Theoretical and Experimental Study of Spin Transparency Mode in an EIC

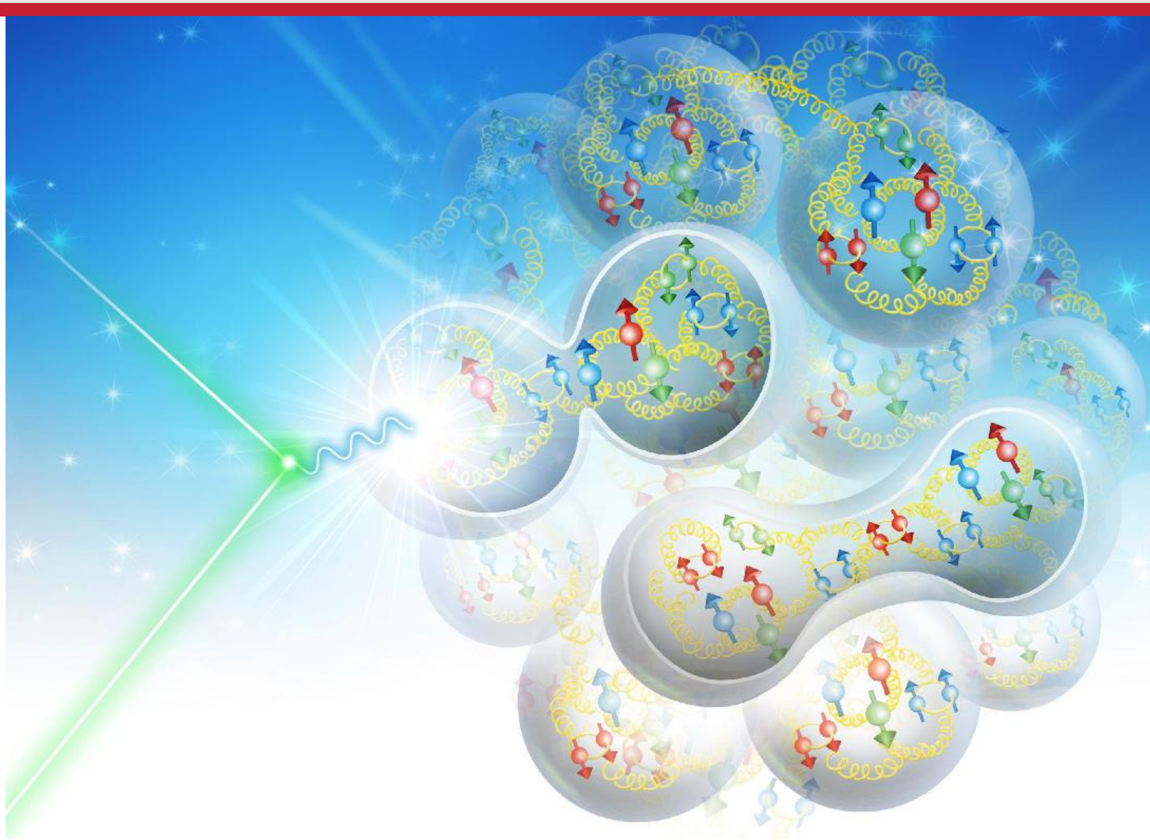
F. Lin, V.S. Morozov (PI), Y. Zhang, Ya.S. Derbenev
Jefferson Lab, Newport News, VA

P. Adams, H.X. Huang (co-PI), F. Méot, V. Ptitsyn, W. Schmidke
BNL, Upton, NY

H. Huang
ODU, Norfolk, VA

A.M. Kondratenko, M.A. Kondratenko
Novosibirsk, Russia

Yu.N. Filatov,
MIPT, Moscow, Russia



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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 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
  - In progress, details later in this presentation
- 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	$217,000	$217,000

- BNL

	FY’18-FY’19	Totals
a) Funds allocated	$552,000	$552,000
b) Actual costs to date	$243,000	$243,000

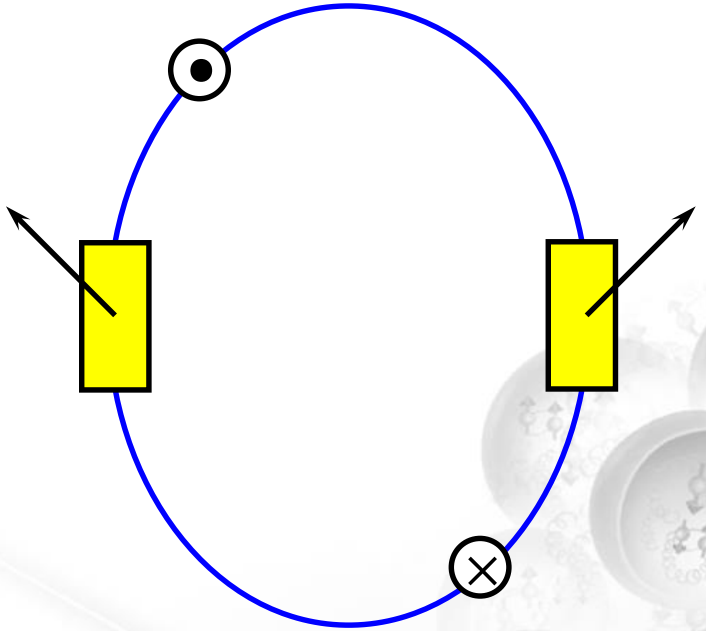
Deliverables and Schedule

- 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 shifted by about a year due to RHIC running schedule. We account for this in the funding profile.
- We were not able to sign a contract with A.M. Kondratenko but the scope has not been affected.

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					+	+	+	+

Conventional “Distinct Spin” Mode

- There exists a unique solution for the periodic spin motion along the closed orbit
- The spin tune is different from zero
- The polarization component along the periodic spin axis is preserved
- All polarized beam machines had run in this mode so far
  - Conventional racetrack accelerator with only vertical fields on the design orbit
    - Distinct spin direction is vertical
  - Racetrack accelerator with a single full Siberian snake
    - Distinct spin direction is in horizontal plane and points along the snake axis at an orbital location opposite to the snake
  - Racetrack accelerator with two full Siberian snakes located opposite to each other
    - Spin tune: $\nu = \varphi/\pi$
    - When snake axes **perpendicular** to each other, $\nu = 0.5$ and distinct spin direction is vertical but changes sign after passing through a snake



“Transparent Spin” Mode

- The spin motion is degenerate, any spin direction is periodic
- The spin tune is zero
- In an ideal case, any polarization direction is preserved
- Examples of spin transparent accelerators
  - Conventional racetrack accelerator with an integer spin tune (imperfection resonance)
  - Racetrack accelerator with two full Siberian snakes located opposite to each other with their axes **parallel** to each other
  - Figure-8 accelerator

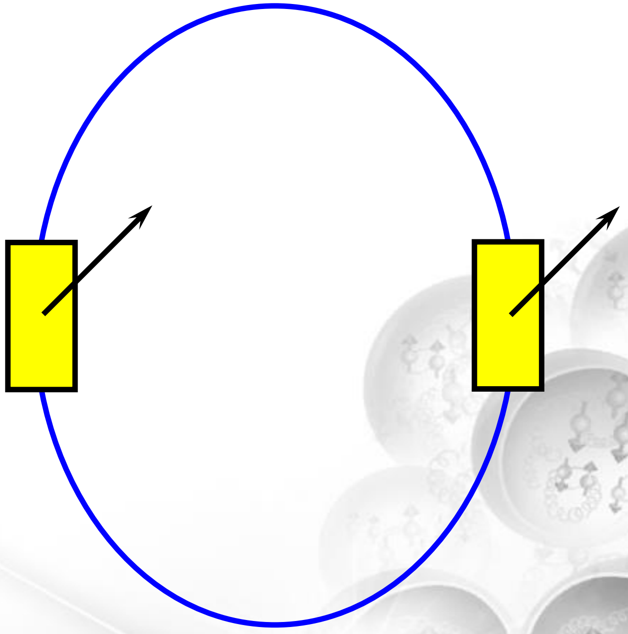
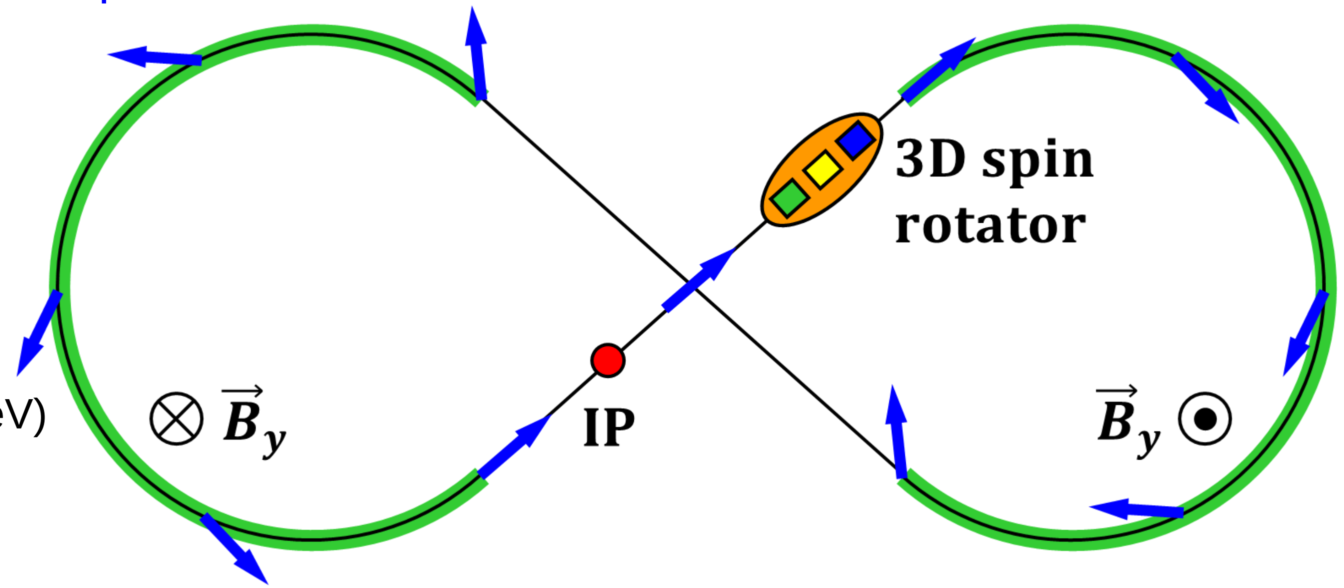
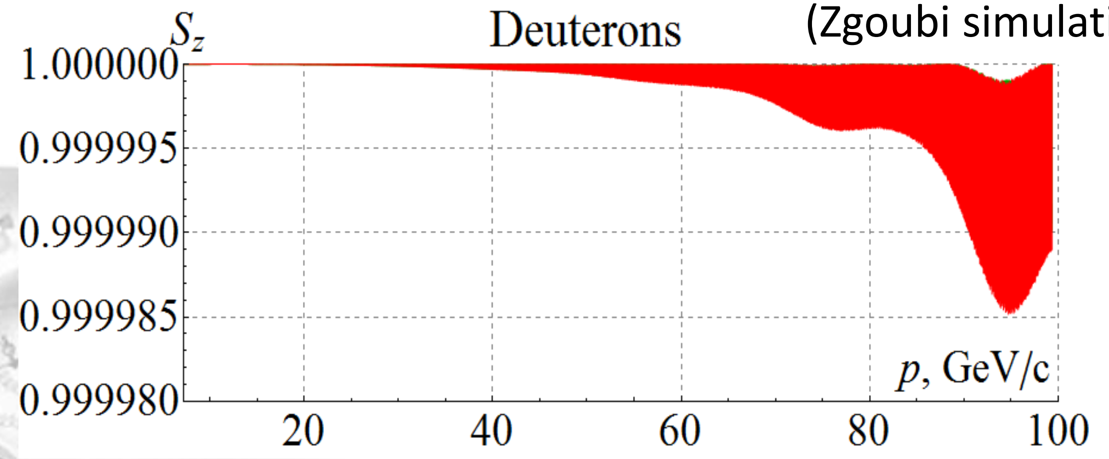


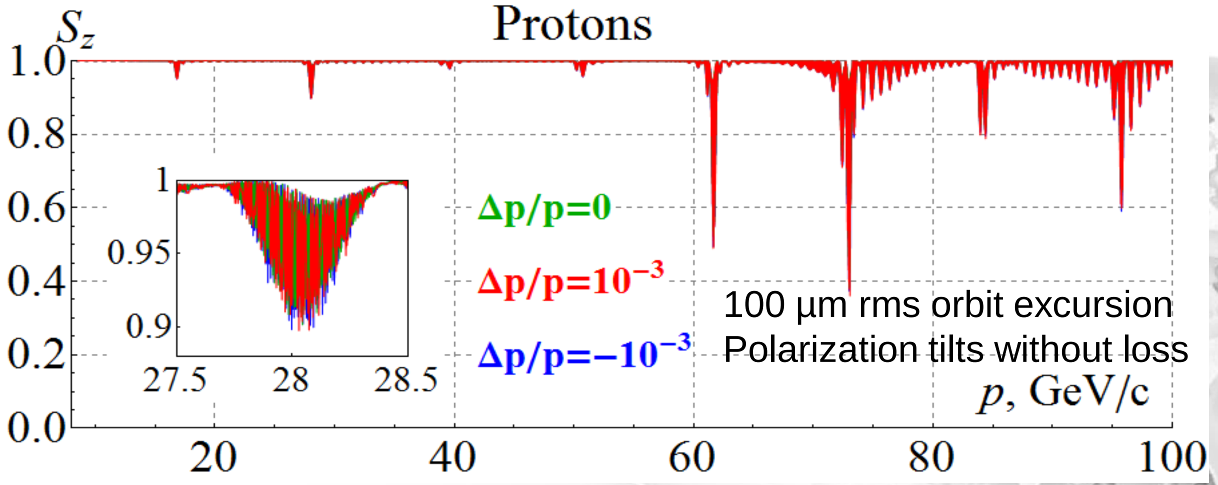
Figure 8 Design of JLEIC

- Zero net spin rotation makes spin motion energy independent
- Additional fields remove dynamic degeneracy
  - Avoid all spin resonances
  - Induced spin rotation >> error effect
  - Only weak magnetic fields necessary
  - Enables 85% polarization
- Easily set any polarization at the IP
- No orbit perturbation
- Polarized deuterons (~3 Tm vs. < 400 Tm at 100 GeV)
- 100% efficient spin flipping
- Experimental verification planned



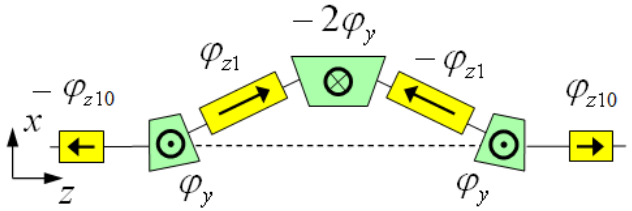
(Zgoubi simulation)





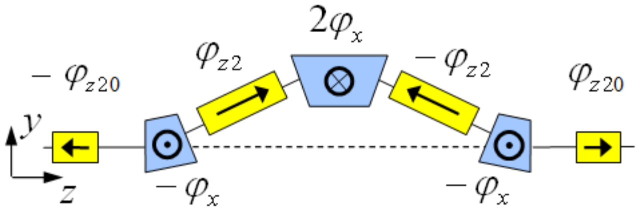
3D Spin Rotator in JLEIC Ion Collider Ring

- Provides control of the radial, vertical, and longitudinal spin components
- Module for control of the radial component (fixed radial orbit bump)

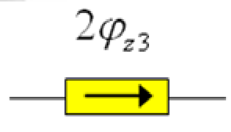


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

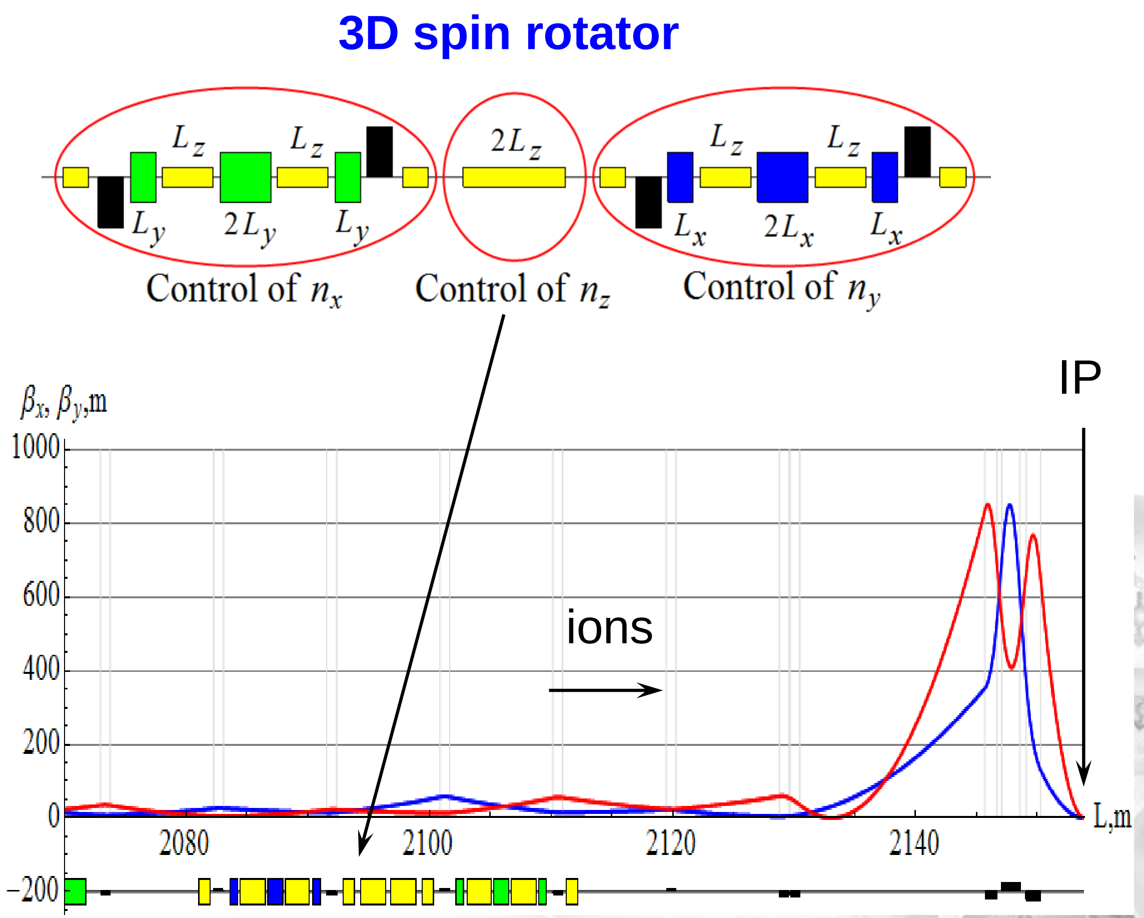
- Module for control of the vertical component (fixed vertical orbit bump)



- Module for control of the longitudinal component

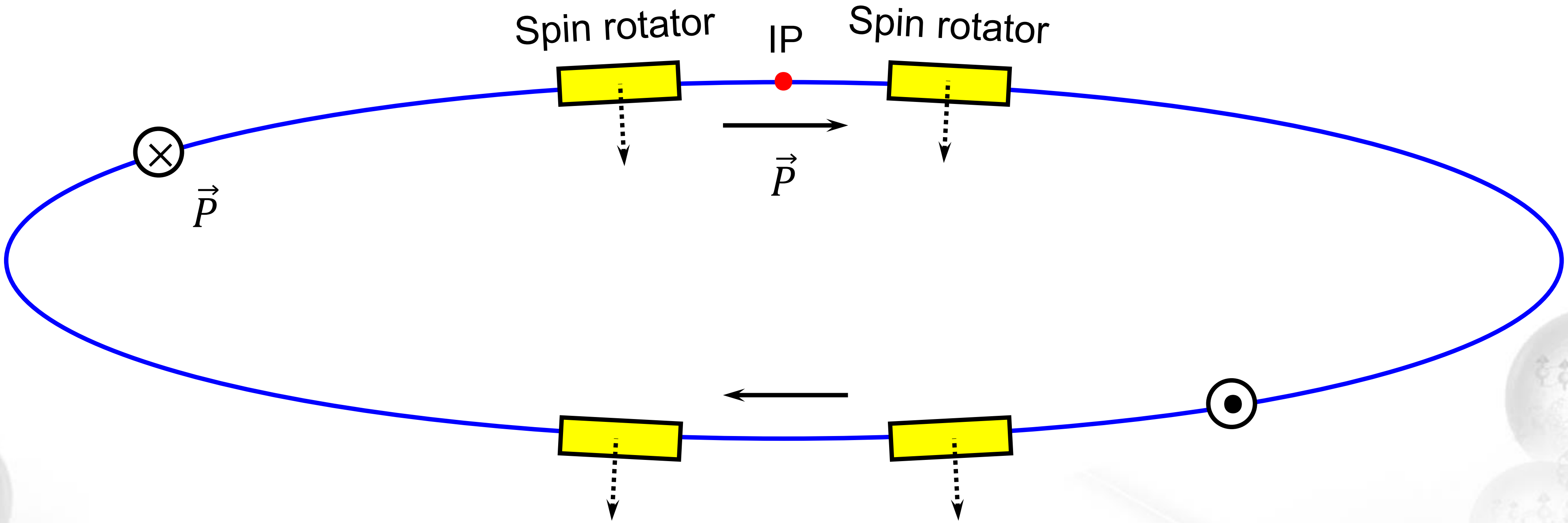


$L_x = L_y = 0.6$ m, $L_{zi} = 2$ m, $L_{zi0} = 1$ m, $\alpha_{orb} = 0.31^\circ$



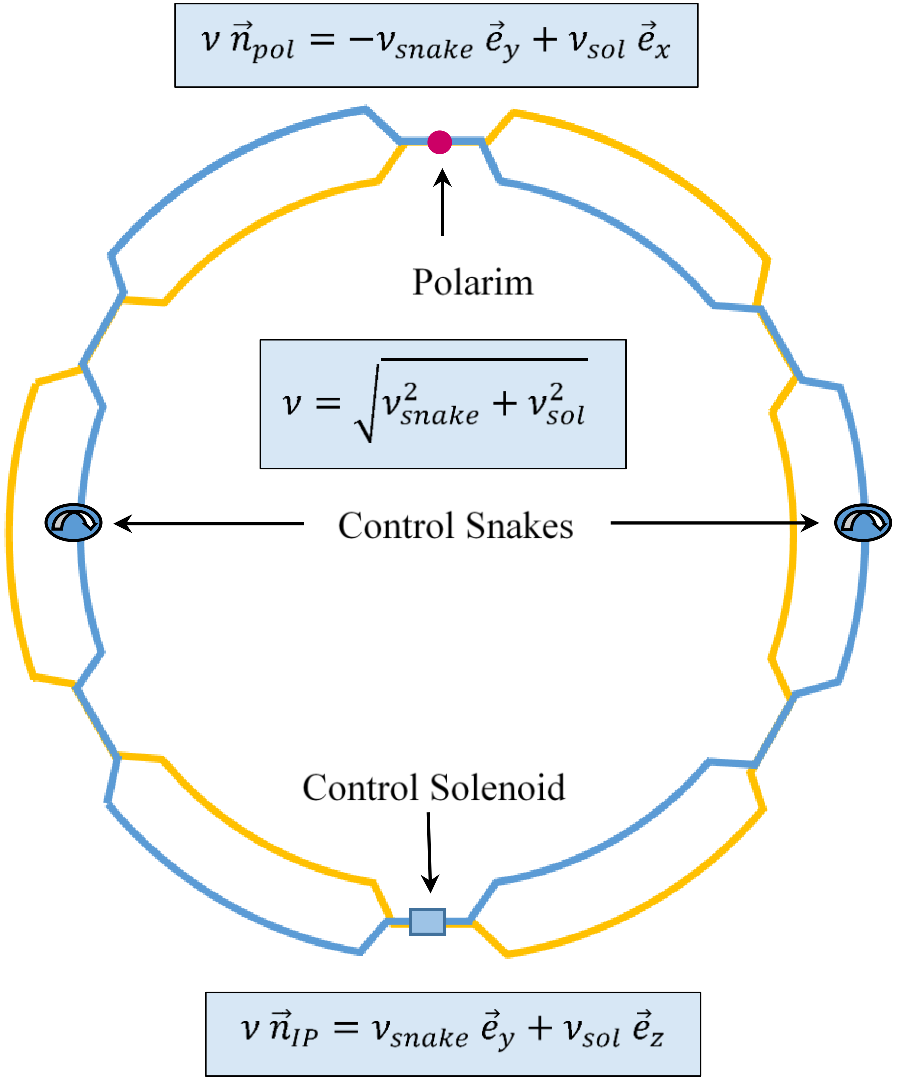
Potential Benefit to eRHIC

- Configure the electron storage ring in the spin transparency mode
- Two electron spin rotators around an IP serve as a full Siberian snake
- Benefits
  - Same lifetimes of the two spin states
  - Simplified spin matching



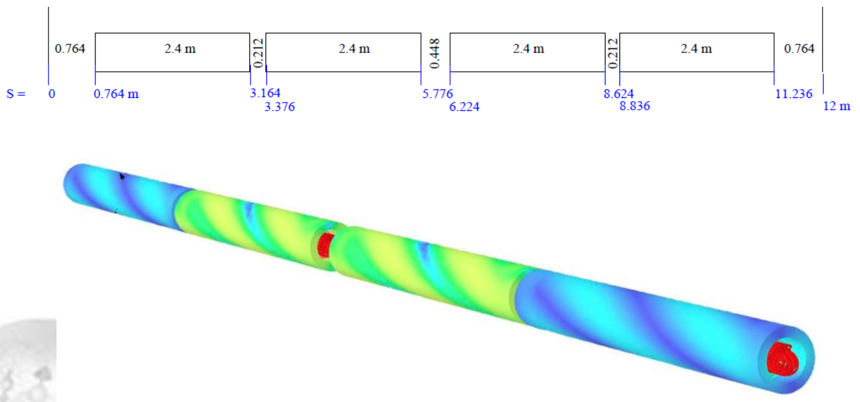
Experimental Test of “Transparent Spin” Mode in RHIC

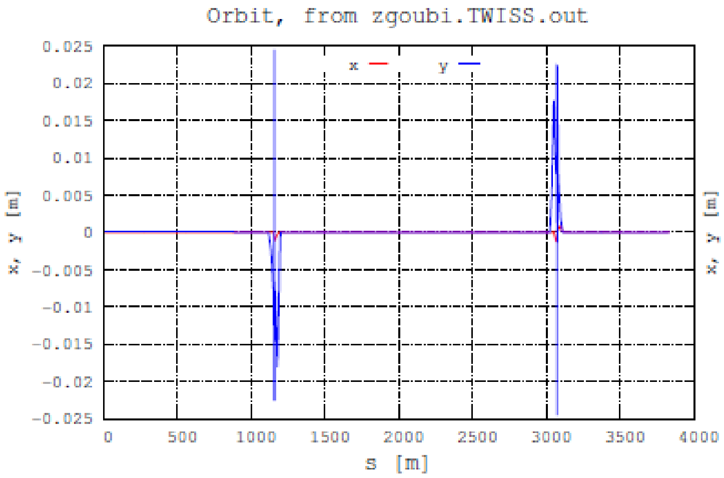
- RHIC already has all of the necessary ingredients
- Make snake axes parallel at 0° to set RHIC in the transparent spin mode
- 3D spin rotator
  - Small angle between the snake axes = vertical module
  - Mismatch of the snake strengths from π = longitudinal & radial modules
- Existing polarimeter with fast measurement time
- Can test many of the features of the spin transparency mode and 3D spin rotator

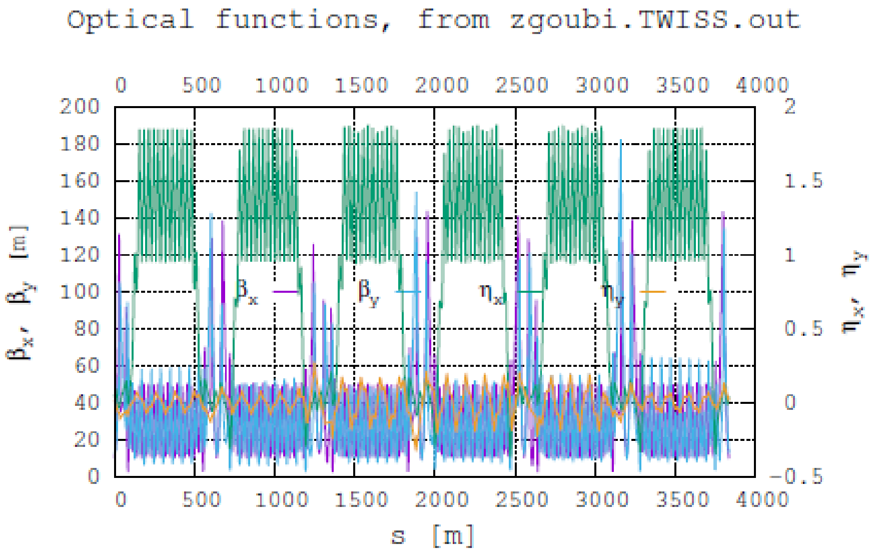


Model of RHIC with Snakes

- 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

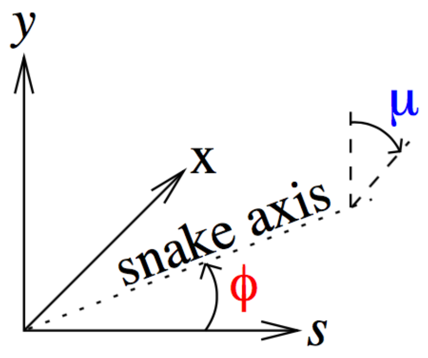


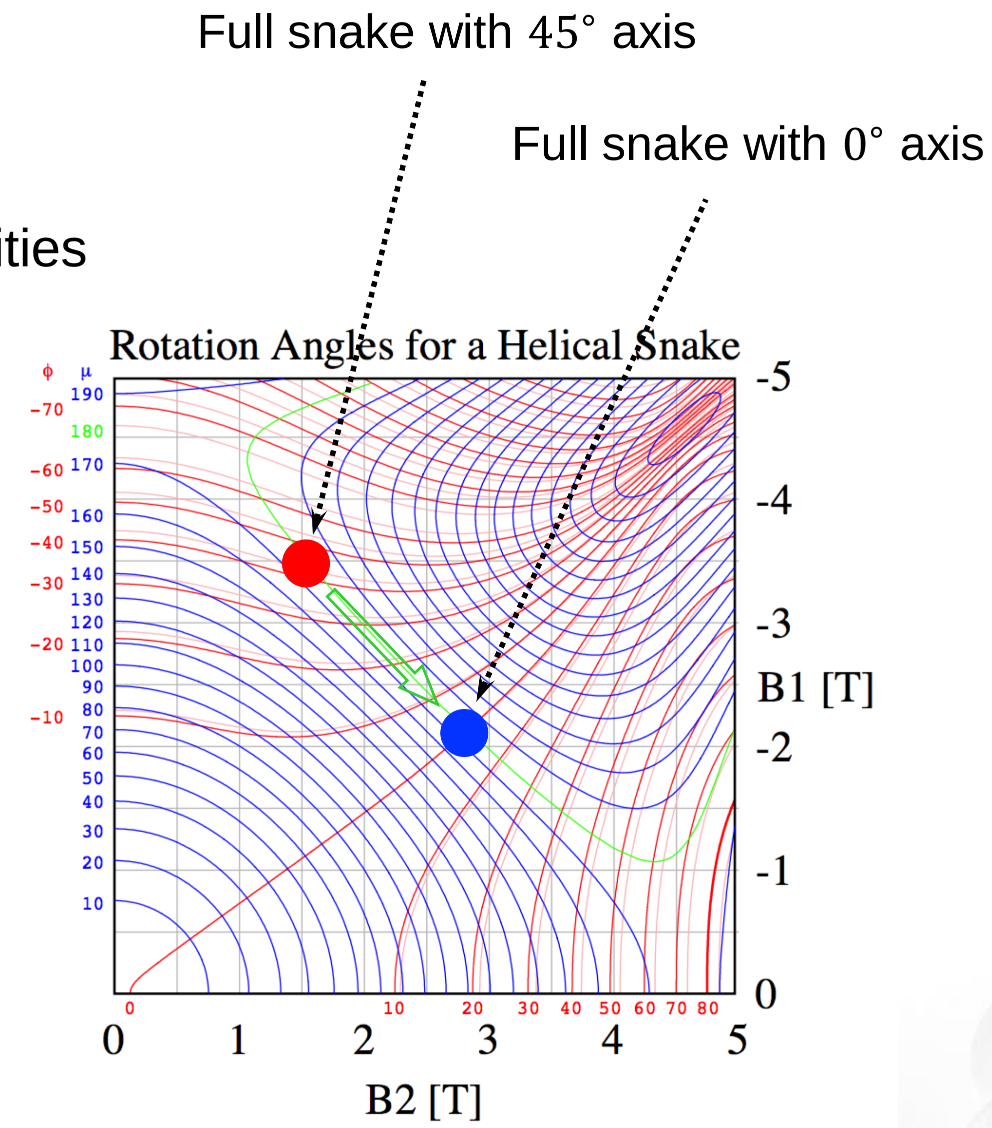




RHIC Snake Adjustment

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





Hardware Requirements

- 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.

Extension of "Transparent Spin" Theory to Racetracks with Two Snakes

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

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

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

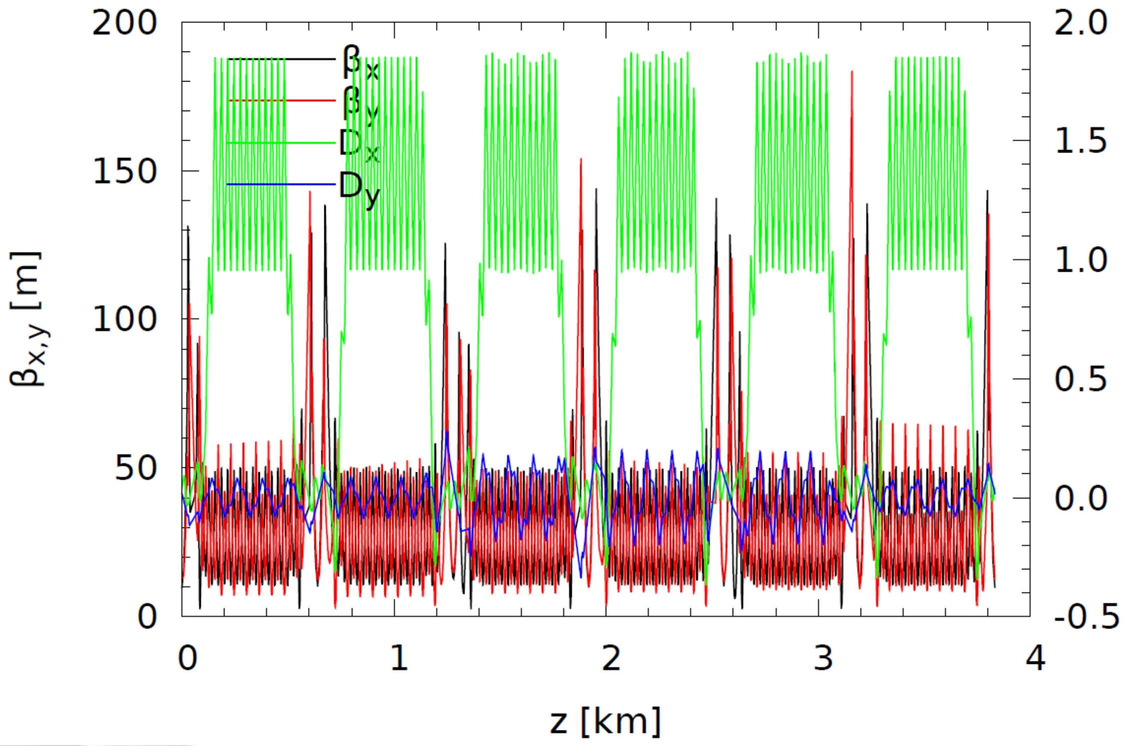
$$F = F_{x1} + iF_{x3} = \frac{\gamma G}{2i}\left[f_y^* \int_{-\infty}^{z} f_y' \left(e^{i\alpha(1-\zeta)}\frac{d}{dz}e^{i\Psi}\right) dz - f_y \int_{-\infty}^{z} f_y^{*\prime} \left(e^{i\alpha(1-\zeta)}\frac{d}{dz}e^{i\Psi}\right) dz\right]$$

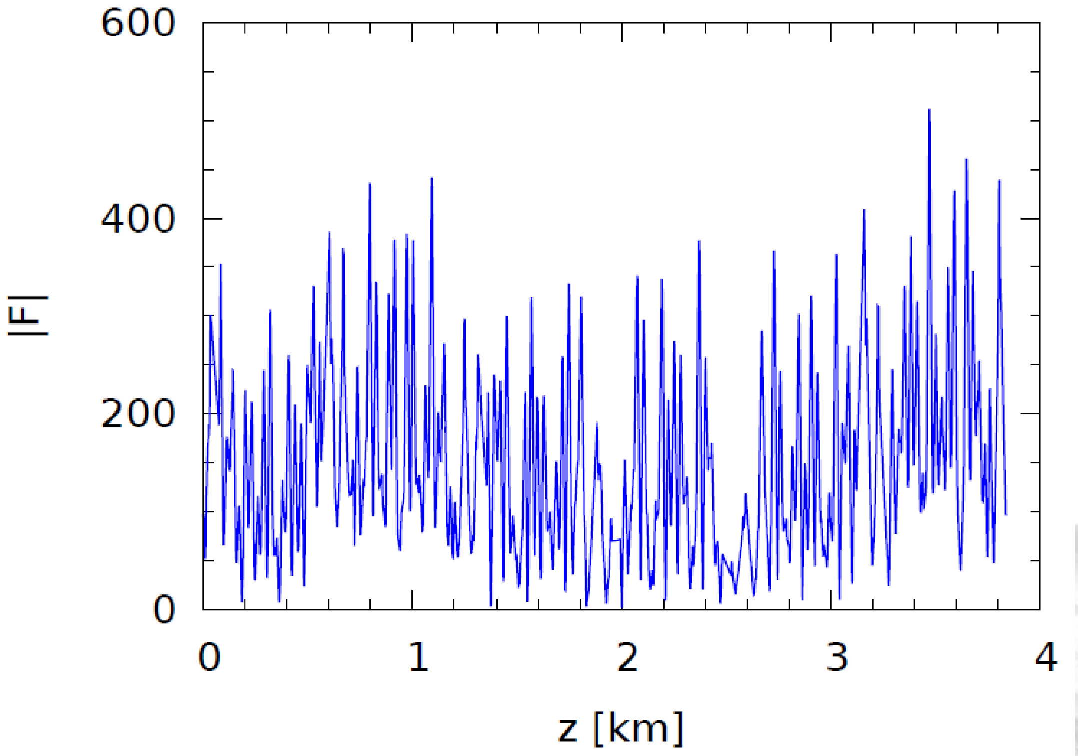
where

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

i.e. by radial perturbing fields

Optics and Spin Response Function of RHIC at Injection Energy





Statistical Model

- Treats random errors in a statistical sense
- Radial perturbing magnetic fields
    - Dipole roll

$$\overline{\Delta B_x^2} L_x^2 = \theta^2 \, \overline{\Delta\varphi^2} (B\rho)^2$$

    - Vertical quadrupole misalignments

$$\overline{\Delta B_x^2} L_x^2 = (k_1 L_x)^2 \overline{\Delta y^2} (B\rho)^2$$

- $\overline{\Delta\varphi^2}$ and $\overline{\Delta y^2}$ are chosen to equally contribute to a closed orbit distortion of 200 μm using

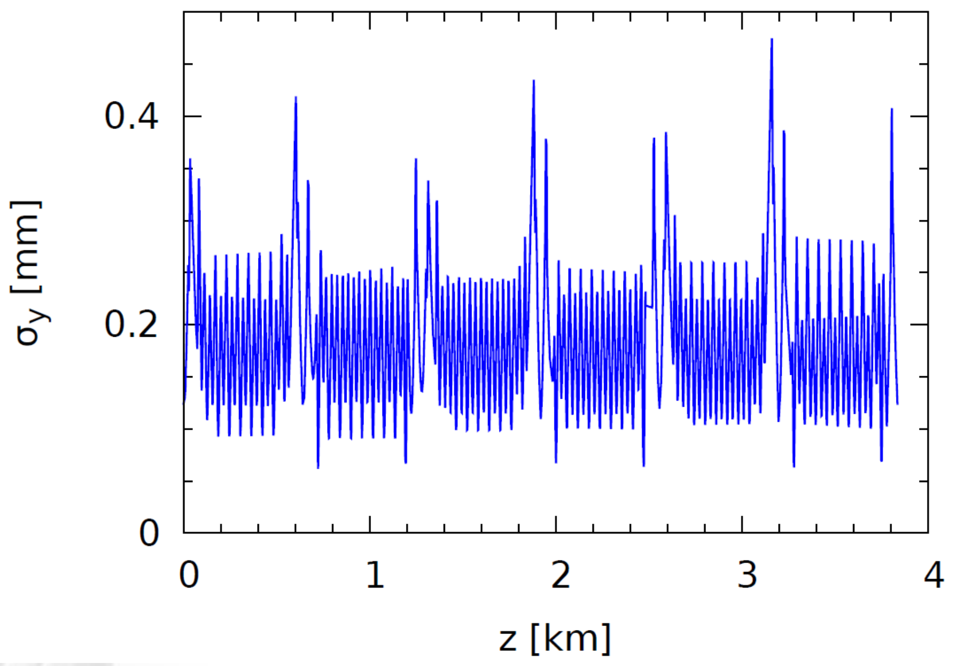
$$\sigma_y = \sqrt{\frac{\beta_y(z)}{8\sin^2(\pi\nu_y)} \sum_{elements} \frac{\overline{\Delta B_x^2} L_x^2}{(B\rho)^2} \beta_y(z_j)}$$

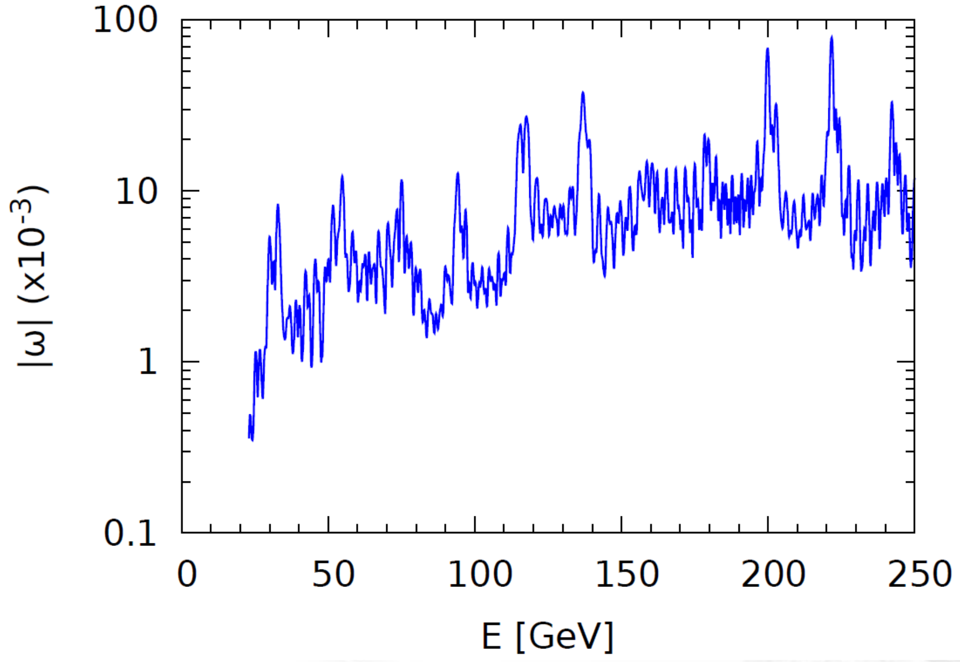
- Then the rms resonance strength is found as

$$|\omega_{coh}| = \sqrt{\frac{1}{4\pi^2 (B\rho)^2} \sum_{\text{elements}} \overline{\Delta B_x^2} \, |F|^2 L_x^2}$$

rms Vertical Closed Orbit and Resonance Strength

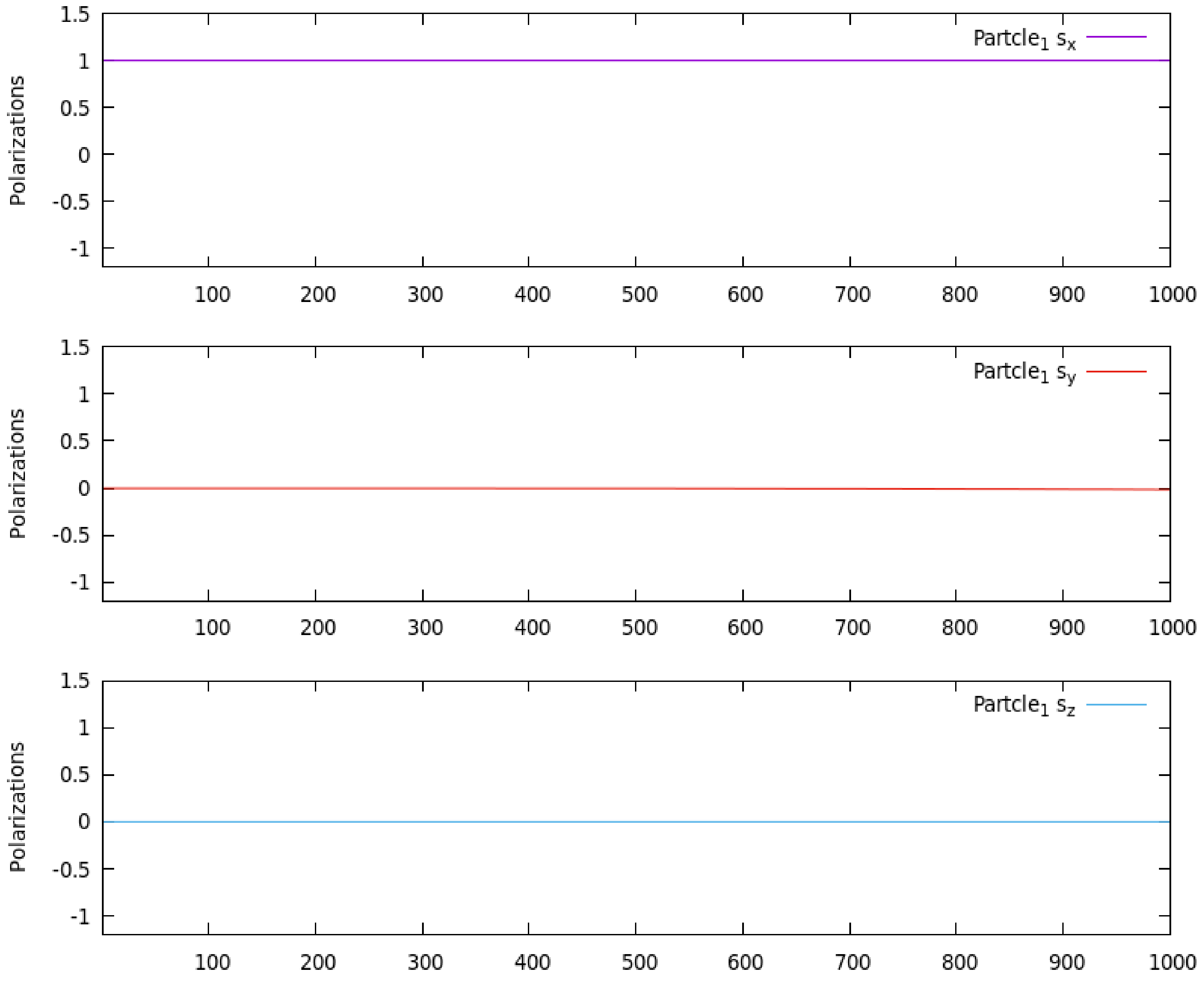
- Statistically calculated closed orbit around the ring with an rms size of 200 μm
- The resonance strength does not exceed 0.01 at least up to 100 GeV
- Spin tune of 0.05 should be sufficient to control the polarization





Model of RHIC with Point-Like Snakes

- Sanity check and accuracy test of the tracking code, Zgoubi
- Ideal lattice
- Ideal point-like full snakes with longitudinal axes having no orbital effect
- All spin directions periodic

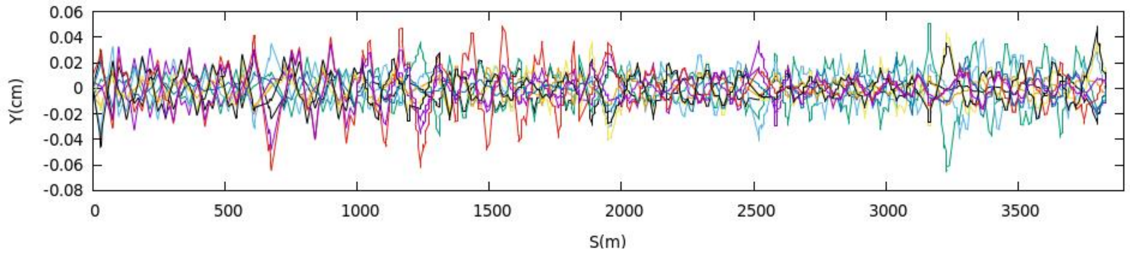


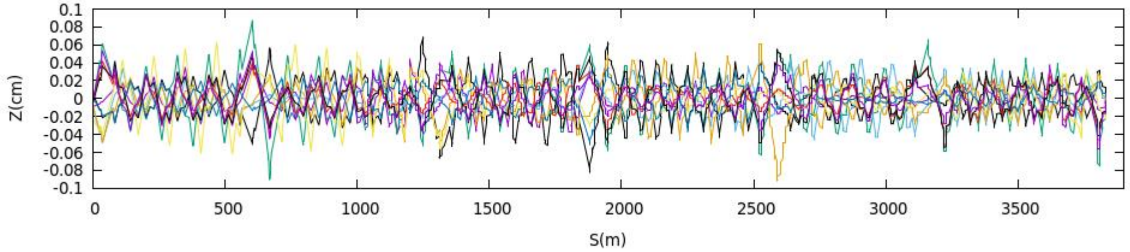
Error Effect

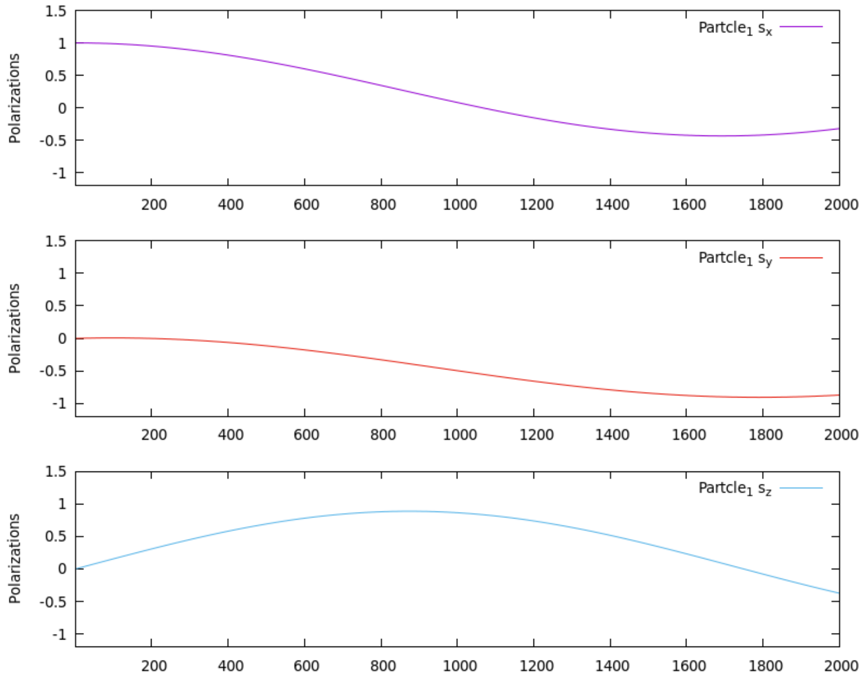
- Still ideal Siberian snakes
- Lattice with dipole roll and quadrupole misalignments obtained from statistical model
- rms closed orbit excursion is consistent with $200\ \mu\mathrm{m}$
- Spin precesses about spin field direction
- Spine resonance strength of $3.0 \cdot 10^{-4}$ extracted using

$$\vec{P}(N) = \vec{P}_i \cos(2\pi\omega_{Coh}N) + \left(\vec{n} \times \vec{P}_i\right) sin(2\pi\omega_{Coh}N) + \vec{n}\left(\vec{n} \cdot \vec{P}_i\right)[1 + \cos(2\pi\omega_{Coh}N)]$$

  agrees with a statistical prediction of $3.2 \cdot 10^{-4}$
- Spin field is nearly horizontal as predicted

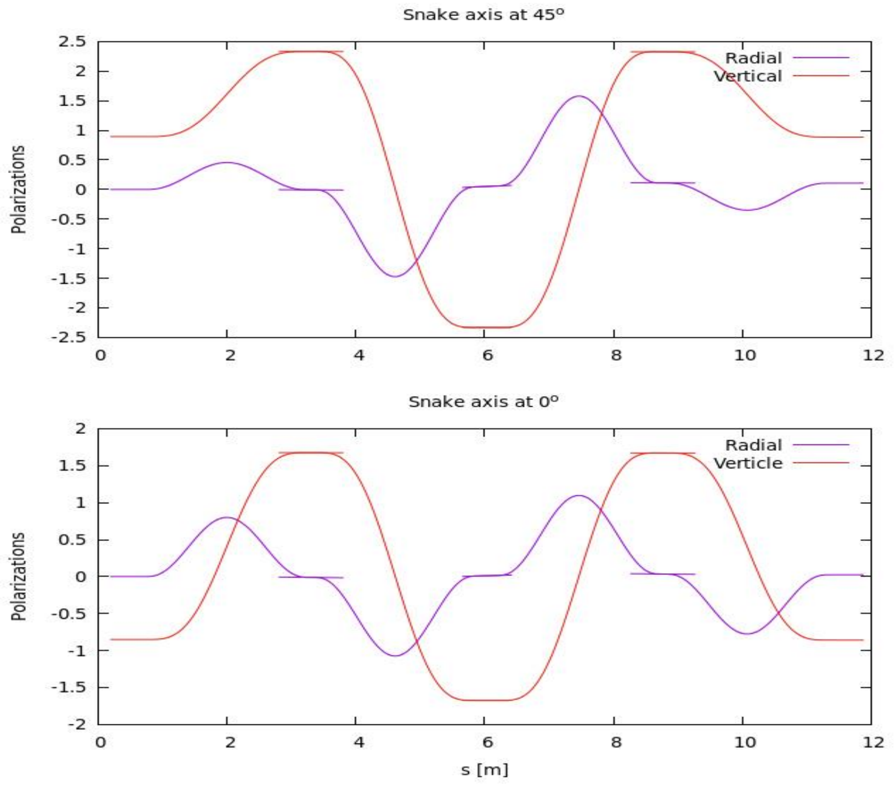


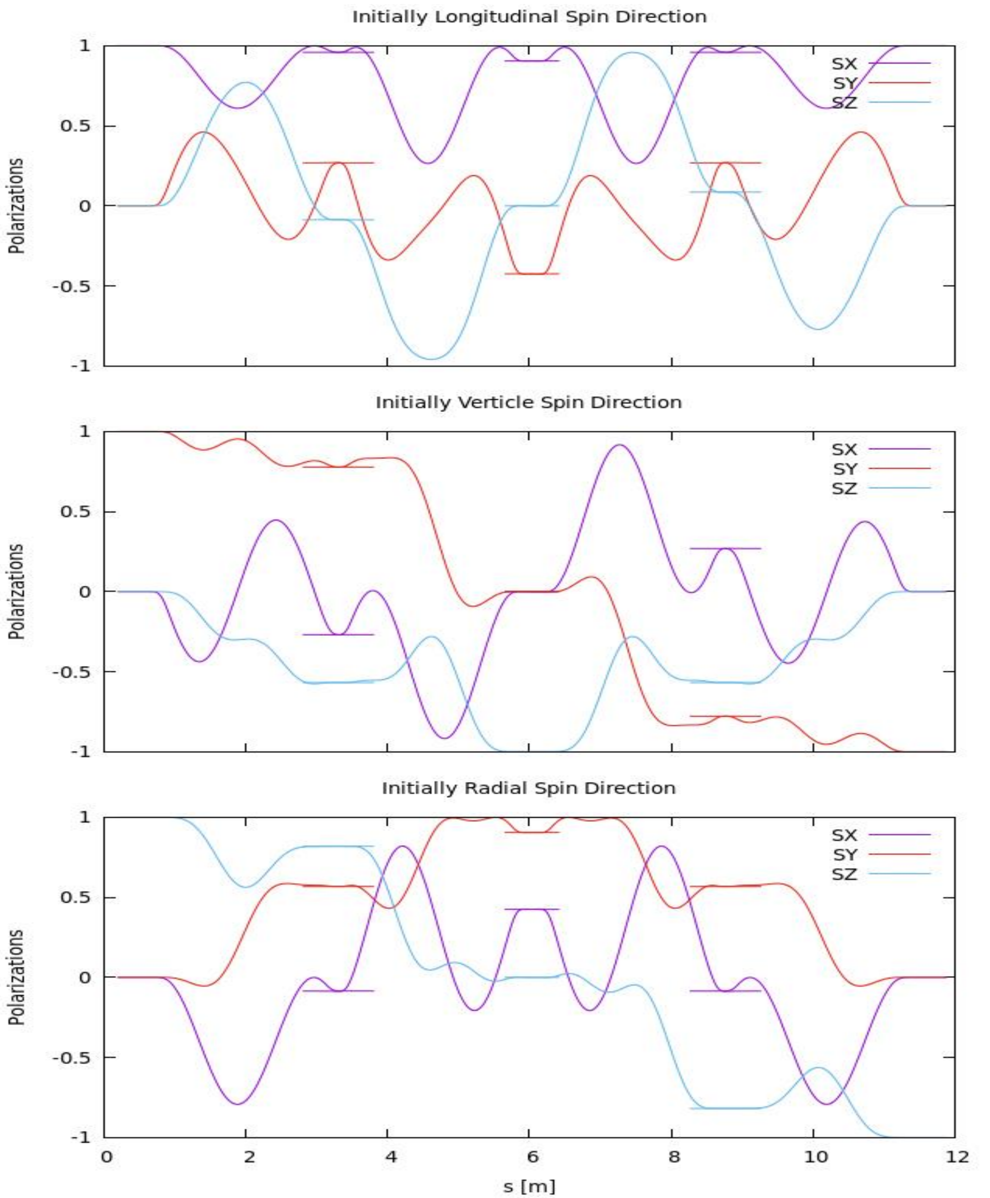




Introducing Realistic Snake Model

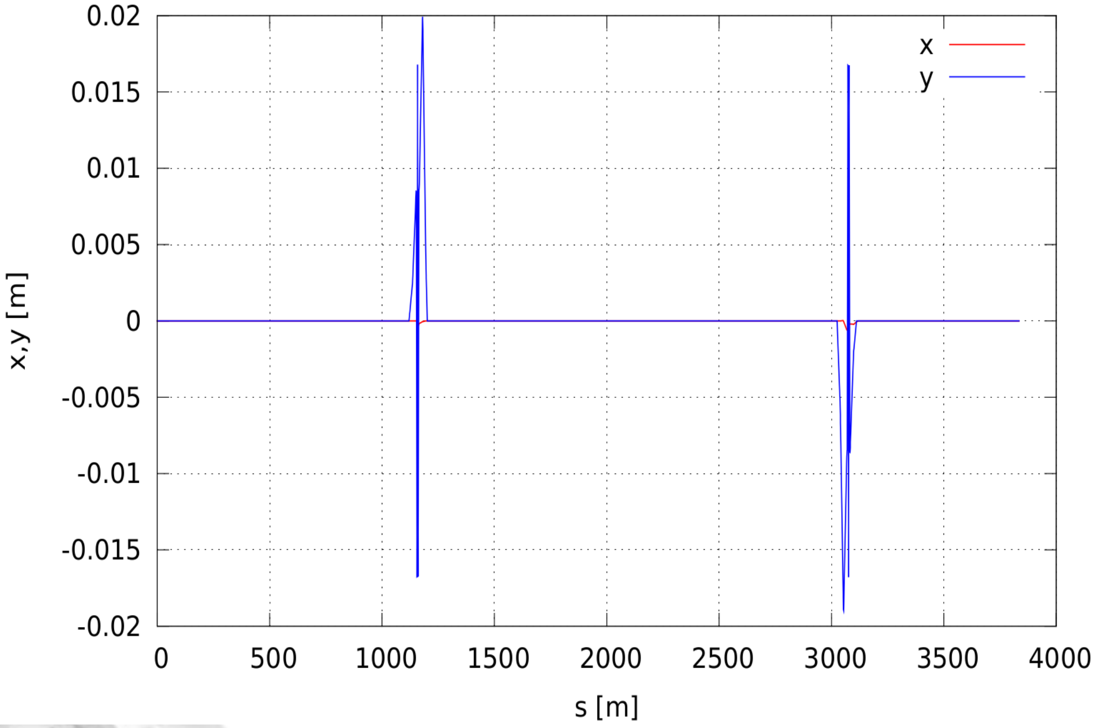
- Snakes are modeled as two pairs of field maps
- Field maps are scaled in Zgoubi using its fitting procedure to set a full snake with longitudinal axis
- Orbit excursion is reduced

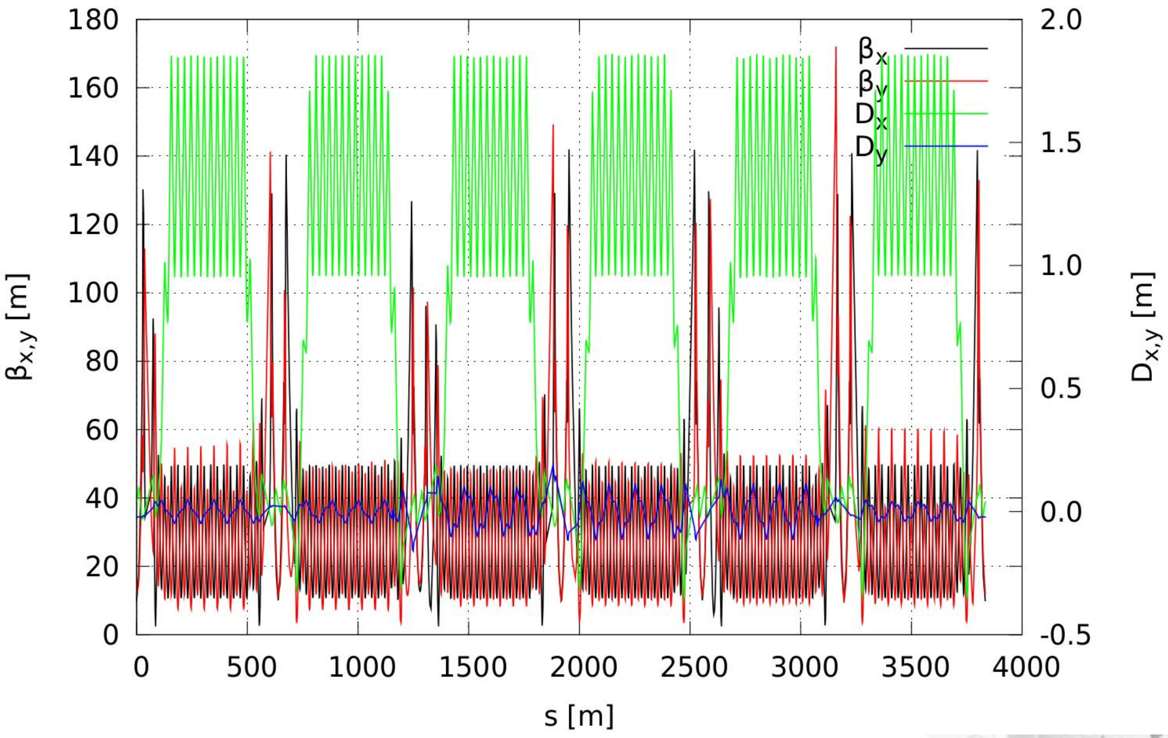




Orbit and Optics of RHIC at Injection Energy

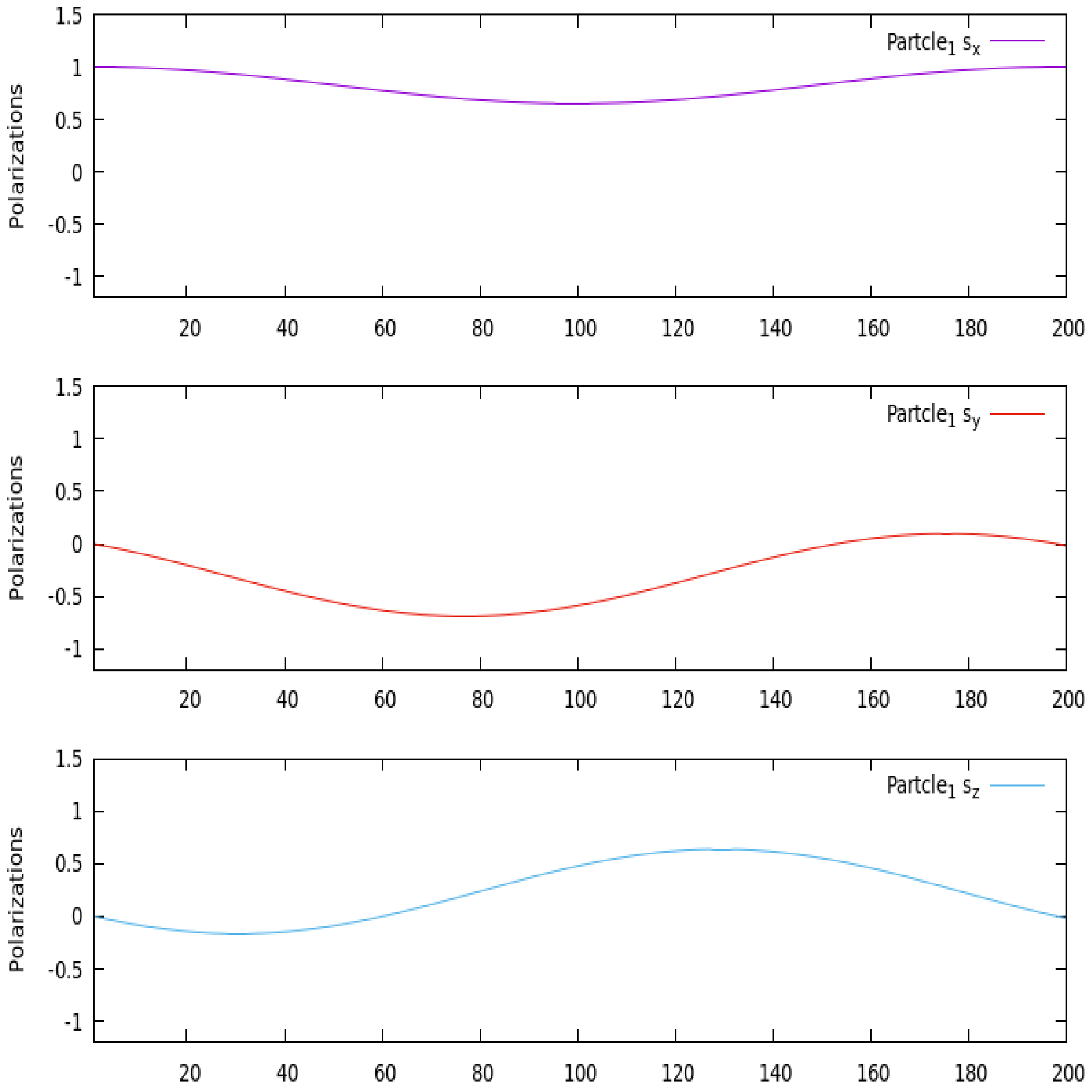
- Snakes are modeled using field maps
- Vertical orbit excursion caused by the snakes is corrected locally





Spin Dynamics with Realistic Snakes

- Snakes are modeled using field maps
- No lattice errors other than orbit excursion due to the snakes
- No perfect spin transparency as with point like snakes
- Vertical obit excursion due to snakes generates a resonance strength of about $5 \cdot 10^{-3}$
- This effect is still much smaller than the planned spin tune of $5 \cdot 10^{-2}$



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

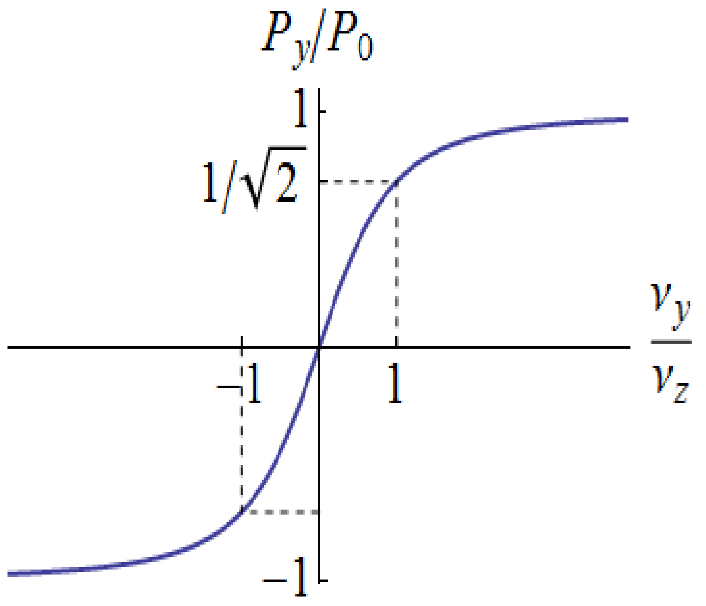
$$\nu_x = \frac{\delta\mu_1 - \delta\mu_2}{2\pi}\sin(\gamma G\pi/2), \qquad \nu_y = \frac{\delta\alpha}{\pi},$$

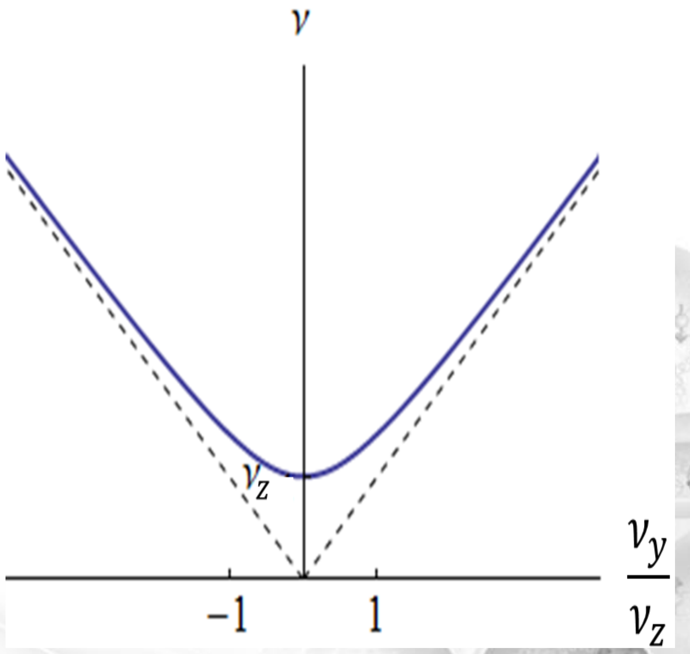
$$\nu_z = -\frac{\delta\mu_1 + \delta\mu_2}{2\pi}\cos(\gamma G\pi/2)$$

  - 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 $\delta\alpha$





Summary

- Extension of the transparent spin theory to a racetrack with two Siberian snakes has been completed
- We are on track with spin dynamics simulations and analysis
- The Zgoubi spin tracking code has been tested and has all of the necessary features
- Simulation results are consistent with theoretical predictions
- It has been verified that RHIC possesses all of the necessary technical capabilities
- The dates of the experiment provided it is approved by APEX depend on RHIC’s running schedule
- Spending profile has been adjusted to bridge the gap between simulation work and the experiment