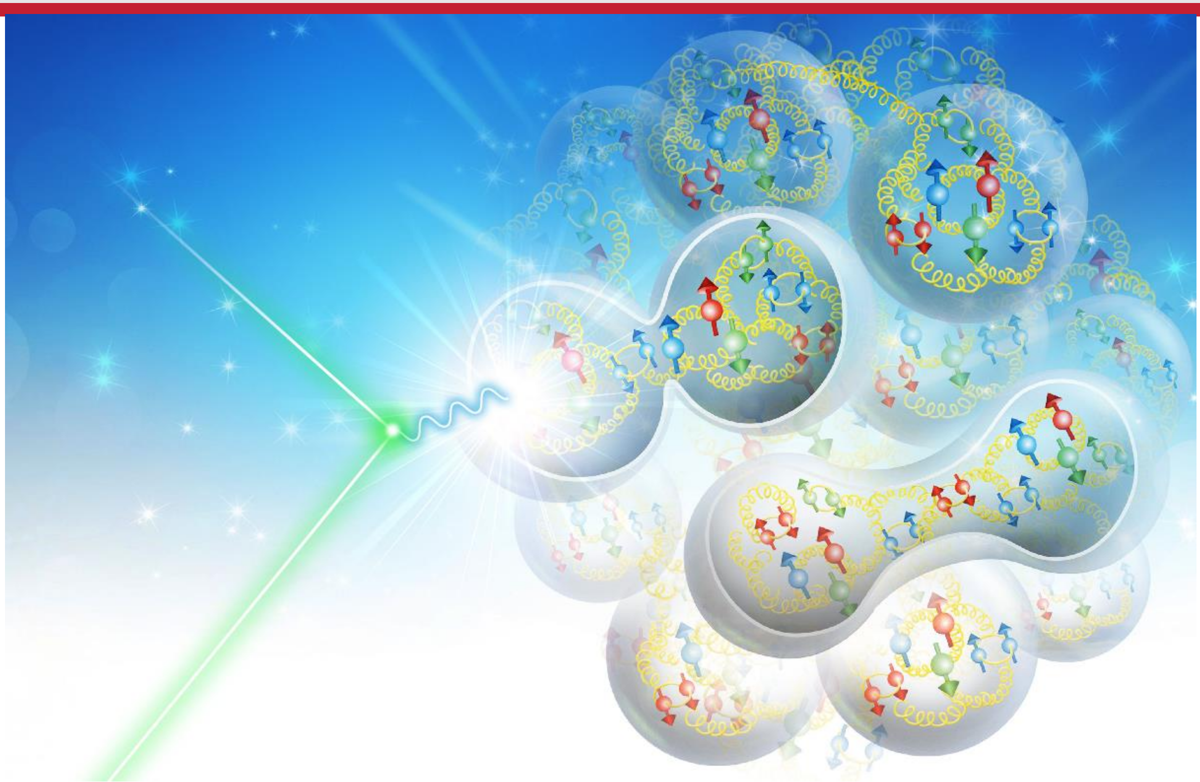
Theoretical and Experimental Study of Spin Transparency Mode in EIC



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U.S. DEPARTMENT OF ENERGY | Office of Science

Theoretical and Experimental Study of Spin Transparency Mode in an EIC

- Project description
  - This project develops a novel technique for preservation and control of electron and ion spin polarizations in a collider or storage ring called a spin transparency mode. The spin transparency is achieved by designing such a synchrotron structure that the net spin rotation angle in one particle turn is zero. It allows for efficient control of polarization by small magnetic fields and offers unique opportunities for design of electron and ion polarization dynamics in ~~JLEIC and electron polarization dynamics in eRHIC~~ the EIC. The spin dynamics theory is being further developed and an experimental test of the spin transparency mode in RHIC is being prepared and is planned to be completed as a part of the project.
- Project status
  - Completed, ready to do the experiment when RHIC's schedule allows
- Main goal
  - Experimental verification of the spin transparency mode for application in an EIC
- Supported by FY 2018-19 DoE NP FOA JLab and BNL Base R&D Funding

Budget

- JLab

	FY'18-FY'19	Totals
a) Funds allocated	$410,000	$410,000
b) Actual costs to date	$267,550	$267,550

- BNL

	FY'18-FY'19	Totals
a) Funds allocated	$552,000	$552,000
b) Actual costs to date	$407,716	$407,716

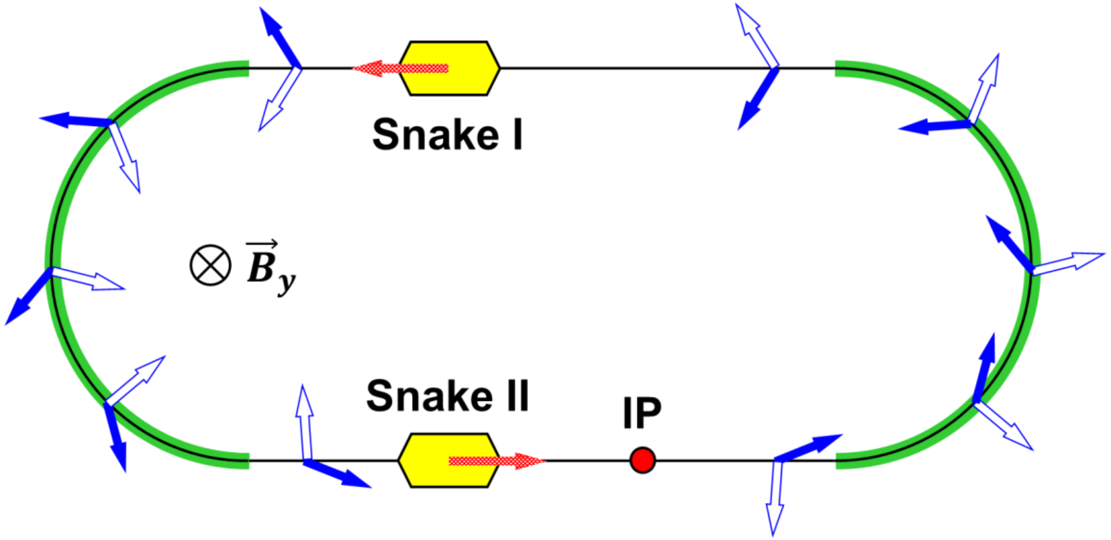
Deliverables and Schedule

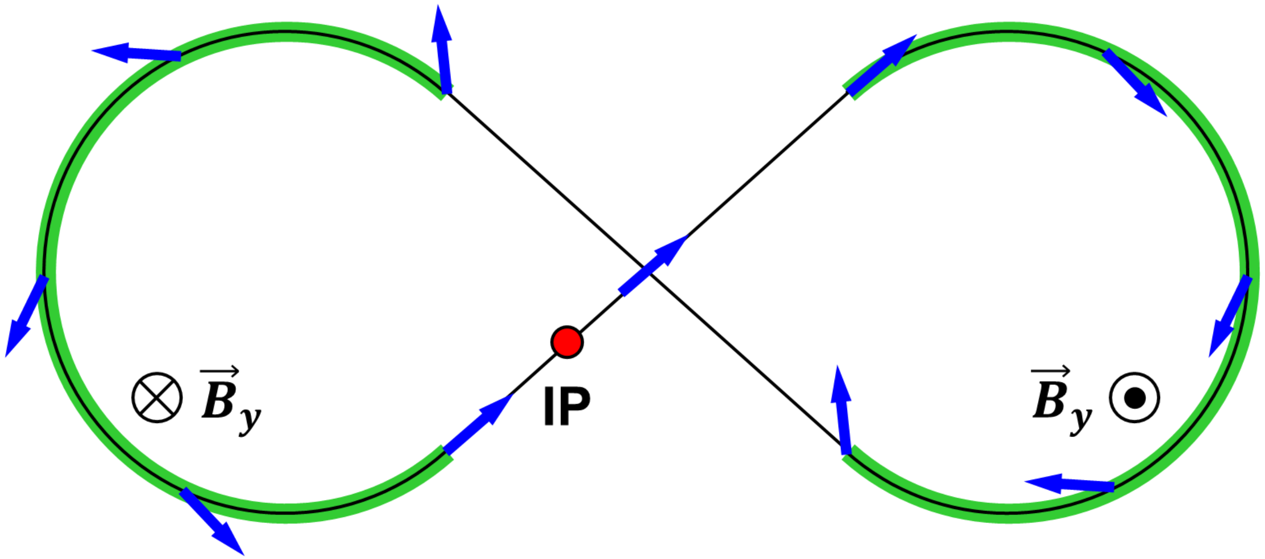
- The project corresponds to Row 4, “Benchmarking of realistic EIC simulation tools against available data”, Priority High-A of the Jones’ Panel report
- Experimental deliverables have to be postponed until polarized protons are available in RHIC.
- We were not able to sign a contract with A.M. Kondratenko.
- Deuteron work was cancelled due to re-prioritization of tasks at JLab after the EIC down-selection.

Task	FY’18				FY’19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Analysis and simulation of spin transparency mode in RHIC	✓	✓	✓	✓	✓	✓	✓	
Evaluation of the technical capabilities of RHIC	✓	✓	✓					
Development of an experimental program		✓	✓	✓	✓	✓		
Preparation and submission of an experimental proposal		✓	✓	✓	✓	✓	✓	→
Completion of an experimental test								→
Analysis and publication of experimental data								→
~~Analysis and simulation of tensor polarization dynamics~~								
~~Verification of tensor polarization results using existing data~~								

Spin Transparency Concept

- No net spin effect in one turn along the design orbit, $\nu_{sp} = 0$
- Racetrack with two identical Siberian snakes separated by 180° bends
- Figure-8 ring
- One arc cancels the spin rotation of the other





PHYSICAL REVIEW LETTERS **124,** 194801 (2020)

Transparent Spin Method for Spin Control of Hadron Beams in Colliders

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We present a concept for control of the ion polarization, called a transparent spin method. The spin transparency is achieved by designing such a synchrotron structure that the net spin rotation angle in one particle turn is zero. The polarization direction of any ions including deuterons can be efficiently controlled using weak quasistatic fields. These fields allow for dynamic adjustment of the polarization direction during an experiment. The main features of the transparent spin method are illustrated in a figure-eight collider. The results are relevant to the electron-ion collider considered in the U.S., the nuclotron-based ion collider facility constructed in Russia, and a polarized electron-ion collider planned in China.

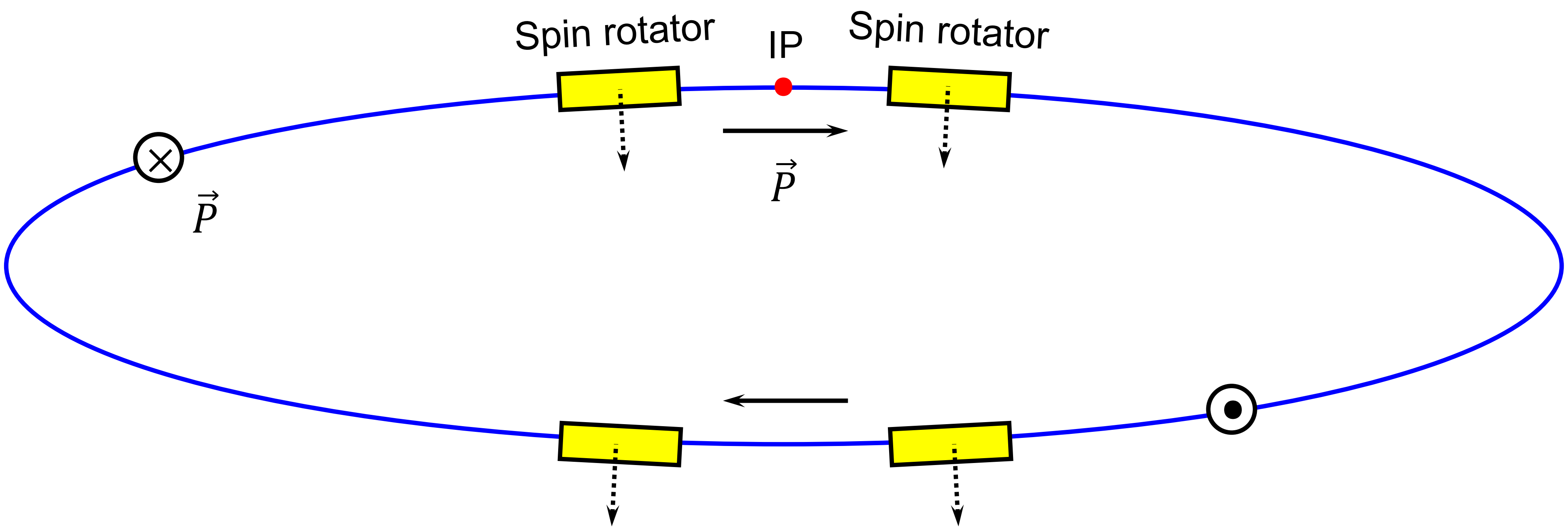
DOI: 10.1103/PhysRevLett.124.194801

Features of Spin Transparency Mode

- Polarization stability due to energy-independent spin tune
- Without additional fields, spin rotation is a priori unknown but occurs only due to closed orbit excursion and beam emittances and therefore is generally small at low to medium energies
- Spin stabilization by small fields: ~3 Tm vs. ~1200 Tm for deuterons at 100 GeV
  - Criterion: induced spin rotation >> spin rotation due to orbit errors
- No effect on the orbit
- Polarized deuterons
- Frequent adiabatic spin flips with no polarization loss

Potential Benefits of Spin Transparency Mode to EIC

- Hadron collider ring configured in the spin transparency mode using two identical Siberian snakes
  - Eliminate the need for spin rotators at certain energies
  - Longitudinally polarized deuterons at certain energies
- Electron collider ring configure in the spin transparency mode using electron spin rotators and additional snake
  - Same lifetimes of the two spin states
  - Simplified spin matching

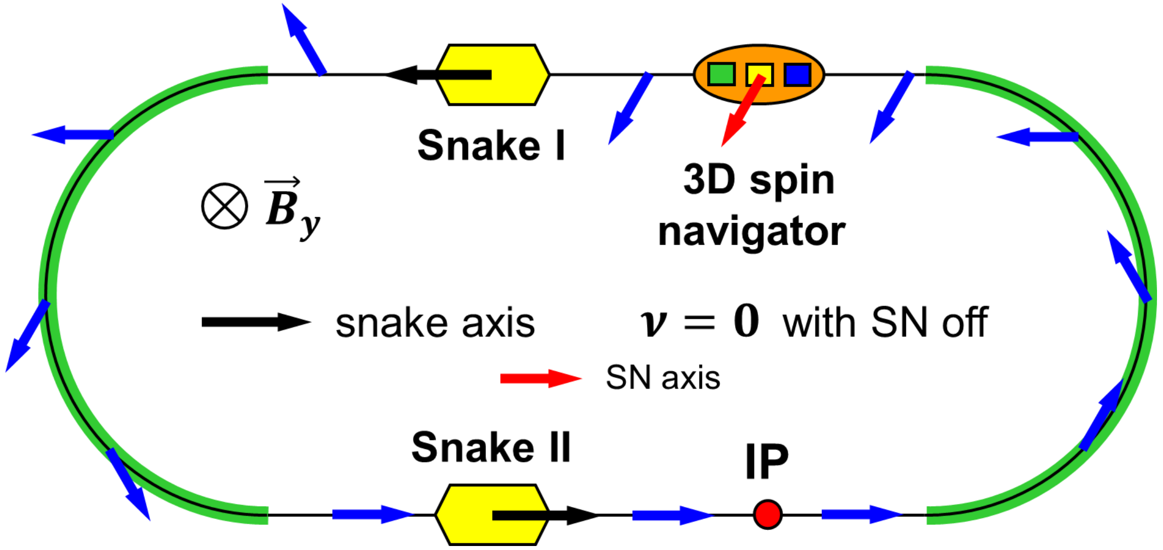


Polarization Stability Criterion

- In the spin transparency mode, the spin is highly sensitive to small perturbing fields
- On the other hand, this sensitivity makes it easy to control the spin by low magnetic field integrals
- A device called a spin navigator (SN) is introduced to rotate the spin by a small angle $2\pi\nu_N$ per turn
- Stable polarization direction is along the SN rotation axis at the SN location
- Polarization is under control if this induced spin rotation dominates over the spin rotation $2\pi w$ due to imperfections and beam emittances

$$\nu_N \gg w$$

where w is the spin transparency resonance strength



Extension of Response Function Formalism to Spin Transparent Rings

- Periodic perturbing magnetic fields $\Delta\vec{B}(z)$ violate spin transparency creating a TS resonance

$$\vec{w} = \frac{1}{2\pi}\int_0^L \left[\frac{\Delta B_x}{B\rho}\vec{F}_x + \frac{\Delta B_y}{B\rho}\vec{F}_y + \frac{\Delta B_z}{B\rho}\vec{F}_z\right] dz$$

where $\vec{F}_i$ is the spin response function determined by the linear lattice.

- At high energy, without coupling, the TS resonance is dominated by

$$F = F_{x1} + iF_{x3} = \frac{\gamma G}{2i}\left[f_y^* \int_{-\infty}^{z} f_y' \left(e^{i\alpha(1-\zeta)}\frac{d}{dz}e^{i\Psi}\right) dz - f_y \int_{-\infty}^{z} f_y^{*\prime}\left(e^{i\alpha(1-\zeta)}\frac{d}{dz}e^{i\Psi}\right) dz\right]$$

where

$$f_y(z) = \sqrt{\beta_y}\exp\left(i\int_0^z \frac{dz}{\beta_y}\right)$$

i.e. by radial perturbing fields

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THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Spin response function technique in spin-transparent synchrotrons

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Statistical Model

- The rms vertical excursion of the closed orbit

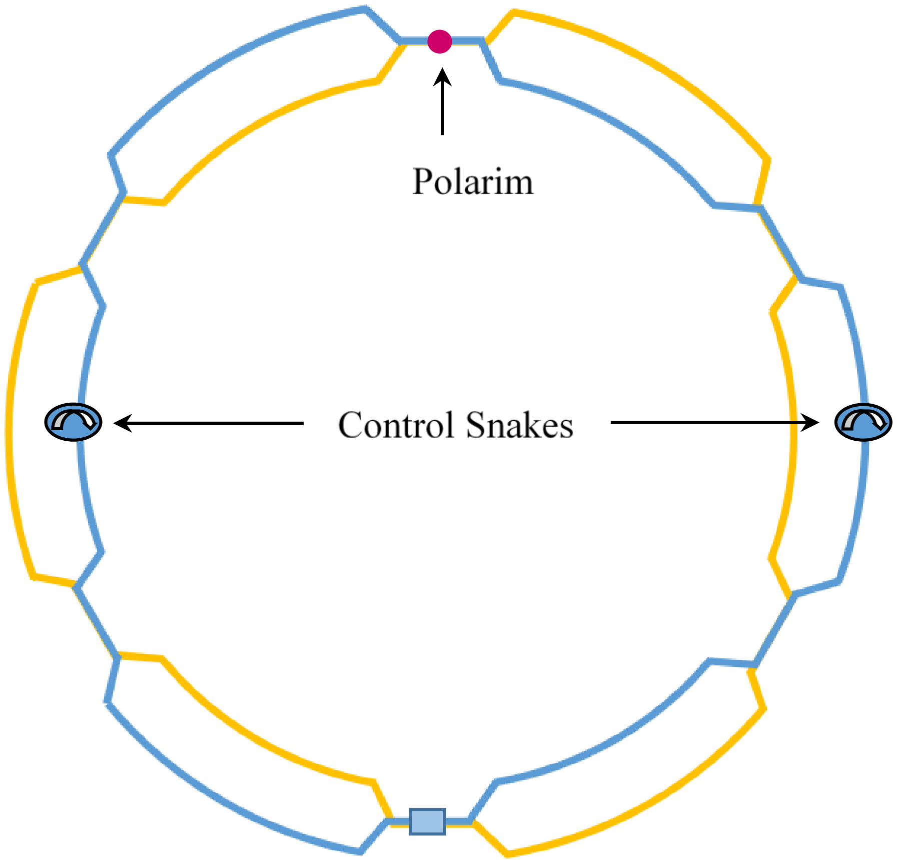
$$\overline{y^2(z)} = \frac{\pi^2 \beta_y(z)}{2\sin^2 \pi\nu_y} \sum_{k=1}^{Q} \left(\frac{l_k}{C}\right)^2 \overline{h_k^2}\, \beta_k$$

- Radial fields h_k of the different elements are evaluated as
  - Rolled dipoles: $\overline{h_k^2} = \theta^2\, \overline{\Delta\varphi^2}$
  - Vertically misaligned quadrupoles: $\overline{h_k^2} = (k_1 L_x)^2 \overline{\Delta y^2}$
- Based on the expected closed orbit excursion, one can find $\overline{\Delta\varphi^2}$ and $\overline{\Delta y^2}$ and then estimate the expected coherent component of the spin transparency resonance strength
- The rms strength of the spin resonance due to Q uncorrelated segments of length l_k with radial fields $h_k \equiv h_x(z_k)$ normalized to $B\rho/R$ where R is the average radius for circumference $C = 2\pi R$

$$\overline{|w_{coherent}|^2} = (\gamma G)^2 \sum_{k=1}^{Q} \left(\frac{l_k}{C}\right)^2 \overline{h_k^2}\, |F_k|^2$$

Experimental Test of Spin Transparency Mode in RHIC

- RHIC already has all of the necessary components
- Make snake axes parallel at $0°$
  to set RHIC in the transparent spin mode
- 3D spin rotator
  - Small angle $\delta\alpha$ between the snake axes
    = rotation about vertical axis
    $\nu_y = \delta\alpha/\pi$
  - Mismatch $\delta\mu_1$ & $\delta\mu_2$ of the snake strengths from π
    = rotation about axis with longitudinal & radial components
    $\nu_x = (\delta\mu_1 - \delta\mu_2)\sin(\gamma G\pi/2)\,/2\pi$
    $\nu_z = -(\delta\mu_1 + \delta\mu_2)\cos(\gamma G\pi/2)\,/2\pi$
- Existing polarimeter with
  fast measurement time
- Can test many of the features of the spin transparency
  mode and 3D spin rotator

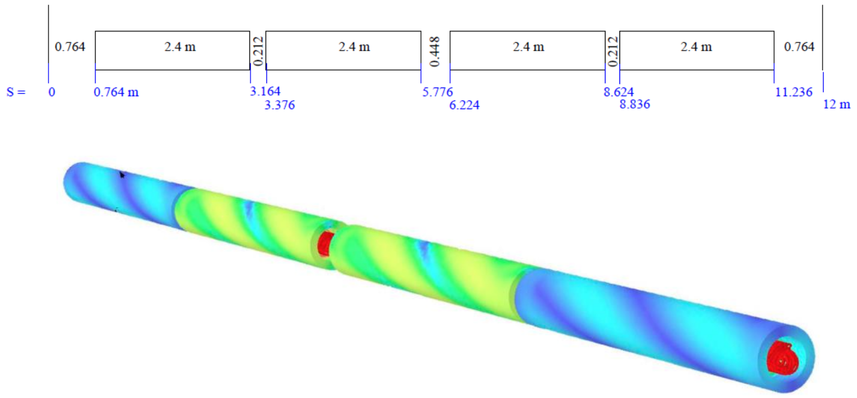


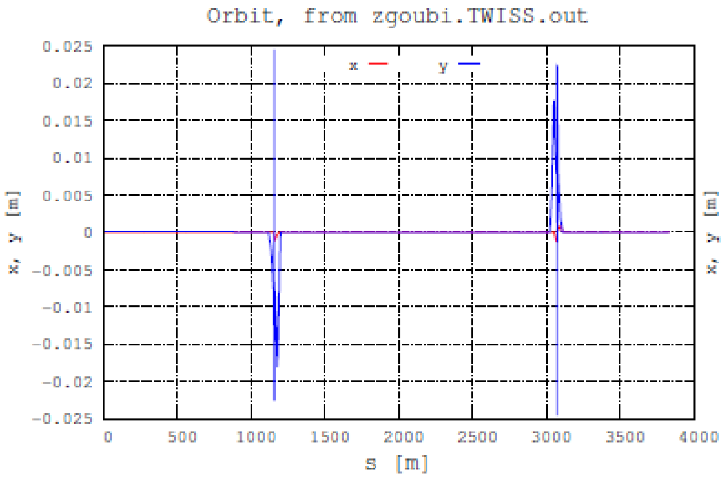
Experimental Equipment

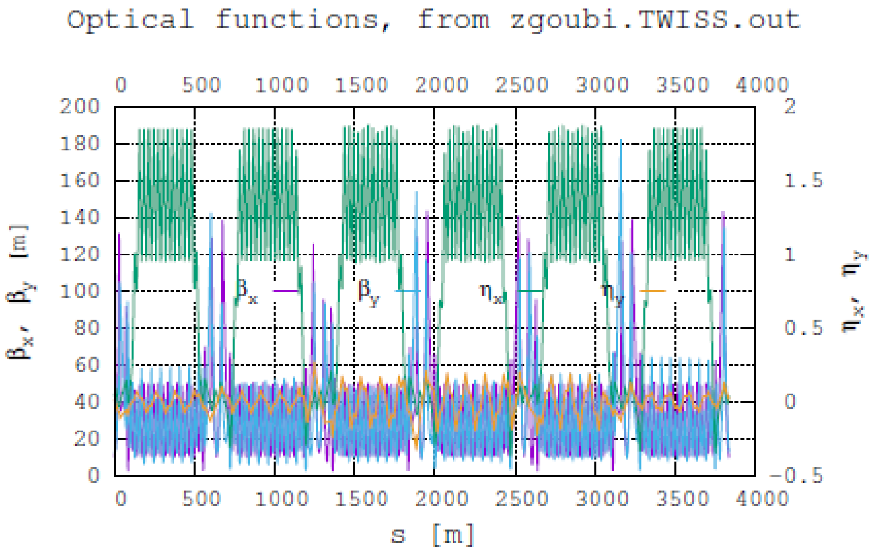
- Two currents of the two helix pairs provide the necessary control of the snake axis and spin rotation angle
- The currents can be adjusted in real time at a rate of 1 A/s
- While the current of one helix pair is reduced, the current of the other helix pair is increased. It was tested that the current of the second helix pair can be increased to the necessary level
- Existing CNI polarimeter can provide relative measurement of both transverse polarization components in a few minutes
- As in any spin dynamics experiment, availability of a spin flipper would be beneficial. Since the spin tune is close to zero rather than the usual 0.5, the existing spin flipper may need minor modifications to operate at the appropriate frequency.

Model of RHIC with Snakes

- Accurate Zgoubi model of RHIC with snakes exists (F. Méot)
- Each snake is represented by four individual field maps for the four helices
- The snake is symmetric with respect to its center
- Can adjust snake strength and axis by adjusting strengths of the outer and inner fields
- Model includes orbit correction

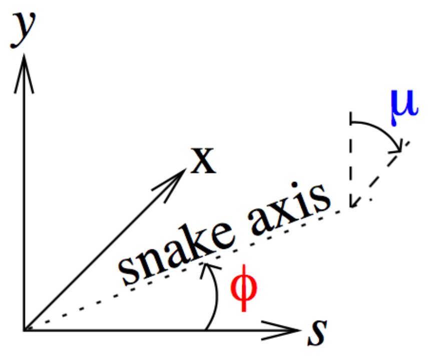


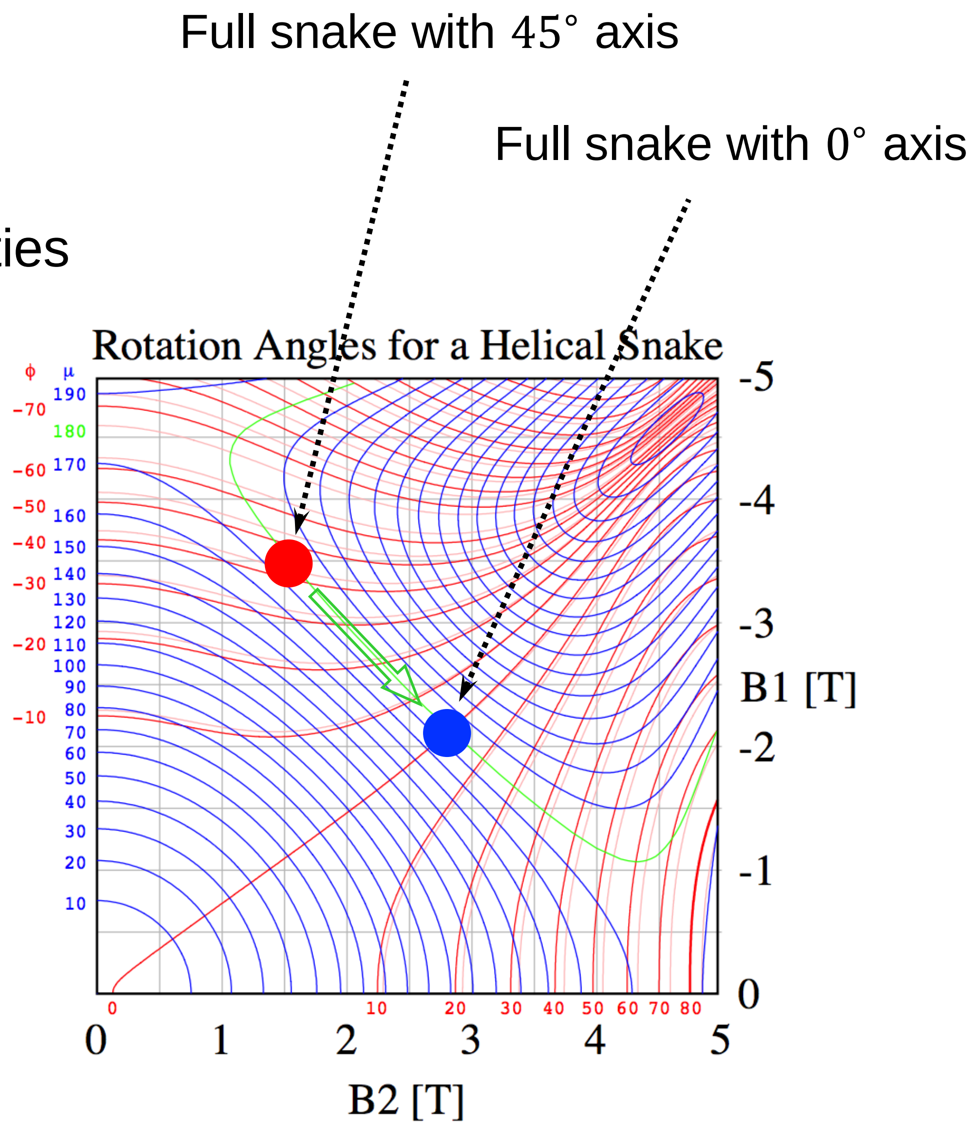




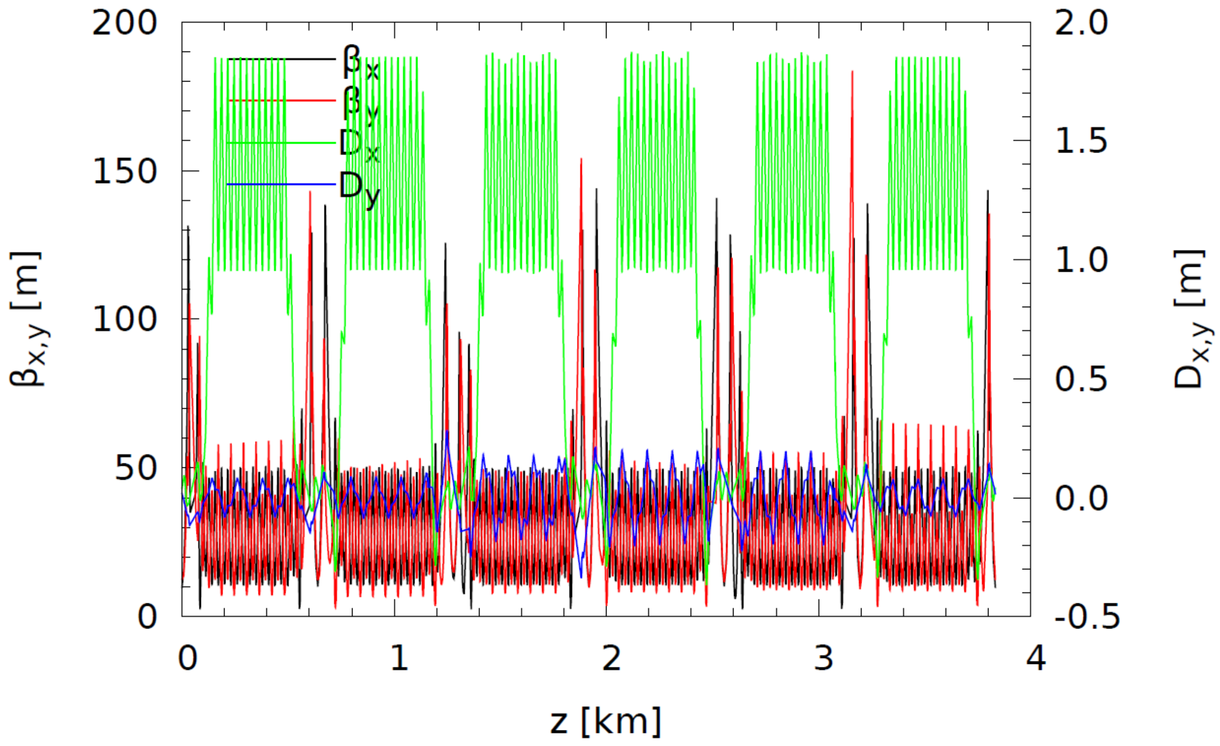
RHIC Snake Adjustment

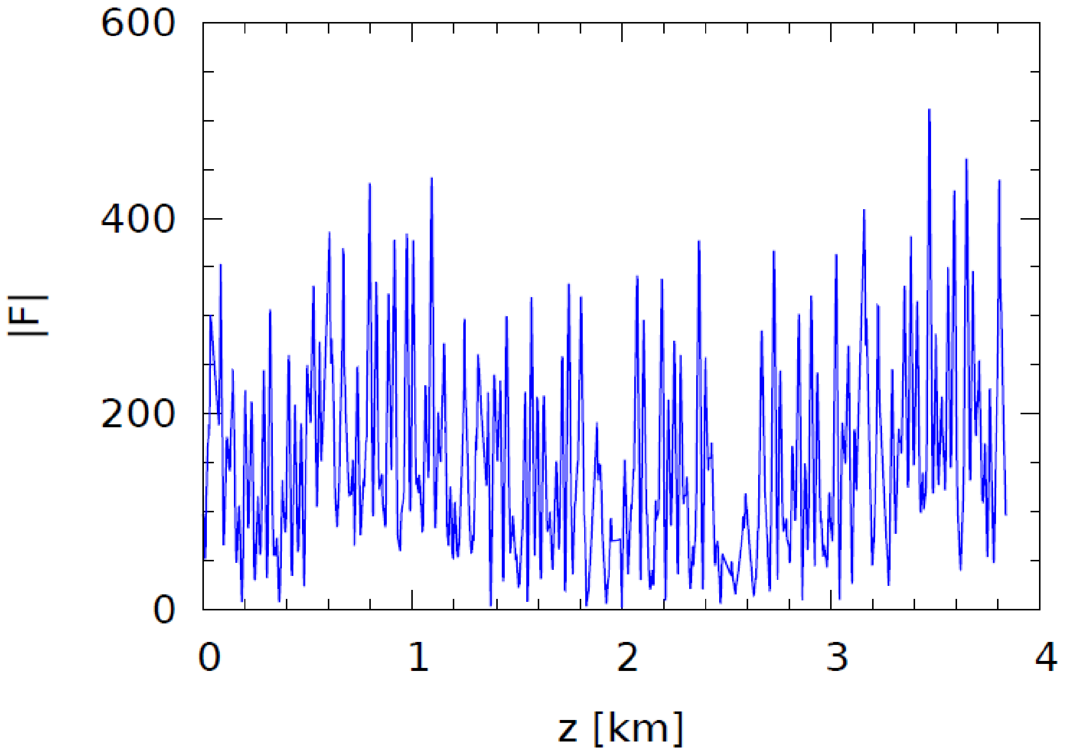
- It is optimal to adjust the snake axes to 0°
  - Minimum field integral
  - Minimum orbit excursion
- No change in field and power supply polarities





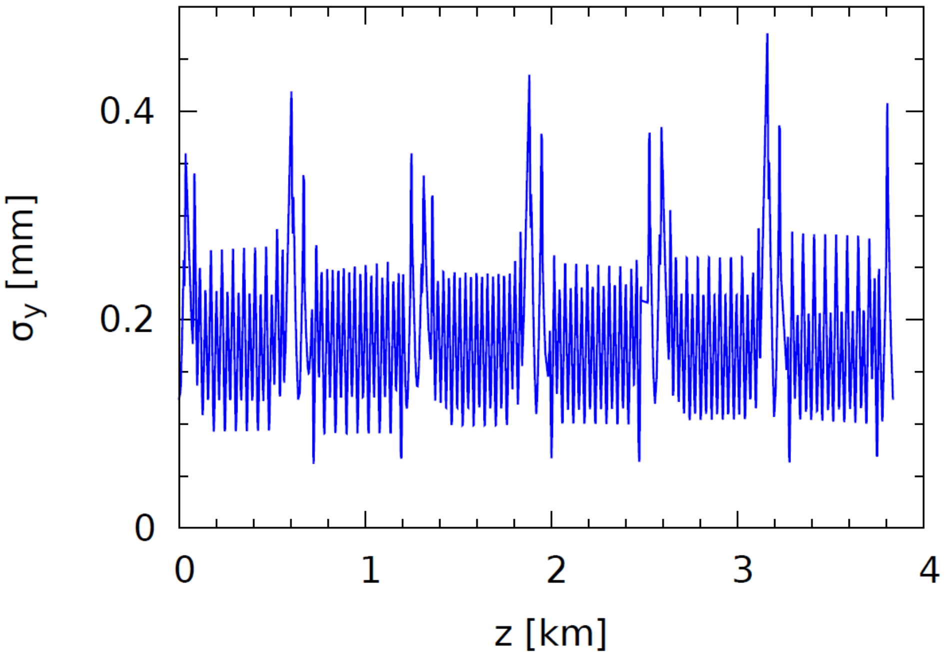
Optics and Spin Response Function of RHIC at Injection Energy

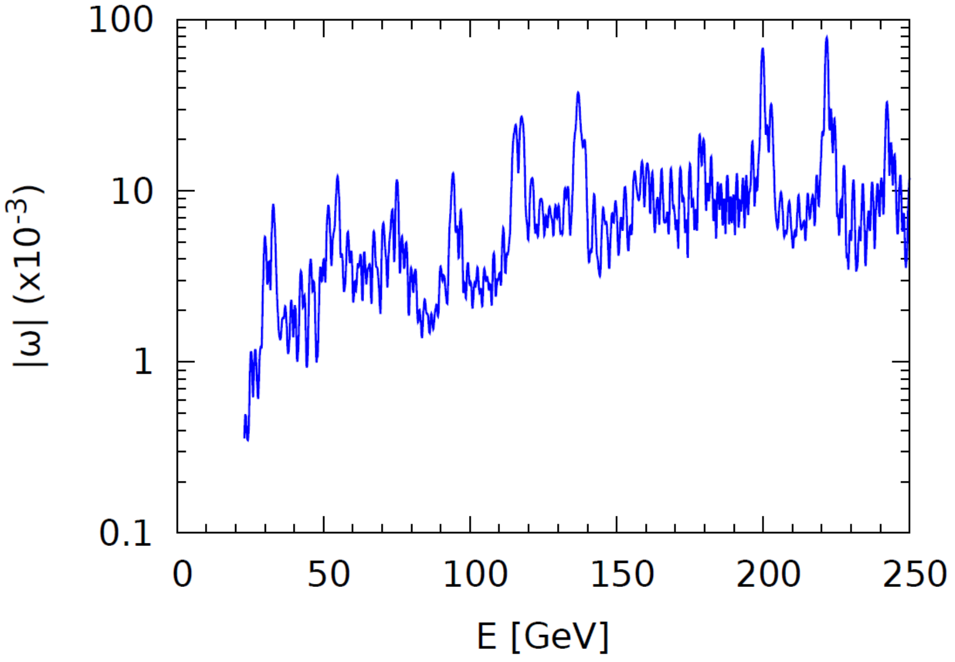




rms Vertical Closed Orbit and Resonance Strength

- Statistically calculated closed orbit around the ring with an rms size of 200 μm
- The resonance strength does not exceed 0.01 at least up to 100 GeV
- Spin tune of 0.05 should be sufficient to control the polarization





Experimental Procedure

- Injection and acceleration
  - Stable vertical polarization with a spin tune of about 0.05 is set by adjusting the angle between the snake axes to about $10°$
  - Beam is injected vertically polarized and accelerated to different energies where polarization is measured
- Polarization control using Siberian snake parameters only
  - Angle between the snake axes $\delta\alpha$ and offsets of the snake spin rotation angles from π denoted $\delta\mu_1$ and $\delta\mu_2$
  - Three orthogonal rotations are given by

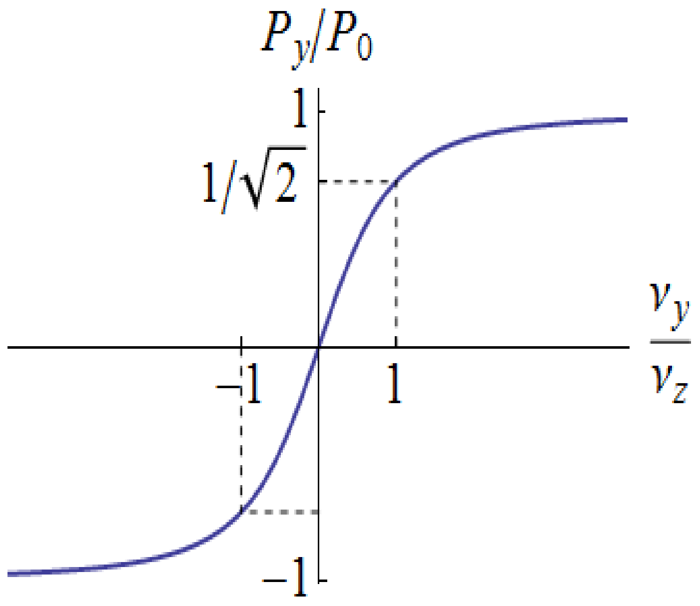
$$\nu_x = \frac{\delta\mu_1 - \delta\mu_2}{2\pi}\sin(\gamma G\pi/2)\,, \qquad \nu_y = \frac{\delta\alpha}{\pi},$$

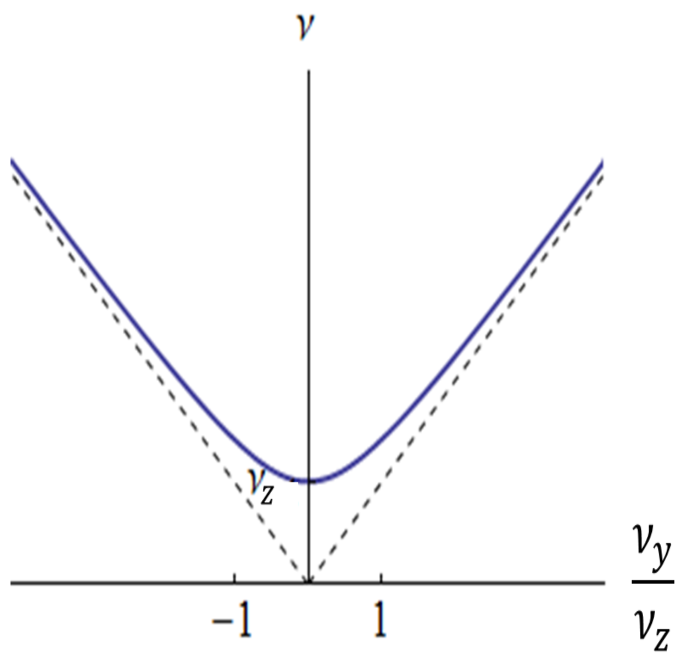
$$\nu_z = -\frac{\delta\mu_1 + \delta\mu_2}{2\pi}\cos(\gamma G\pi/2)$$

  - With $\delta\mu_1 = \delta\mu_2$, vertical polarization component at the polarimeter

$$n_y = \nu_y/\sqrt{\nu_y^2+\nu_z^2}$$

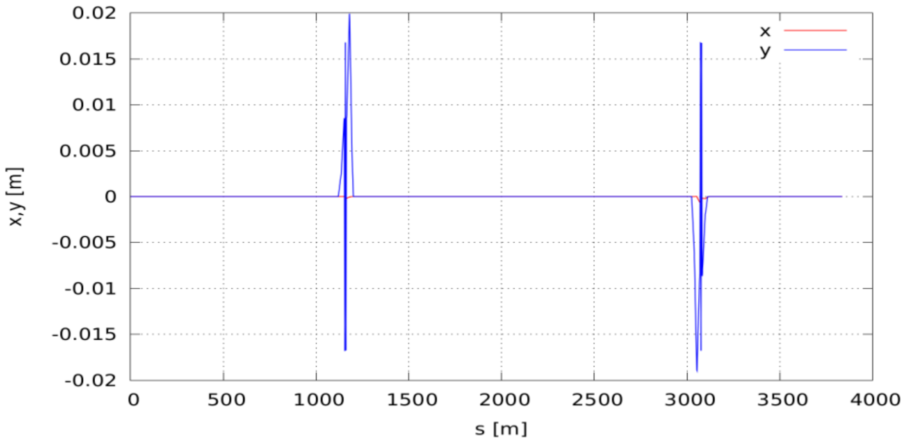
  - At fixed $\delta\mu_1 = \delta\mu_2$, polarization direction controlled by $\delta\alpha$

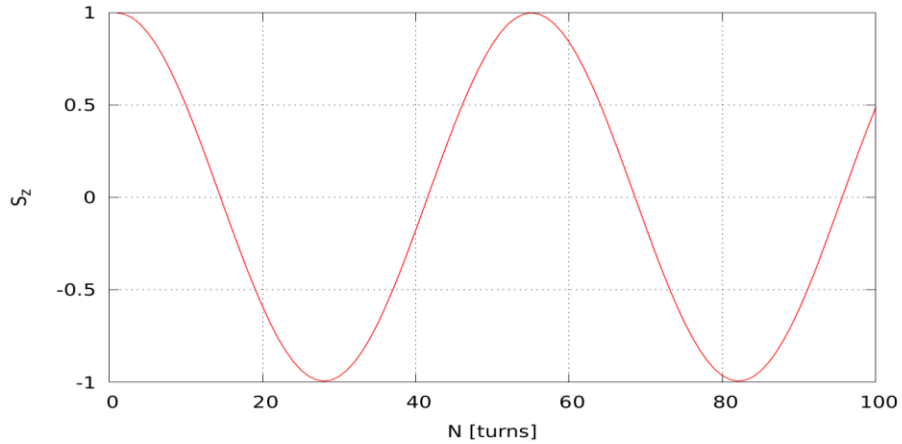




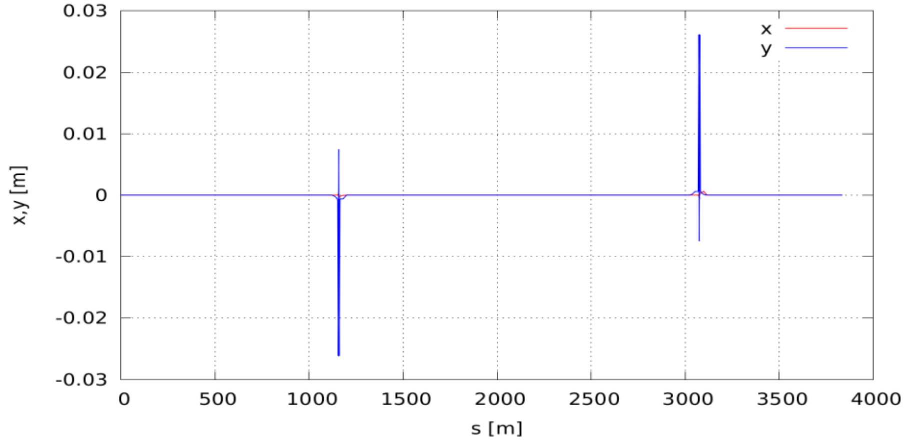
Adjustment of Spin Transparency in RHIC

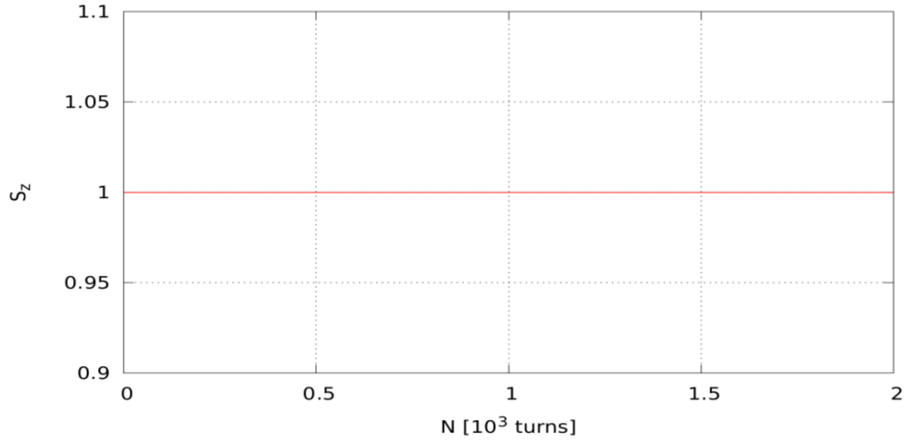
- Snakes modeled using field maps
- Separate optimization of snakes and orbit correction: resulting $\nu_{sp} \approx 1.85 \cdot 10^{-2}$





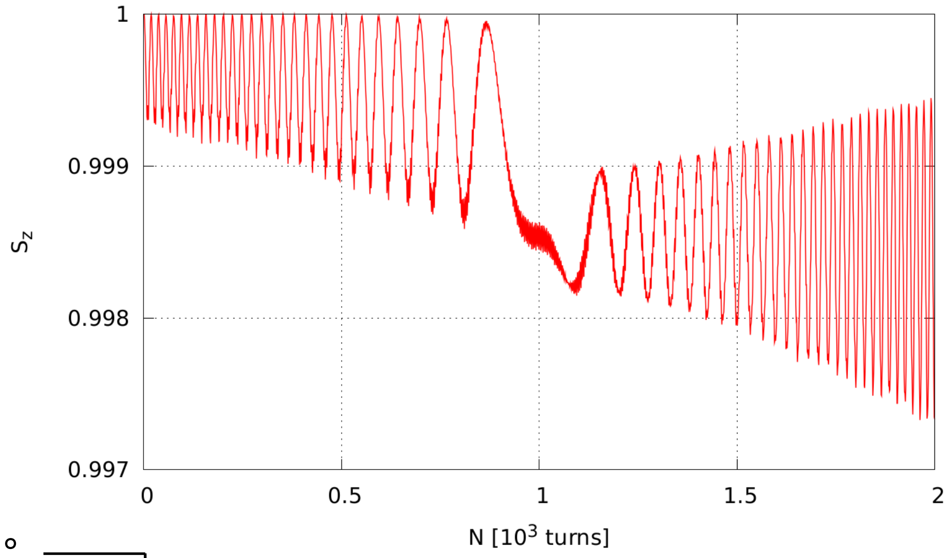
- Simultaneous adjustment of snakes and orbit correctors: $\nu_{sp} \sim 6 \cdot 10^{-7}$



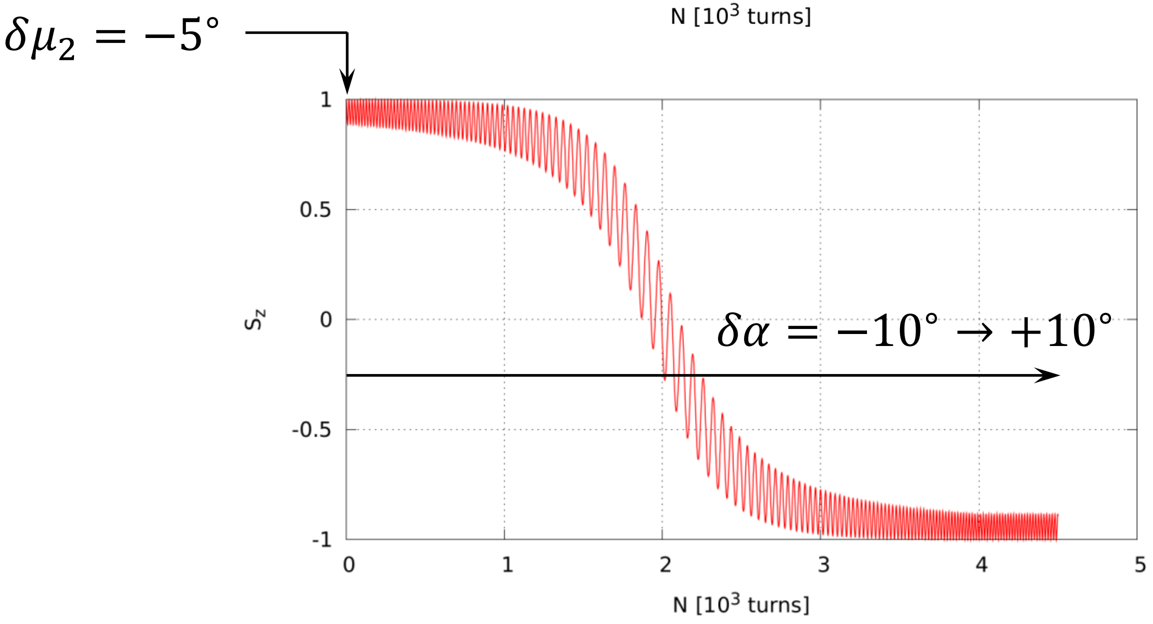


Adiabatic Spin Flip and Role of Stabilizing Spin Field Component

- Direction of Snake 1 axis adiabatically changed from -10° to $+10^\circ$
- No stabilizing spin field component



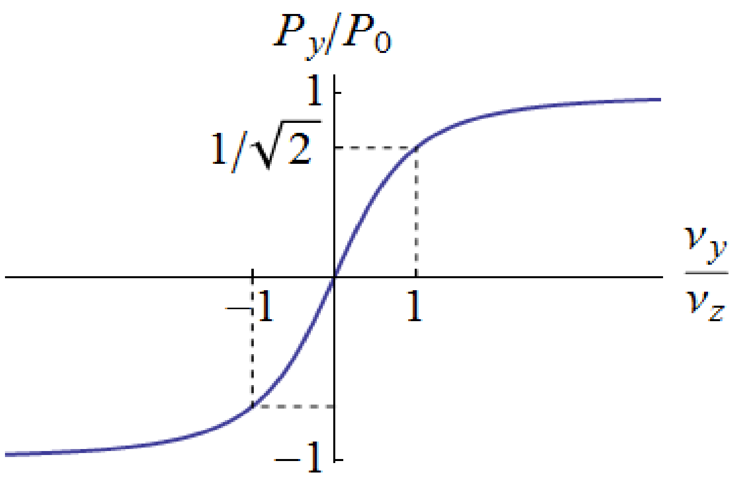
- Instant turn on of the stabilizing spin field component



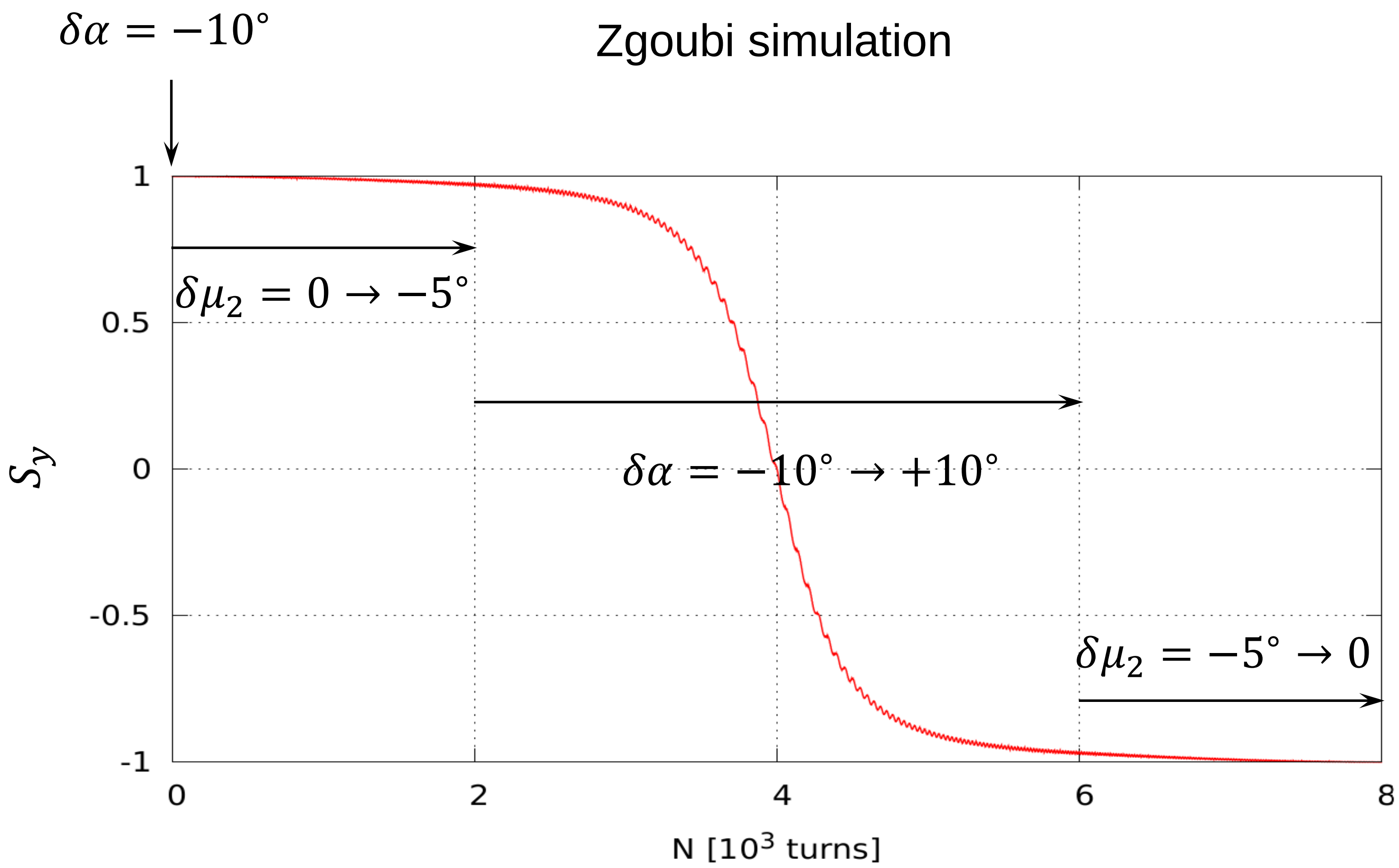
Adiabatic Spin Flip

- Direction of Snake 1 axis adiabatically changed from $-10°$ to $+10°$
- Near $0°$, spin stabilized by shifting Snake 2 spin rotation angle from $180°$ to $175°$

Analytic prediction

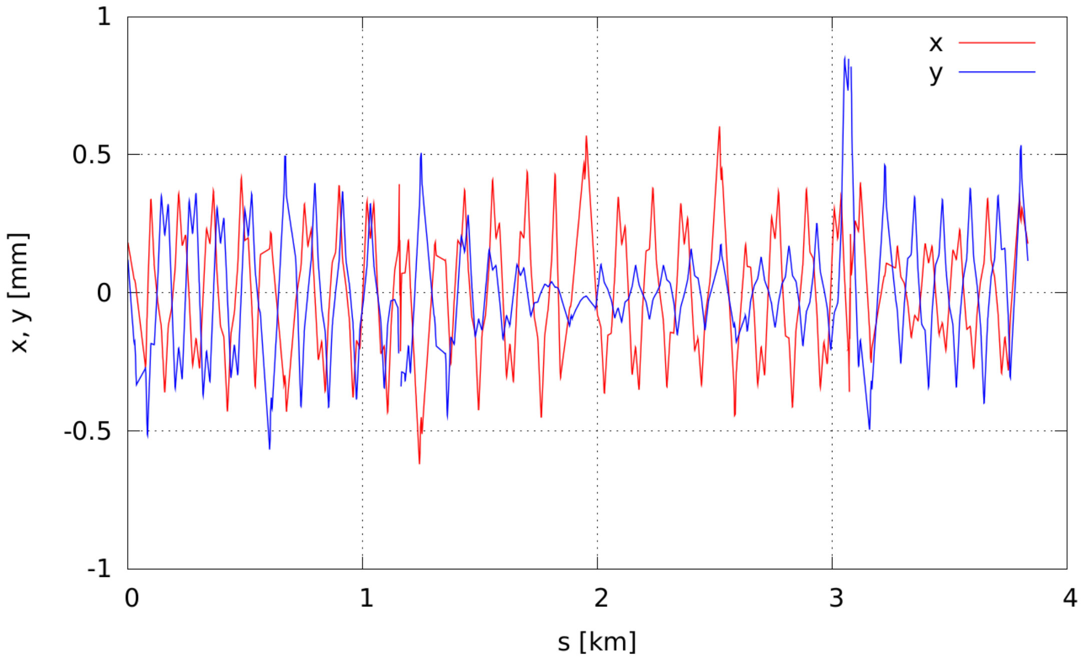


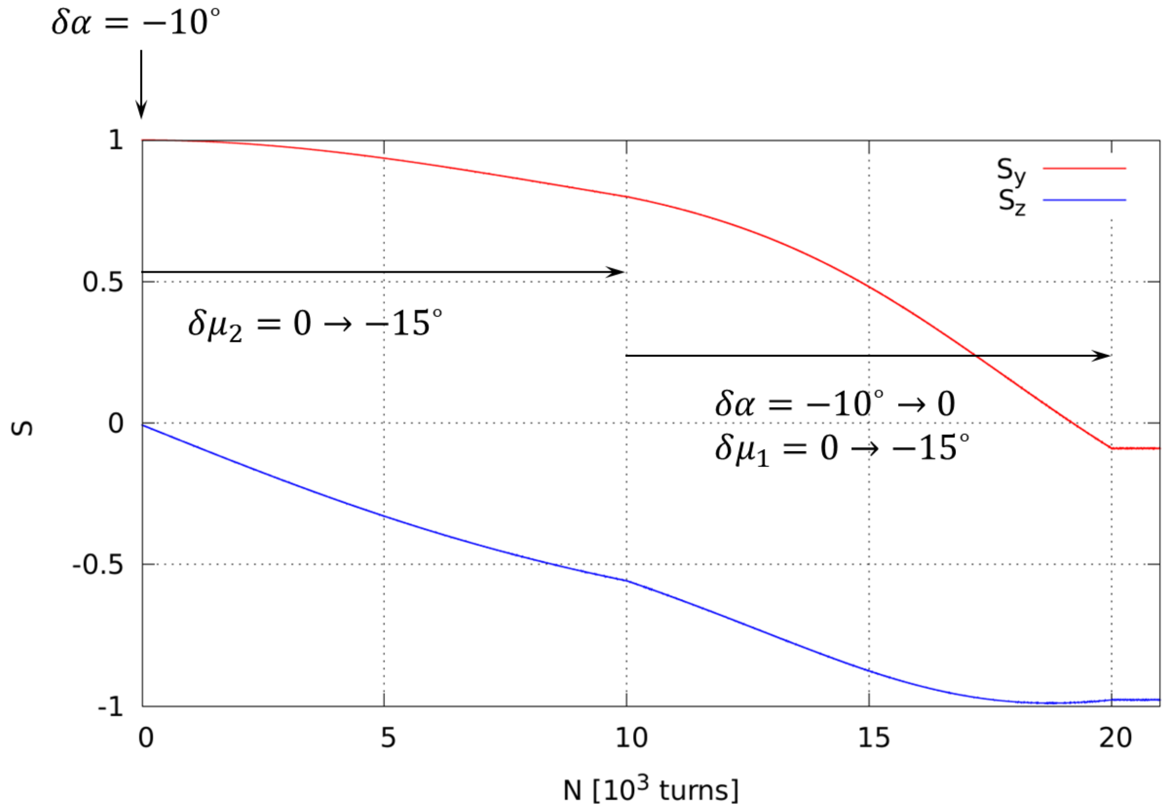
Zgoubi simulation



Adjustment of Longitudinal Polarization at IP

- Random dipole roll and quadrupole misalignments introduced according to statistical model
- rms closed orbit excursion is consistent with $200\ \mu m$
- Adiabatic change of the spin direction by adjusting snake parameters
  - Initial vertical spin: $\delta\alpha = -10°$
  - Final longitudinal spin: $\delta\alpha = 0°$, $\delta\mu_1 = -15°$, $\delta\mu_2 = -15°$





Spin Navigator Calibration

- Spin as a function of time

  $\vec{S}(N) = \vec{v}(N)/v(N)$

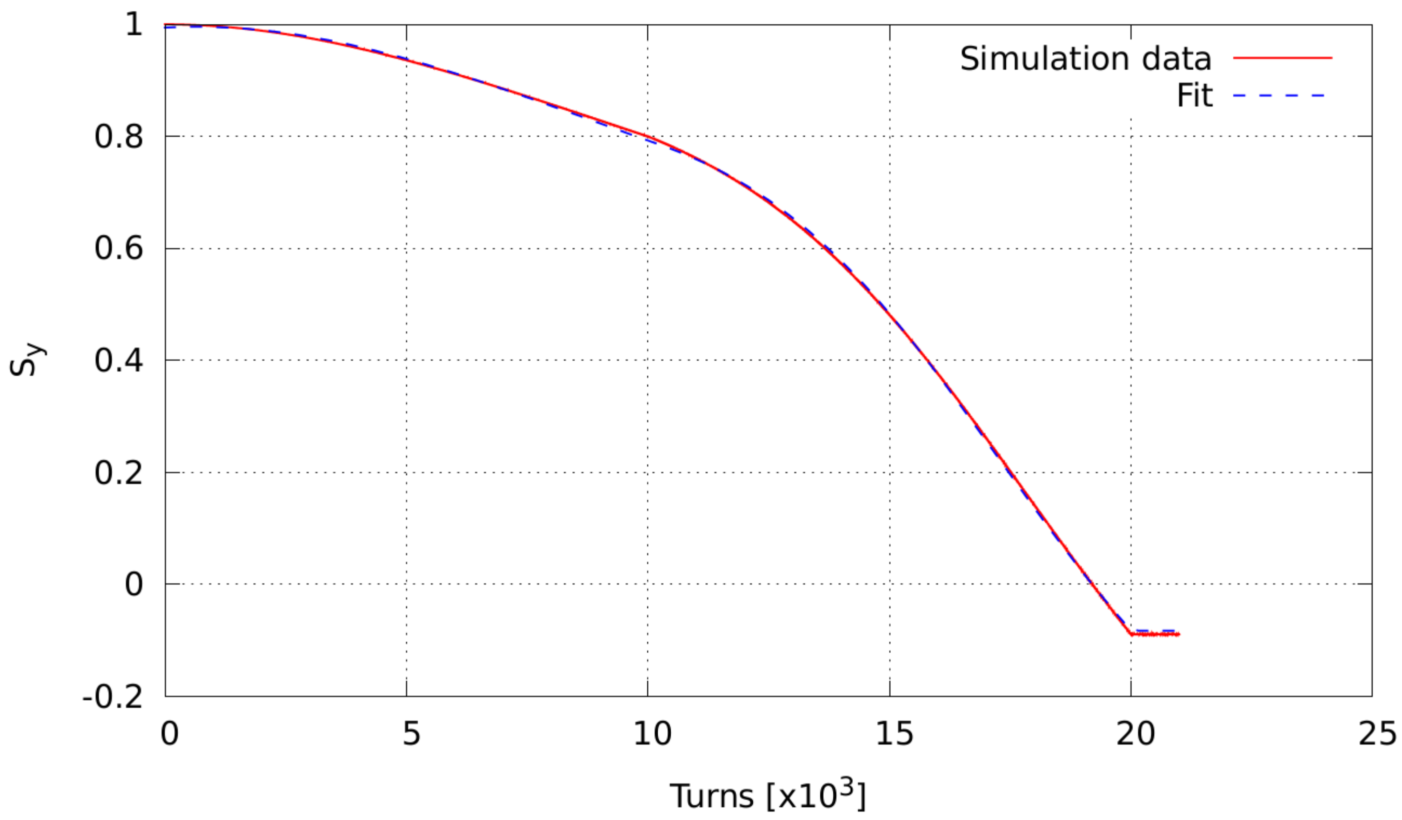
  where

  $$v_x(\mathrm{N}) = \frac{\delta\mu_1(N)-\delta\mu_2(N)}{2\pi}\sin\left(\frac{\gamma G\pi}{2}\right) + w_x,$$

  $$v_y(N) = \frac{\delta\alpha(N)}{\pi} + w_y,$$

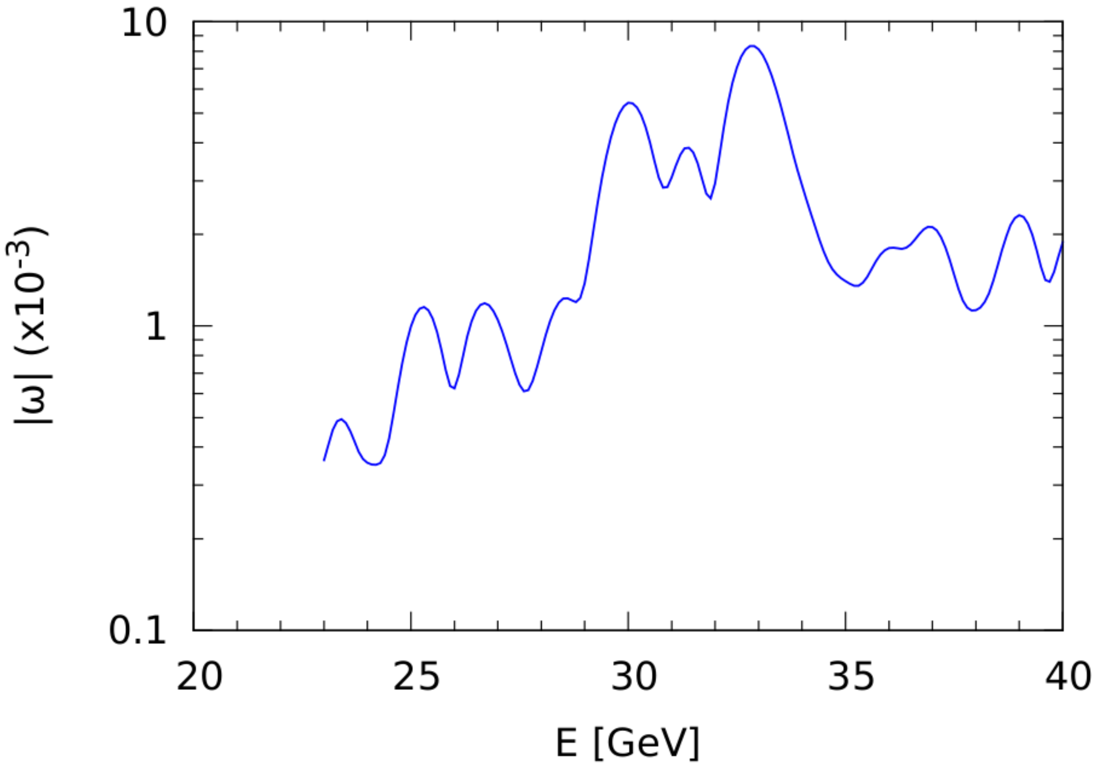
  $$v_z = -\frac{\delta\mu_1(N)+\delta\mu_2(N)}{2\pi}\cos\left(\frac{\gamma G\pi}{2}\right) + w_z$$

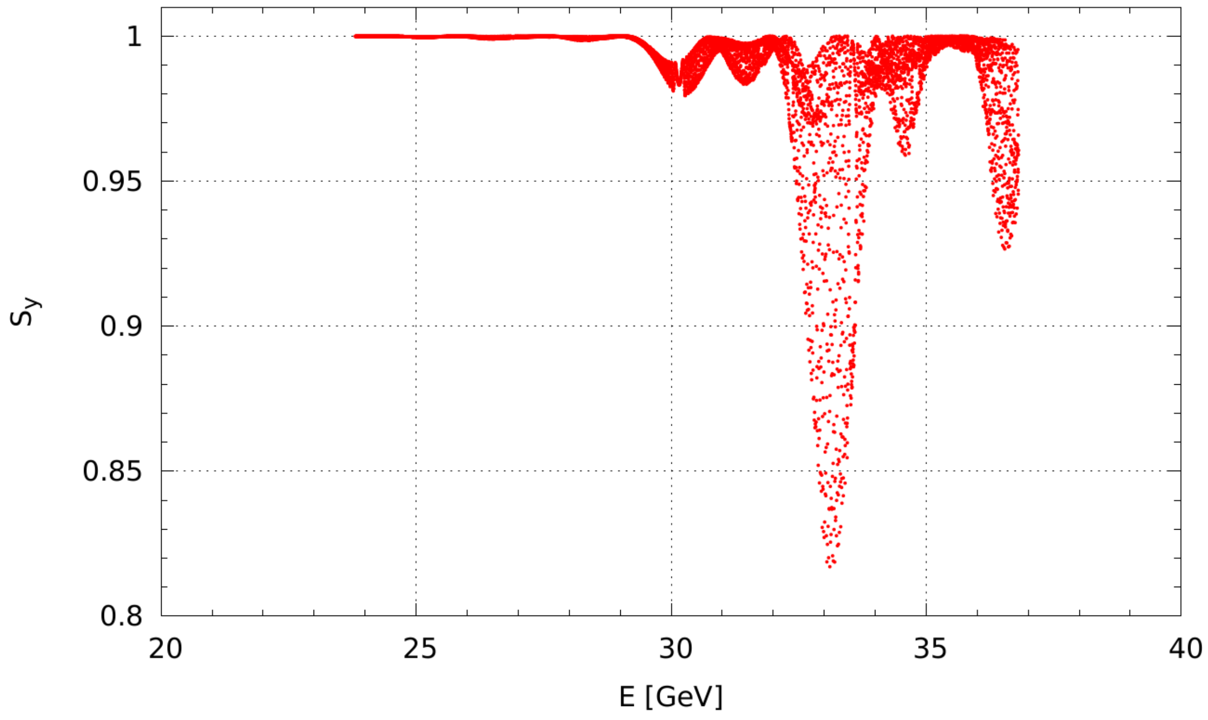
  and $\vec{w}$ accounts for imperfections and calibration errors



Acceleration

- Initially vertical spin: $\delta\alpha = -10°$
- Errors included
- Acceleration rate of 1.165 GeV/s
- Dips in polarization consistent with peaks of the resonance strength





Conclusions

- Spin transparency mode is beneficial to the EIC
  - Hadron beam
    - May be used to control the polarization direction instead of spin rotators in certain cases
    - Longitudinally polarized deuterons
  - Electron beam
    - Equal lifetimes of the two spin states
    - Simplified spin matching
- Adjustment of the spin transparency mode in RHIC demonstrated using accurate model
- Impact of imperfections evaluated
- Experimental program developed and verified by spin tracking
  - Spin flip
  - Adjustment of longitudinal polarization
  - Acceleration
  - Spin navigator calibration
- It has been verified that RHIC possesses all of the necessary technical capabilities
- Ready to present proposal to APEX and if approved complete the experiment when schedule allows
- PRL and EPJC papers published on relevant topics