Driven Spin Coherent Motion

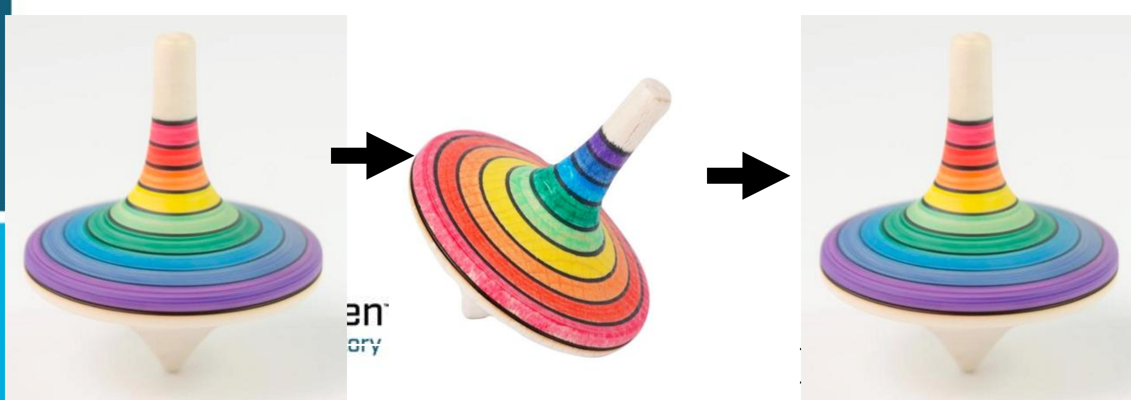
Nearby an isolated spin resonance, the stable spin direction is given by

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

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

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

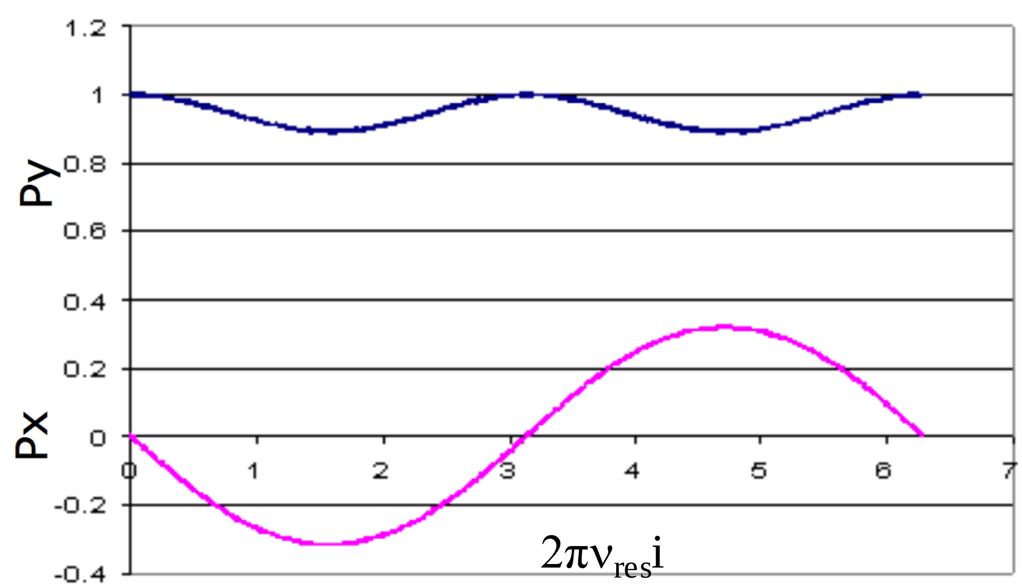
The advantage of this method is that it is nondestructive. When the driving force is adiabatically removed, the spin will return to vertical.



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.



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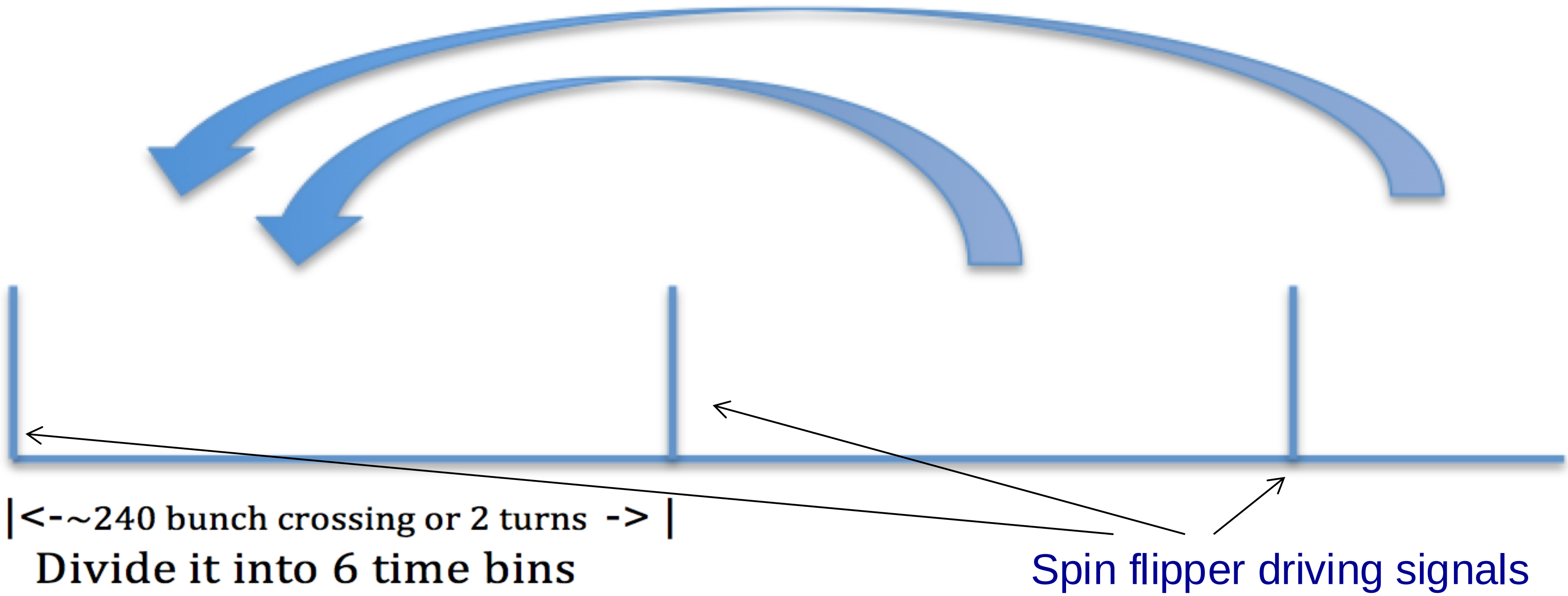
Spin Tune Measurement Data Flow



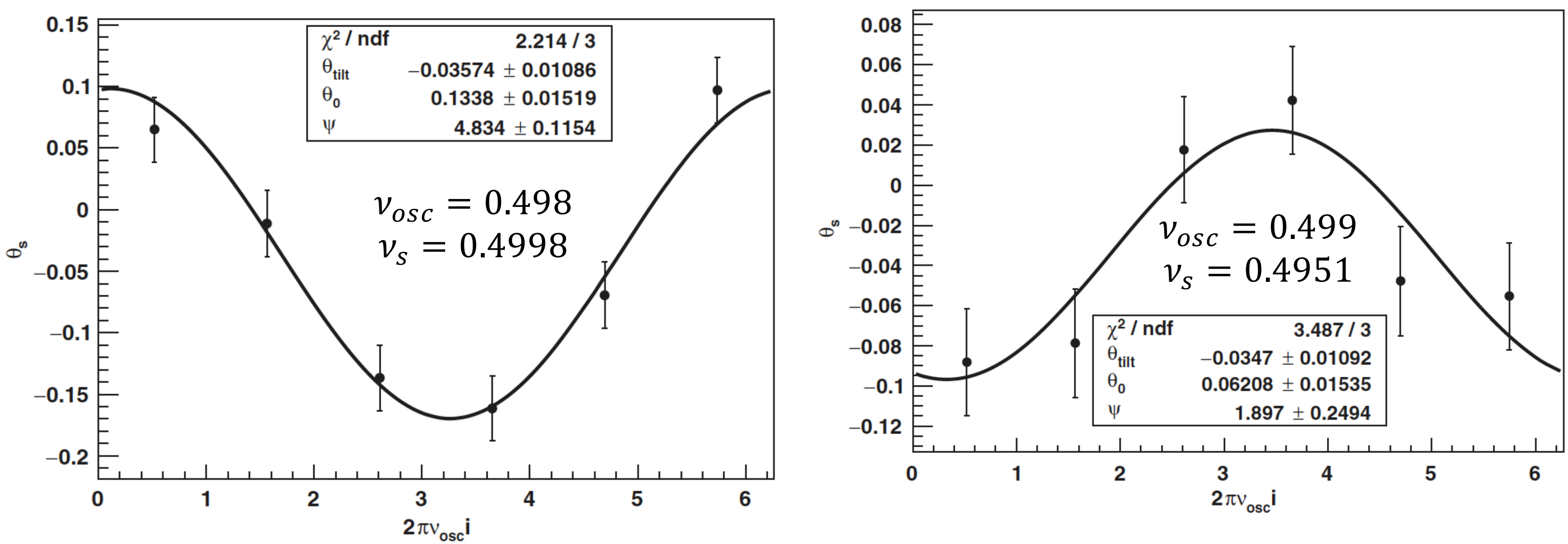
- We binned the carbon events in bins of bunches crossings since the most recent spin flipper signal, ~39kHz. We then grouped these bins into 6 big bins, 1-40, 41-80, 81-120, etc.
- The data in each of bin is then analyzed normally, to get the polarization and the tilt angle.

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.

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



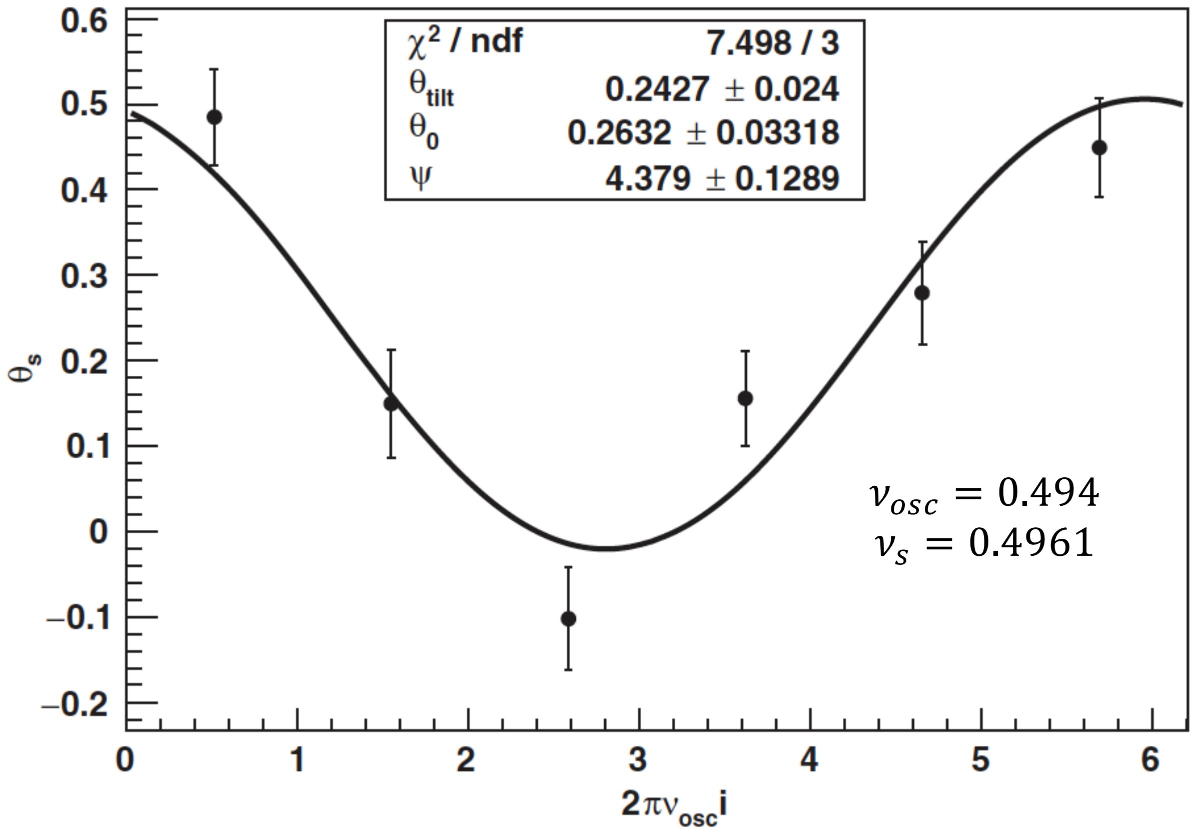
The curve can tell if the driving tune is higher or lower than the spin tune. The left is with driving tune below spin tune. The right one is the opposite.

Driving Coherent Spin Precession at 255GeV

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

i is the No. of bins.

$$\theta_s(i) = \theta_{\text{tilt}} + \tan^{-1}\left[\tan\theta_0 \cos(2\pi\nu_{\text{osc}} i - \Psi)\right]$$



The driving tune is below spin tune.

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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 0.004. All of these measurements were done with small ΔD’ lattice.

H. Huang J. Kewisch, C. Liu, A. Marusic, W. Meng, F. Méot, P. Oddo, V. Ptitsyn, V. Ranjbar, T. Roser, and W. B. Schmidke, PRL 122, 204803(2019).

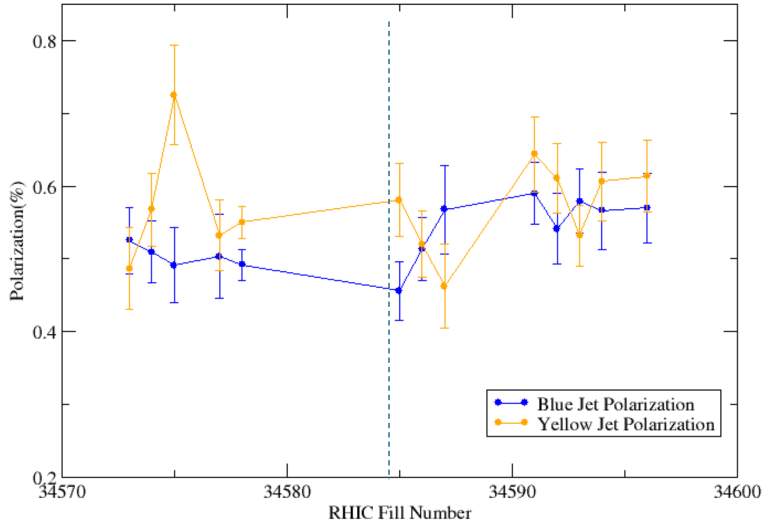
Spin Tune Measurement with AC Dipole

- Without mirror resonance compensation, The driving tune range is limited to above or below 0.5. In our case, it is limited to 0.5-0.51.
- There was a concern in run24 if the spin tune is indeed near 0.5.
- DC dipoles require water cooling, and we could not turn them on. Instead, we use AC dipole to generate resonance, and the lattice was not $\Delta D'$ suppressed lattice.
- The idea is as following: first, we need to search for spin flip or depolarization (due to the lattice choice). Then we narrow down the driving tune range to locate the range of spin tune.

Spin Tune Measurement with AC dipole in Run24

Sweep range	Pol. dip?	Snake current	
0.50-0.51	No	95A	start setting
0.50-0.51	No	90A	
0.50-0.51	Yes	100A	
0.505-0.51	Yes	100A	
0.505-0.5075	Yes	105A	
0.505-0.5075	No	110A	
0.5025-0.505	No	110A	
0.5-0.5025	Yes	110A	end setting

- Outer magnet current was increased 15 A to move ν_s from: $\nu_s > 0.51 \Rightarrow 0.5025 > \nu_s > 0.5$
- The blue snake setting was adjusted in fill 34584 (in 2024 100GeV pp operation). The relative polarization gain is about 10% after the change.



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Summary

- Polarization can be flipped by sweeping rf device frequency cross the spin precession frequency. At high energies, full spin flip has more constraints. The RHIC 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 tune, 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 can be introduced during the measurement and removed afterward. The key is to get driving tune close to the spin tune without destabilization.
- Both techniques could also be used at EIC, but stronger magnets are needed.
- Without stronger magnets, AC dipole can still be used to check spin tunes, but in a destructive way.

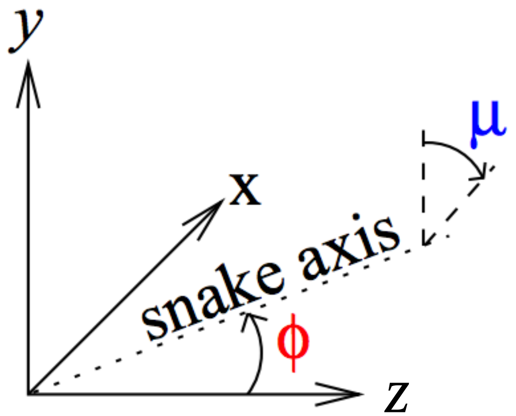
Backup Slides

RHIC Snake Configuration

It is optimal to adjust the snake axes to 0°

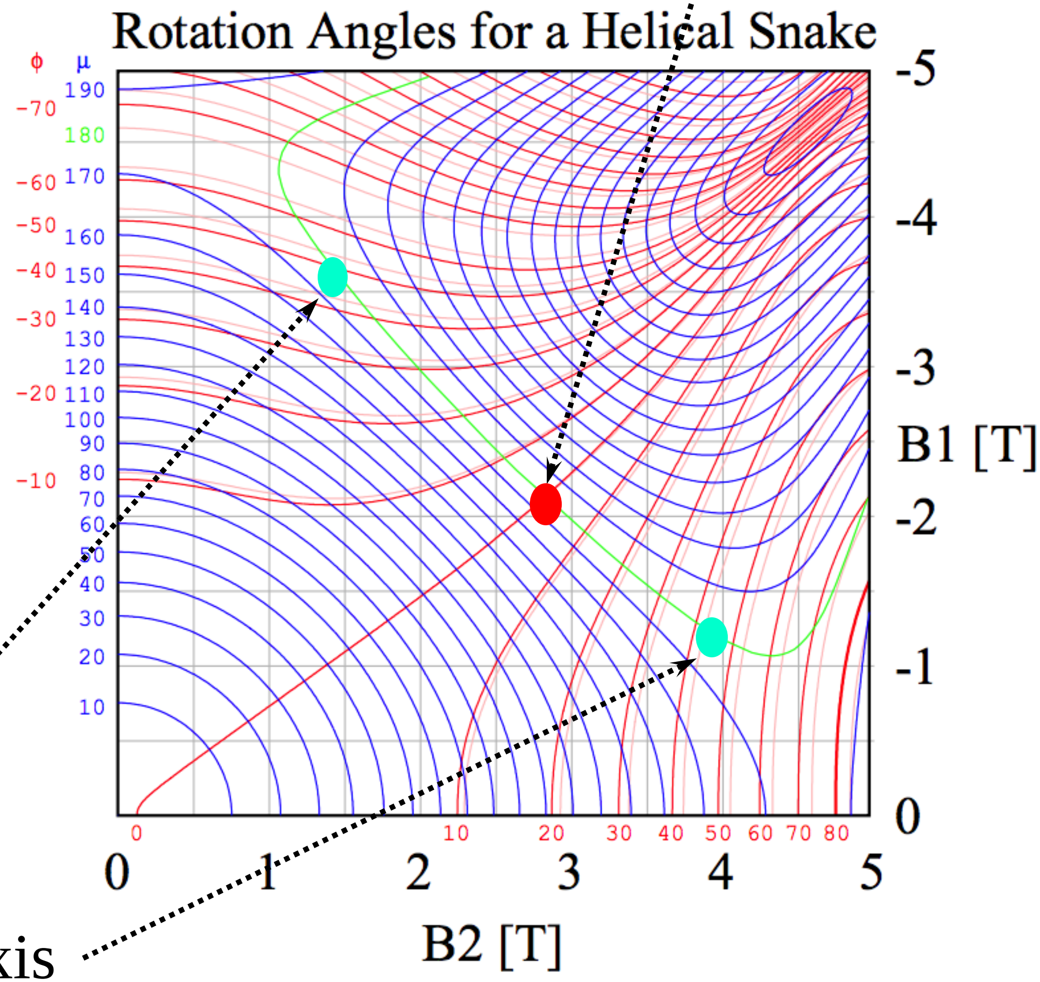
- Minimum field integral
- Minimum orbit excursion

No change in field and power supply polarities



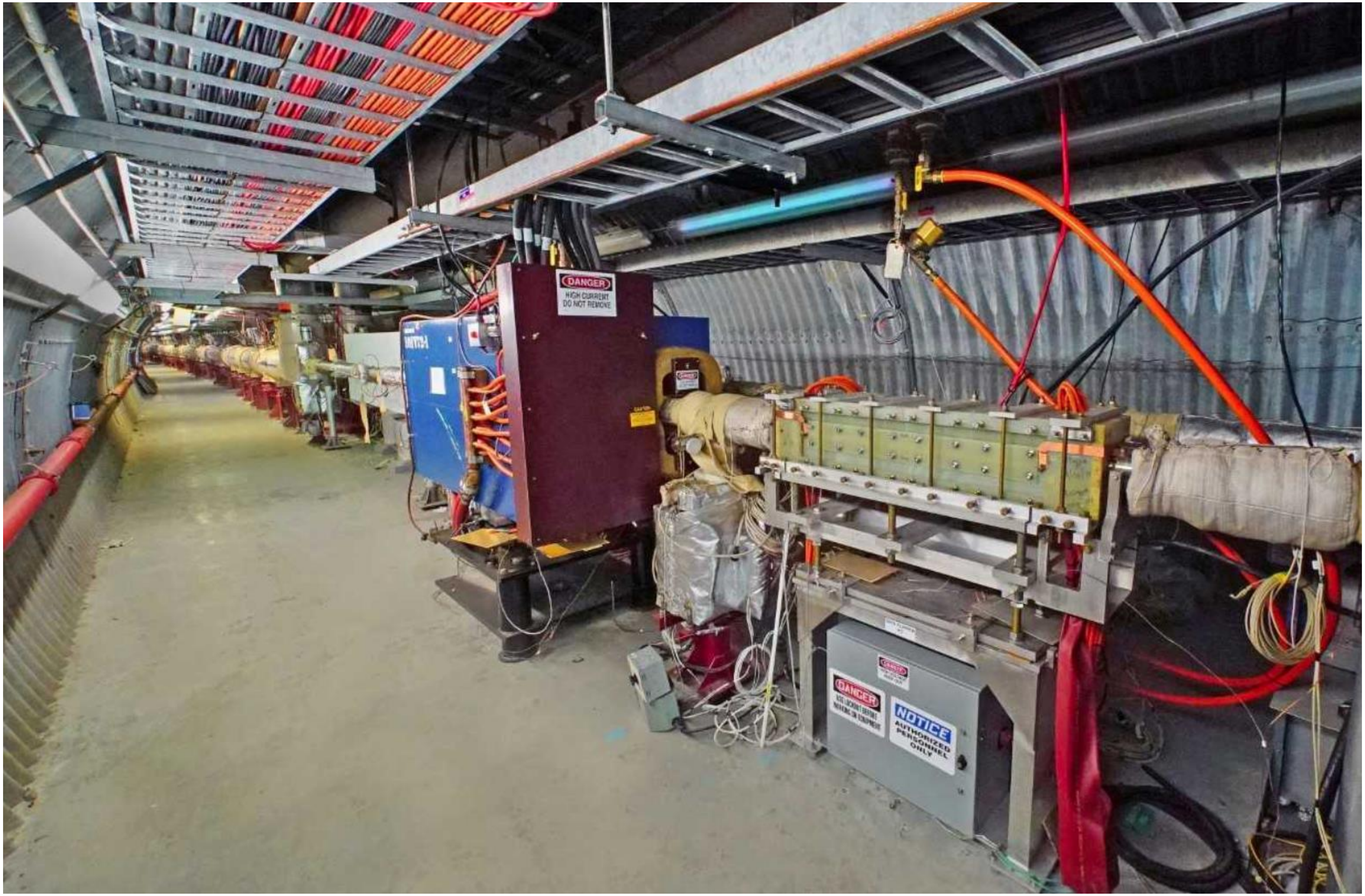
$\nu_s = (\varphi_1 - \varphi_2)/\pi = ½$

Full snake with 0° axis



Full snake with ±45° axis

A Pair of AC and DC Dipoles in the RHIC Tunnel



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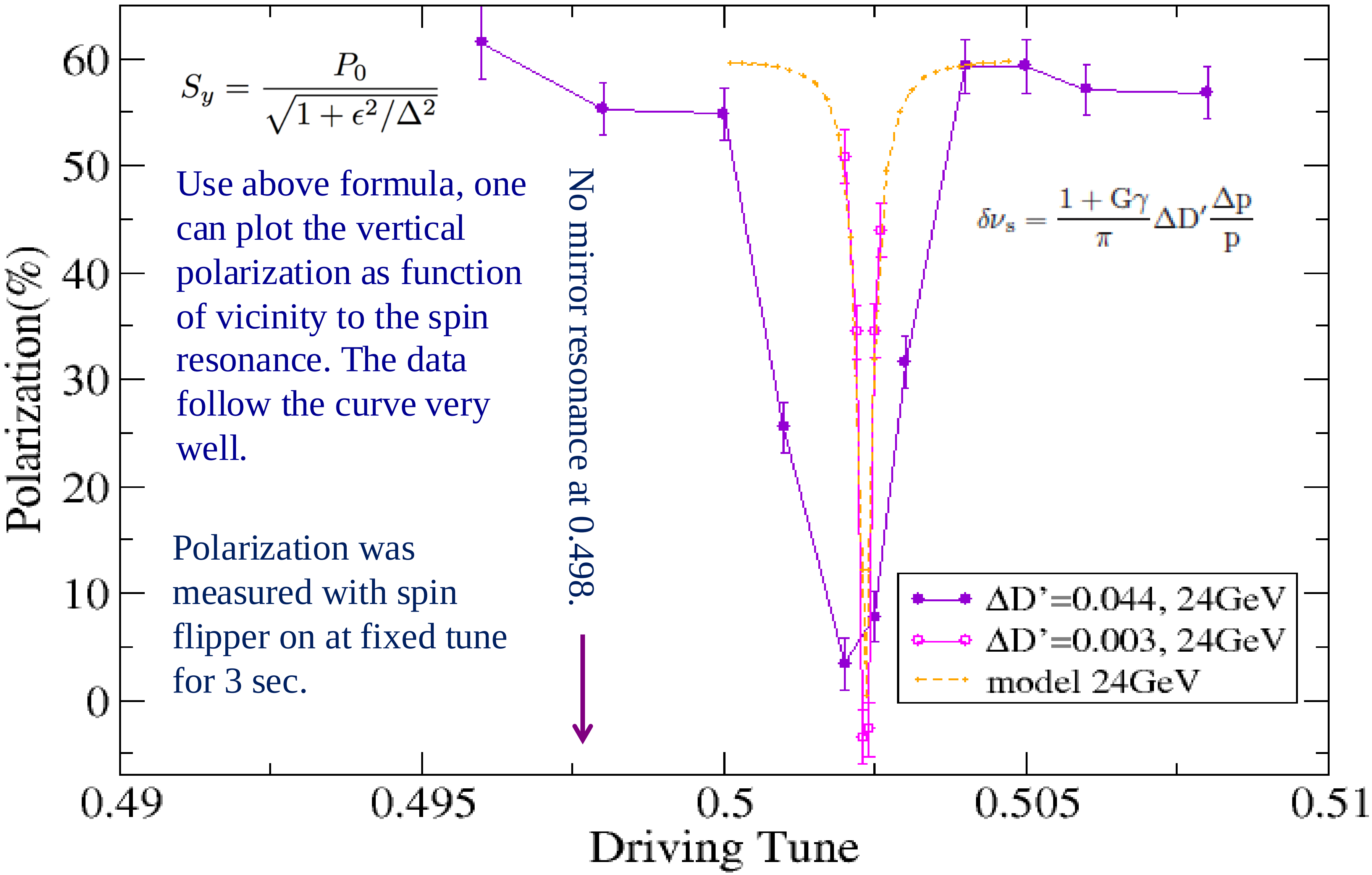
Spin Tune from Driving Tune Scan @ Injection



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

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

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

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

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