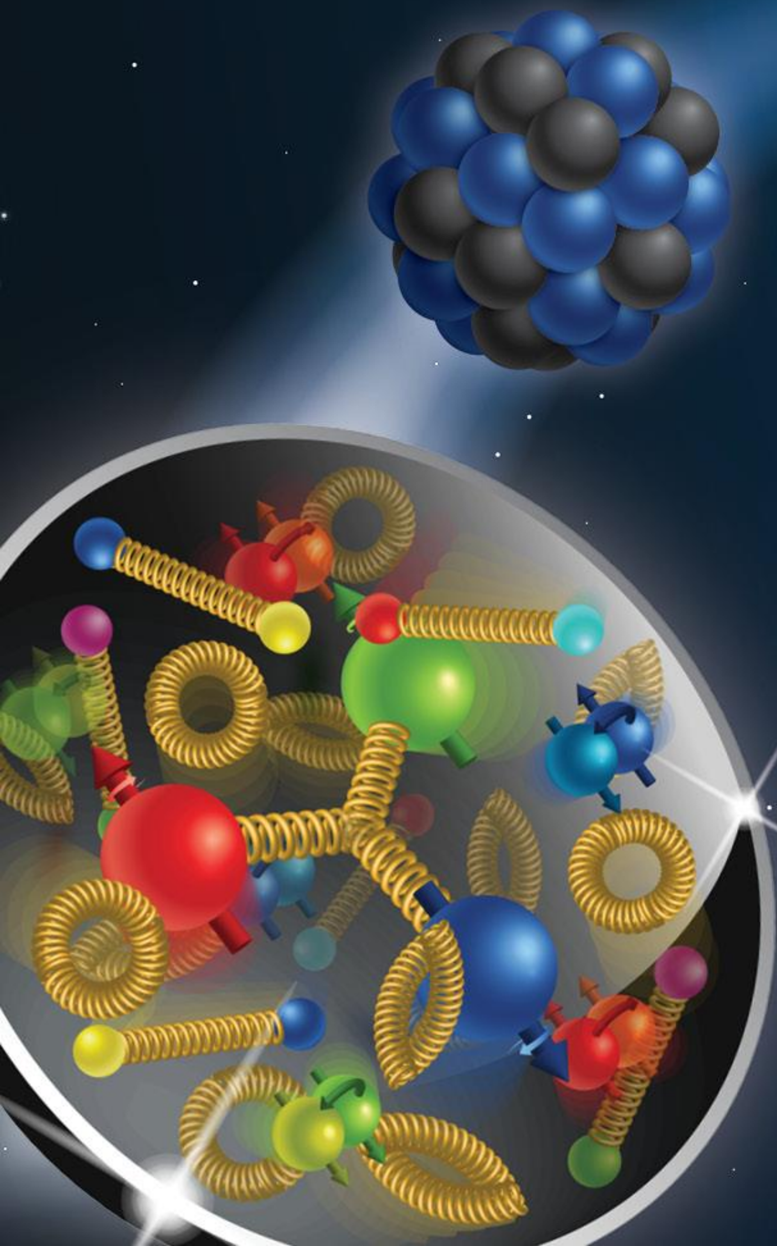

Progress of Polarization Studies for eRHIC

Nuclear Physics Accelerator R&D

PI Meeting

Vahid Ranjbar, BNL

November 13-14, 2018

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Contributors at BNL

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- Mike Blaskiewicz
- Christoph Montag

Progress of Polarization Studies for eRHIC

Funding Source	PI	R&D Report Priority #	R&D Panel Priority Rating	Total $
FY17 Base	Michael Blaskiewicz	4, 12, 31	Hi-A, B, B-	$517K
FY17 Additional	Michael Blaskiewicz	4, 12, 31	Hi-A, B, B-	$42K

<u>Lines from Jones Panel Report</u>

- 4 – “Benchmarking of realistic EIC simulation tools against available data”
- 12 – “Complete design of an electron lattice with a good dynamic aperture and a synchronization scheme and complete a comprehensive instability threshold study for this design”
- 31 – “Study of Electron Spin Polarization in the Storage Ring”

Used part of Base Funding and all of additional Funding for polarization related studies

Outline

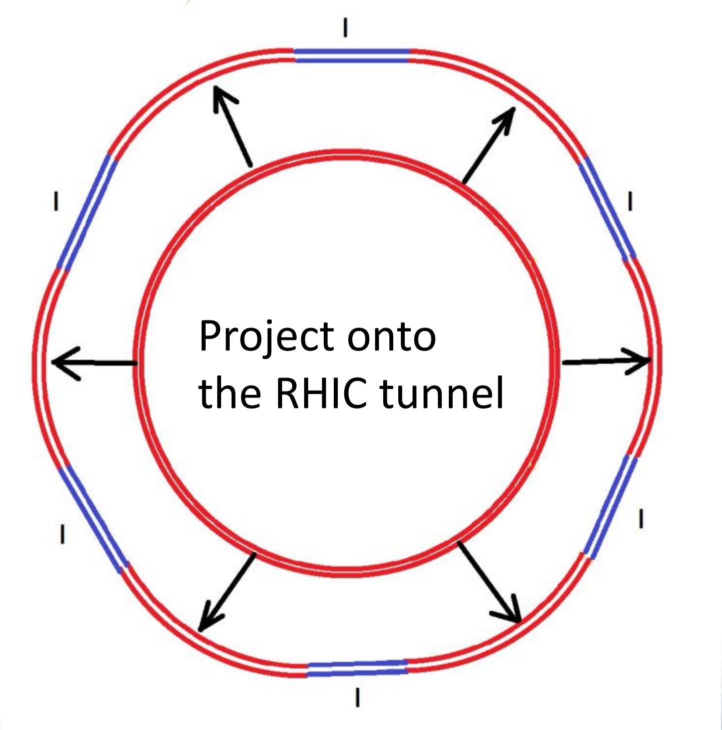
- eRHIC Electron Polarization Studies
  - RCS Injector
    - Concept Overview
    - Polarization Performance
  - Storage Ring Spin Matching
    - Spin Rotation Scheme
    - Spin Matching
- eRHIC Hadron Polarization Studies
  - Protons
  - $^{3}He^{+2}$
  - Deuterium
- Summary of Costs

Concept Overview: Spin Resonance Free Lattice

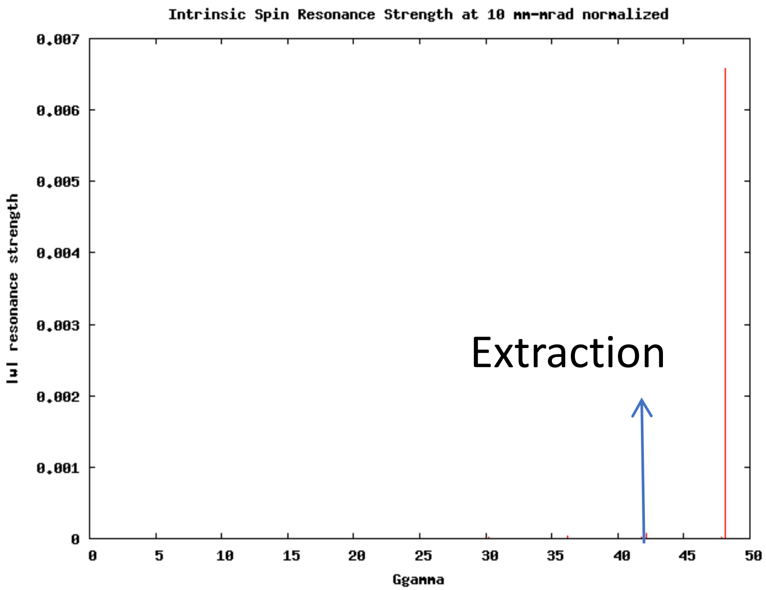
- Both the strong intrinsic and imperfection resonances occur at:
  - K = nP +/- Qy
  - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\gamma < 41$.**
- If we use a periodicity of P=96 and a tune with an integer value of 50 then our first two intrinsic resonances will occur outside of the range of our spin tunes
  - K1 = 50+v_y (v_y is the fractional part of the tune)
  - K2 = 96 – (50+v_y) =46-v_y
  - Also our imperfection will follow suit with the first major one occurring at K2 = 96 – 50 = 46

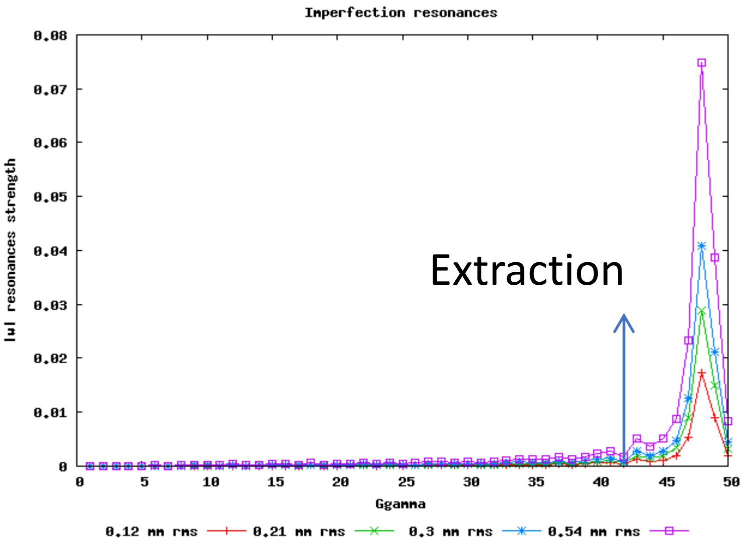
How to Make This Work in the RHIC Tunnel?

- It is easy to accomplish this with a perfectly circular ring. Just construct a series of FODO cells with bending magnets so that we have total periodicity of 96.
- The problem is that the RHIC tunnel is not circular and has an inherent six-fold symmetry.
- Solution: make the spin resonance integrals over the straight sections equal to zero.



Calculating Spin Resonances





- No polarization loss from cumulative effectc of intrinsic spin resonances for distributions with RMS normalized emittance > 1000 mm-rad (100 msec ramp rate)
- At 200 mm-mrad RMS normalized emittance, we can tolerate beyond 2% field errors and still maintain above 95% polarization transmission
- Issue to control: Imperfection spin resonances. Need vertical RMS orbit of ~0.5 mm to keep losses < 5% (verified by Zgoubi multiparticle tracking with N=10000 macroparticles)

Studies with SVD Orbit Correction: Quadrupole Misalignments

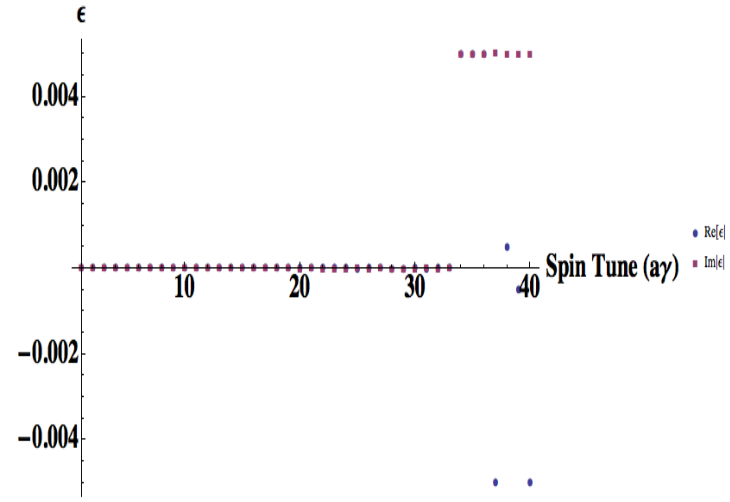
Polarization transmission to 18 GeV for random gaussian quadrupole misalignments with SVD orbit correction for 4 different random seeds.

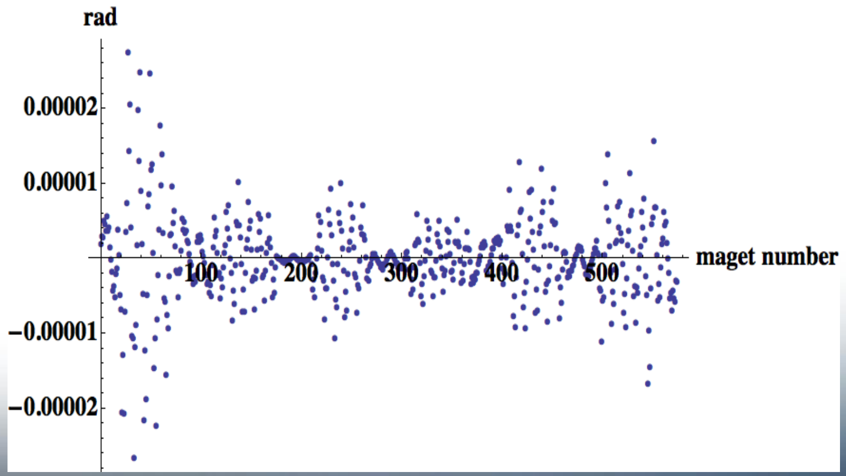
* indicates tests with BPM misalignments of 0.2 mm RMS

rms quad misalignment	random seed	100 msec transmission [%]	200 msec transmission [%]
0.4	100000	97	95
0.4	12001	99	98.2
0.4	1200	99	98.7
0.4	120033	99.0	99.0
0.3	100000	99	98.
0.3	12001	99	98
0.3	1200	99	97.5
0.3	120033	99	98.6
0.2*	100000	99	99
0.2	12001	99	99
0.2	1200	99	99
0.2*	120033	99	98

Orthogonal Imperfection Bump

- **Static imperfection** bumps at any imperfection resonance location on the ramp.
- **Bumps are orthogonal** to each other and localized in energy space → no bandwidth required beyond what is needed to ramp the dipoles with the energy.
- **Example on right**: Shows a 10 to 15% (0.005 res.) Depolarization Kick per crossing for both the Imaginary and Real parts. No kicks anywhere else.





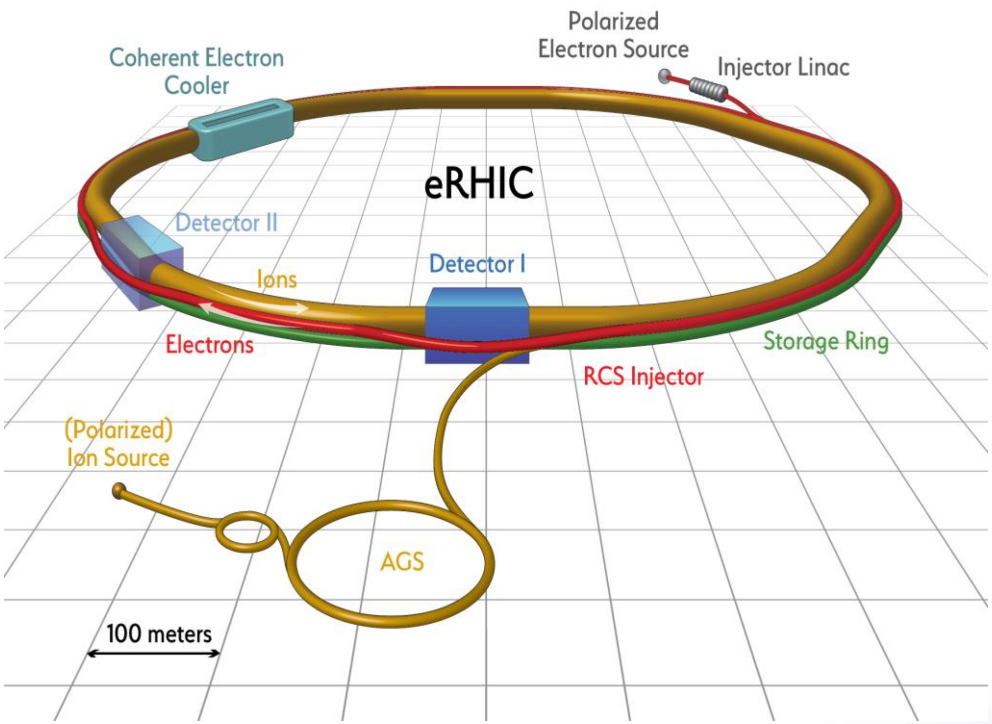
RCS Performance: Summary

- Resonances in this lattice are driven by imperfections
- Intrinsic resonances are so weak that even large field distortions don't hurt
- Resilient to misalignments, dipole rolls and orbit distortions:
  - Up to 0.4 mm quadrupole misalignments and 2.5 mrad dipole rolls are tolerable provided the orbit is corrected to 0.5 mm RMS level
  - Assume orbit correction using SVD algorithm with a corrector and a BPM next to each quadrupole
  - within state-of-the art orbit control hardware and software
- This will result in > 95% polarization transmission
- To provide additional margin we show that fixed orthogonal imperfection bumps are capable of removing any residual polarization losses

Thanks: V. Ptitysn

Spin Matching for Rotators in the Electron Storage Ring

- Depolarization in the storage ring dominated by Sokolov-Ternov and spin diffusion processes.
  - Goal: reduce spin diffusion effects and limit losses to only Sokolov-Ternov lifetime.
- Spin rotators are used around IP(s) for longitudinal polarization. These can introduce additional spin diffusion effects



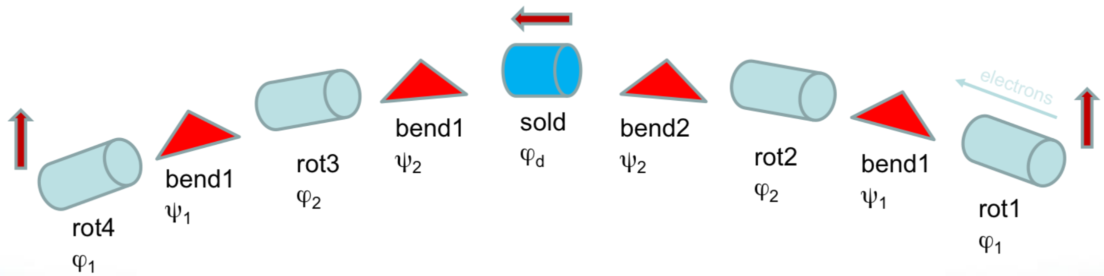
Thanks: V. Ptitysn

Design of Spin Rotators for eRHIC

- Electron energy range: 5 to 18 GeV
- Must use solenoid-based rotators
  - A HERA-type rotator (based on sequence of vertical and horizontal bends) cannot be used since it creates meter scale orbit excursion at lower energies.
  - Using a combination of solenoids and horizontal bending magnets, the rotator design works at all energies.

eRHIC spin rotator

C-type bending configuration

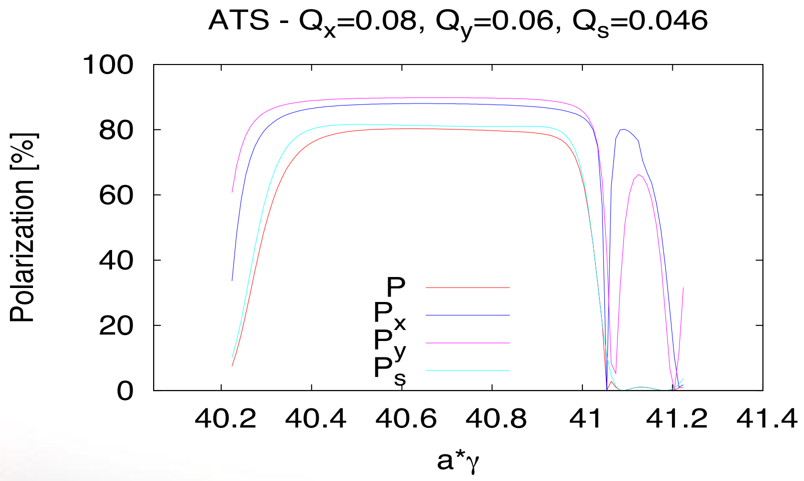


φ_j – spin rotation angle in solenoids

ψ_i – spin rotation angle in bends

First-Order Spin Resonances due to Spin Rotators

- Even without misalignment and magnet errors the spin rotators create a pattern of depolarizing resonances. Spin matching is required to minimize depolarization.

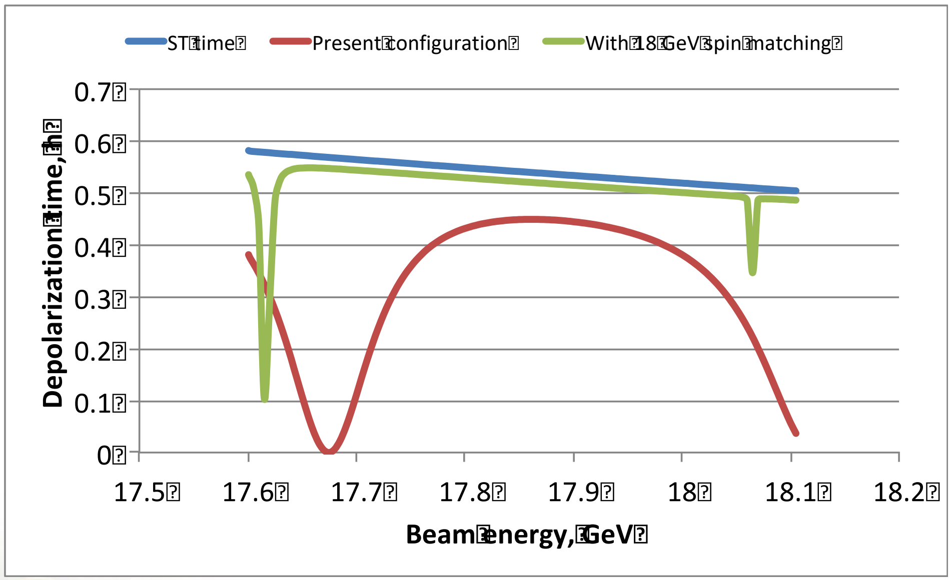


eRHIC first-order calculation near 18 GeV. No longitudinal matching of spin rotators, and imperfect betatron spin matching. (thanks E.Gianfelice-Wendt).

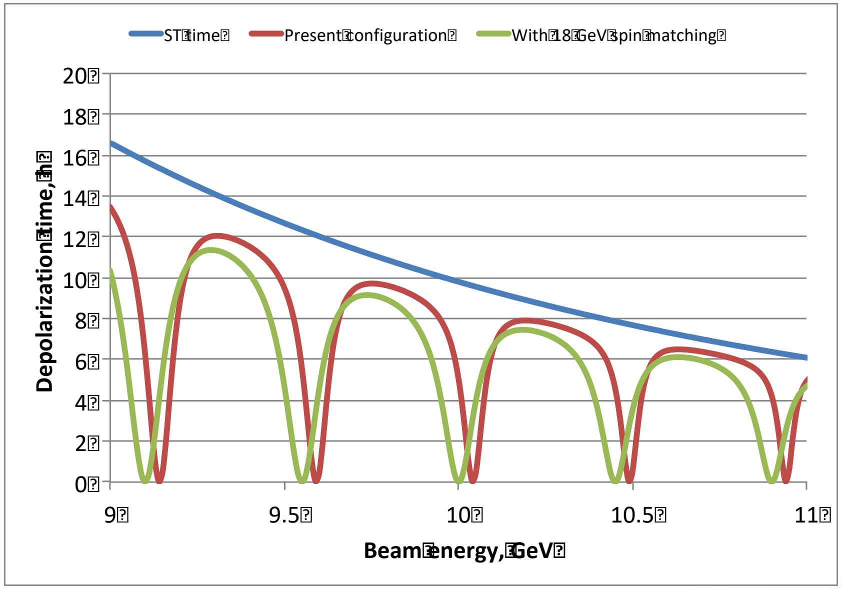
Thanks: V. Ptitysn

eRHIC Depolarization Time

At high energies in eRHIC spin matching provides considerable improvement of the depolarization time.



At lower energies spin matching, optimized for 18 GeV, is not effective. However, depolarization time is very large anyway.



Note: since synchrotron motion is not included, there is no split into first-order sidebands on the plots.

Thanks: V. Ptitysn

Storage Ring Spin Matching: Summary

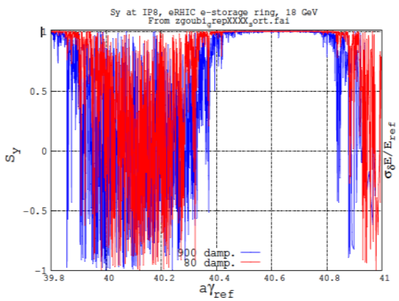
- To maximize the depolarization time the spin rotator insertions need spin matching.
- The conditions for spin matching of rotators based on a sequence of solenoids and bending magnets have been derived from spin-orbital integrals.
- Betatron related spin-matching can be done by using a special transport matrix of solenoidal insertions.
- eRHIC rotator parameters providing longitudinal spin matching would improve the depolarization time at higher energies. However, this still needs to be verified beyond first-order with 6D spin simulations (time consuming).

Accelerating Studies of Depolarization Time: Ergodic Sampling

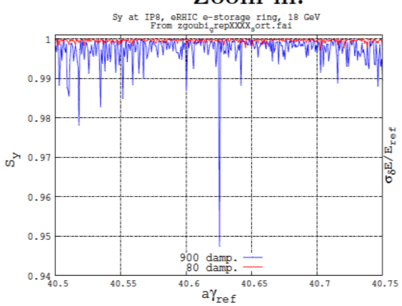
Thanks: F. Meot

- Track a single particle per bin
  - ◇ 1 bin is 1 ring, set for a specific rigidity (here, "$a\gamma_{ref}$")
  - ◇ about 1000 rings (bins) here

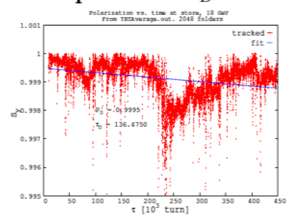
Spins at 80 and $900\times\tau_{SR}$

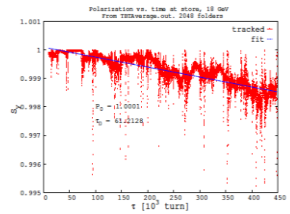


Zoom-in:

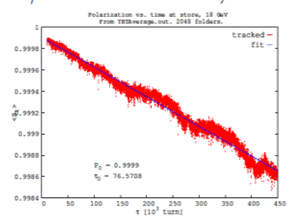


- Monitor individual spins: A linear regression on $P/P_0 = \exp(-t/\tau_D) \approx 1 - t/\tau_D$ provides τ_D.





- Possibly, average over reduced $a\Delta\gamma_{ref}$ interval, *i.e.*, a few rings/bins ($\Delta\gamma$: 40.60 – 40.62, here):



- Faster computation allows easier exploration of parameter space in design optimizations.
- It remains to determine how close the single-particle method can get to the accuracy of the 1000-particle bunch method (an ongoing work).

eRHIC Hadron Polarization Studies

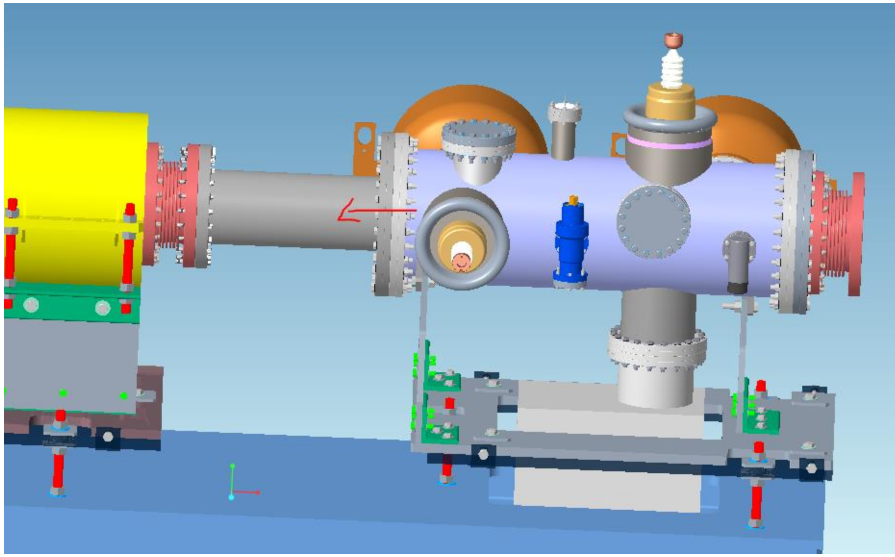
Thanks: H. Huang

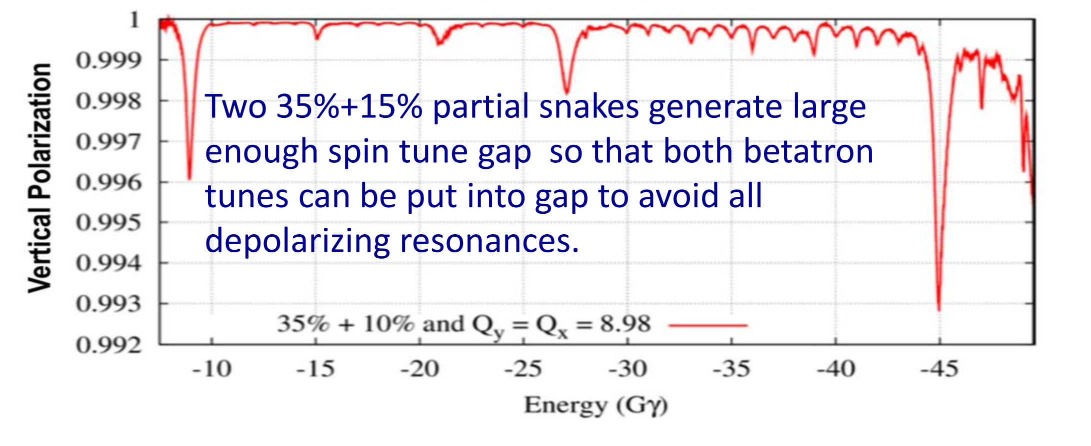
- Injector Studies:
  - An AC dipole will be added in the Booster to overcome two intrinsic resonances for polarized $^3He^{+2}$ so that the AGS injection energy can be increased and the effect of the stronger AGS cold snake on orbit excursion can be mitigated.
  - The partial AGS snake strengths are set as 35% (cold) and 15%(warm) with both vertical and horizontal betatron tunes inside the spin tune gap.
- RHIC Studies:
  - 6 snakes are needed for polarized $^3He^{+2}$ beam in eRHIC. These will also improve polarization transmission for protons.
  - Simulations show that polarization can be preserved beyond 275GeV for protons, and at least up to 170GeV/u for 3He (crossing of the strong resonance at E~170GeV/u requires simulations).
  - Polarized deuterons: Partial Snake and Spin Tune Jump

Thanks: H. Huang

Polarized $^3He^{+2}$ in the Injectors

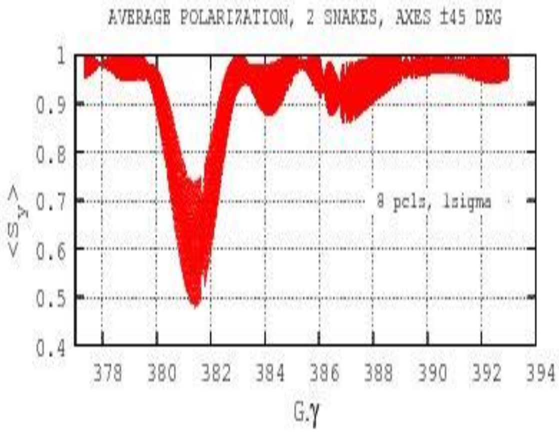
- An AC dipole will be installed in the Booster to overcome the few intrinsic resonances. This opens doors to raise the injection energy in the AGS.→ PoP experiment next pp AGS run (PhD thesis topic since 2016).
- The polarized 3He+2 source will be ready by 2020.
- The test of polarized 3He+2 acceleration in the injectors will follow after that.



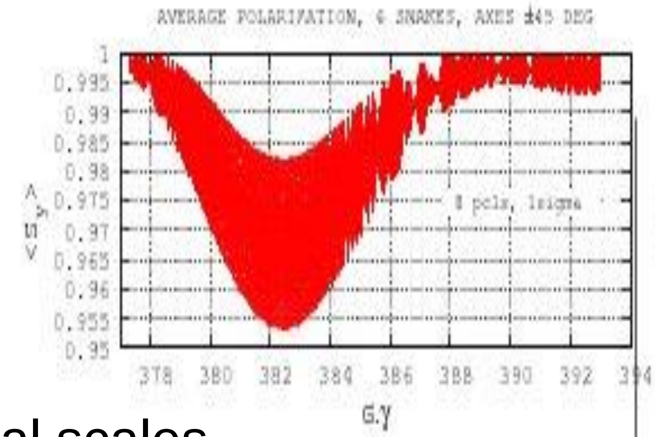


Thanks: H. Huang

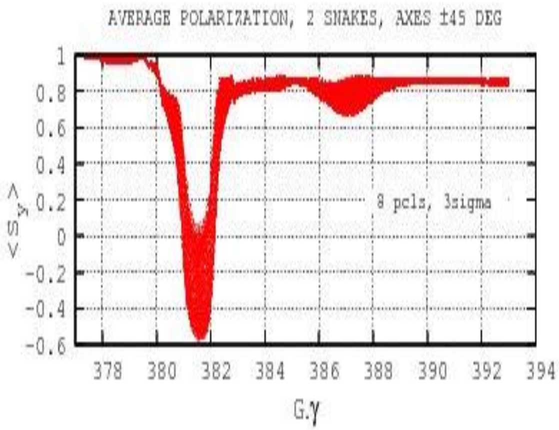
2-Snake (Left) vs. 6-Snake(Right)



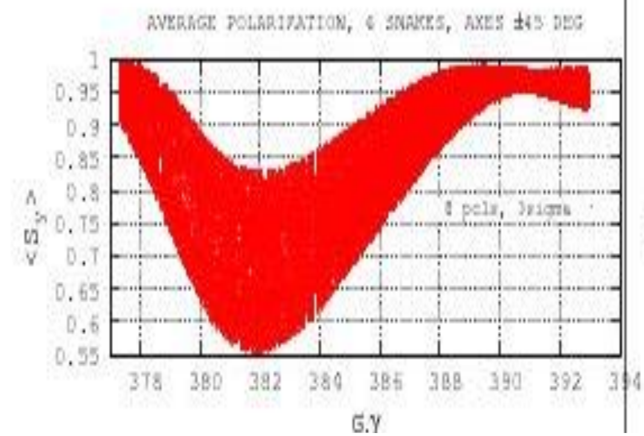
1σ



Note different vertical scales.



3σ



ZGOUBI tracking for particles with σ=2.5π crossing one of three strongest intrinsic resonances: 411-Q_y.

Thanks: H. Huang

Simulations for Polarized $^3He^{+2}$

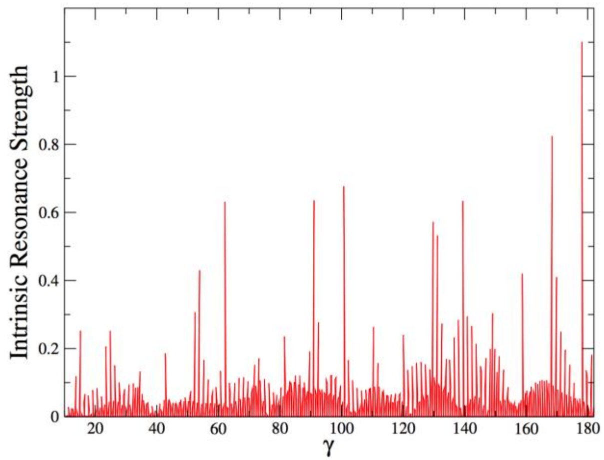


Figure 5.25: The intrinsic depolarizing resonance strengths for ^{3}He as a function of the Lorentz factor γ for a particle on the 10 μm emittance ellipse

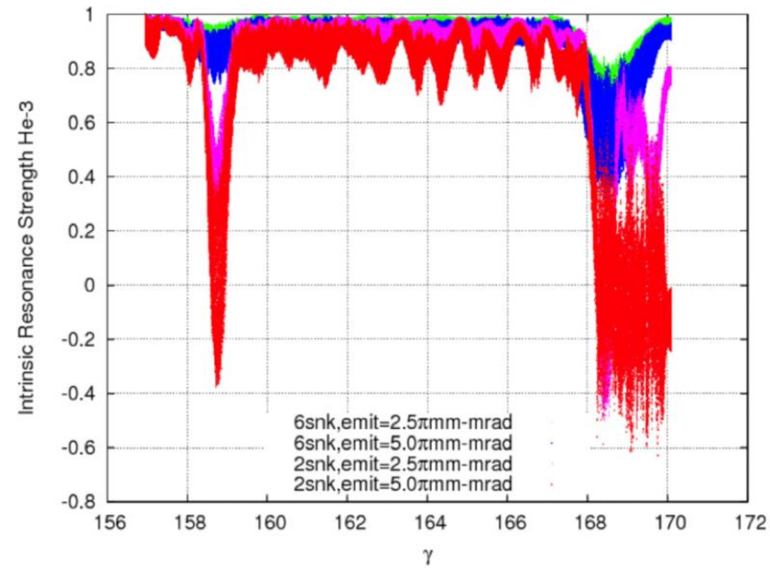


Figure 5.27: Zgoubi simulation results with various snake combinations and beam emittances for intrinsic resonances at $G\gamma = -636 - Q$ ($\gamma \approx 159$) and $G\gamma = -735 + Q$ ($\gamma \approx 169$)

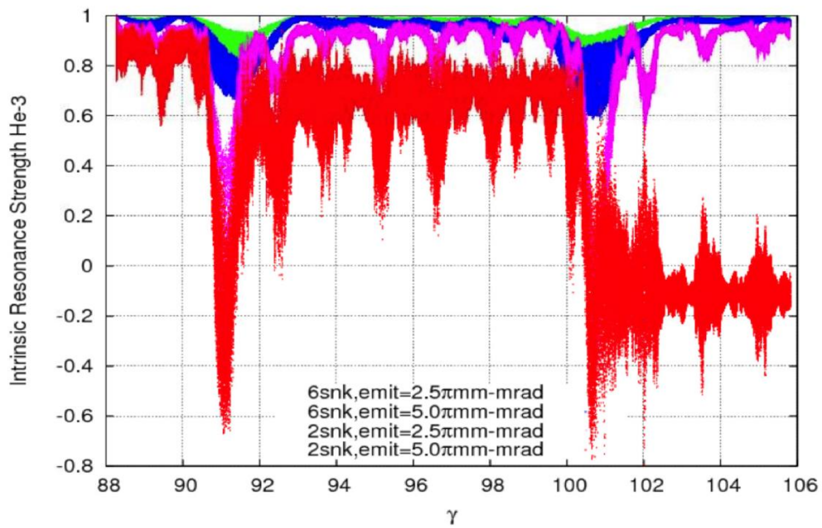
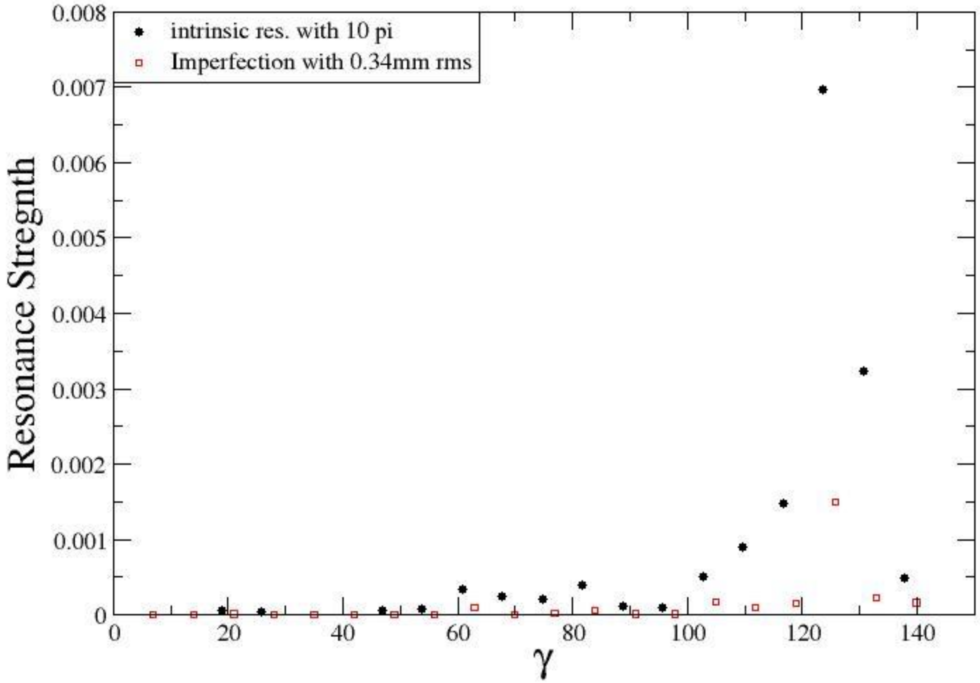


Figure 5.26: Zgoubi simulation results with various snake combinations and beam emittances for intrinsic resonances at $G\gamma = -411 + Q$ ($\gamma \approx 91$) and $G\gamma = -393 - Q$ ($\gamma \approx 101$)

The simulation to cross last strong intrinsic resonance remains to be done.

Thanks: H. Huang

Resonance Strength for Deuterons in Hadron Ring (DEPOL)

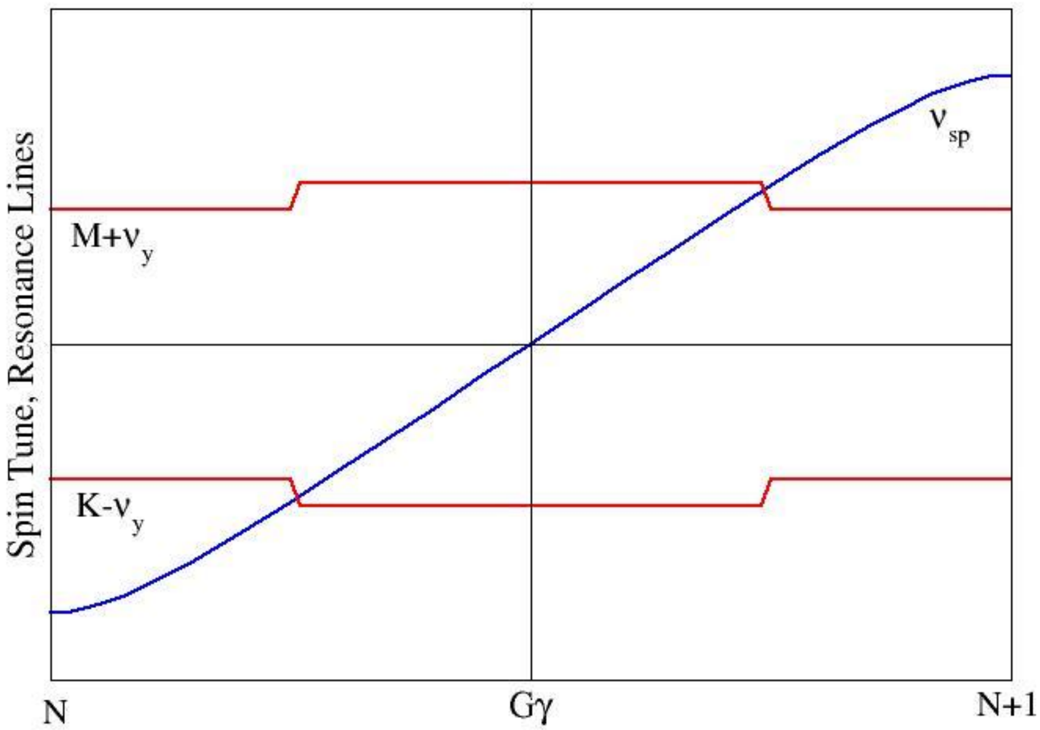


- **Gγ range from -1.6 to -20.9**
- **From the d-Au run in 2016, the expected RMS emittance of deuteron beams will be less than 2π. The RMS orbit error can be corrected to under 0.3mm.**

- We will cross 19 imperfection resonances. With RMS orbit error of 0.3mm, the strongest resonance strength is less than 0.0015. From the nominal ramp rate in RHIC d-Au run, the ramp rate is about $d\gamma/dt=90/220s$=>resonance crossing rate is $\alpha=1.2E-7$.
- A partial snake can be used to overcome these resonances. The required partial snake snake strength is 0.22%. The existing snake is not strong enough. Adding a solenoid is a solution. 15Tm warm solenoid (0.22% partial snake) should work. AGS Solenoid: 4.7Tm and 2.4m long. Alternatively, it may be feasible to use existing rotators as partial snakes.

Modest Vertical Tune Jump

Thanks: H. Huang



For an isolated resonance,

$$P_f = P_0\left(2e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1\right)$$

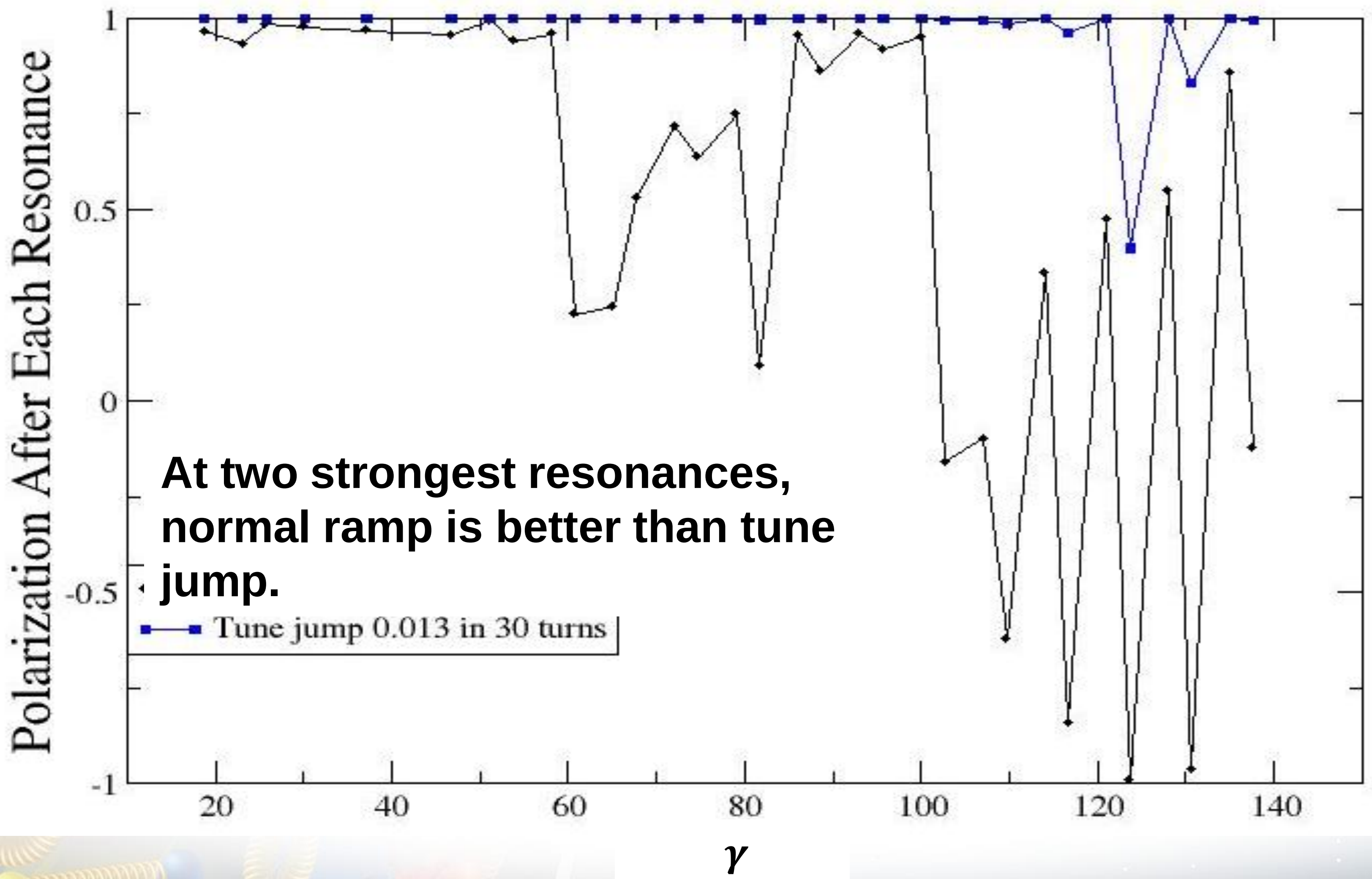
And resonance crossing rate is given by:

$$\alpha = \frac{dG\gamma}{d\theta} + - \frac{d\nu}{d\theta}$$

AGS tune jump system ramps n_x by 0.04 in 100 ms. If we use a similar PS at an 11 times larger rigidity in the hadron ring, the expected tune change would be 0.04 in 1140μs or 0.013 in 380μs (30 turns). The resonance crossing speed would be 7E-5, which is 600 times faster than the regular ramp rate in RHIC. One possibility is to use existing γ_{tr} quads.

Polarization After Each Resonance

Thanks: H. Huang



At two strongest resonances, normal ramp is better than tune jump.

Summary of Costs

Lab Base R&D	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	Totals
a) Funds allocated				516,927	516,927
b) Actual costs to date				516,927	516,927

We used our base funds first and are starting to use the supplemental funds.

	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	Totals
a) Funds allocated				42,000	42,000
b) Actual costs to date				0	0

Activity	Start Date	End Date
Beam Dynamics Study	May 1, 2016	September 30, 2018
Design Choice Validation Review	April 6, 2017	April 7, 2017

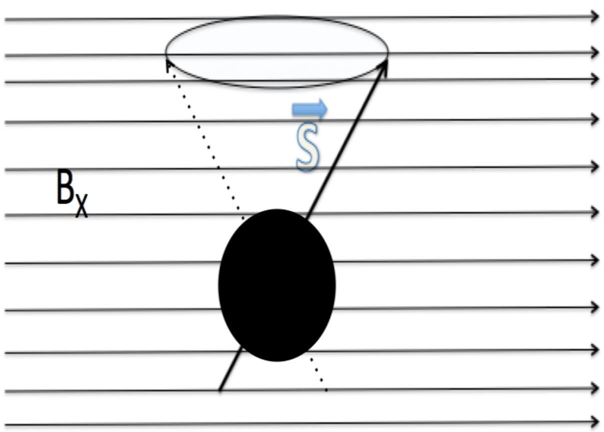
✓
✓

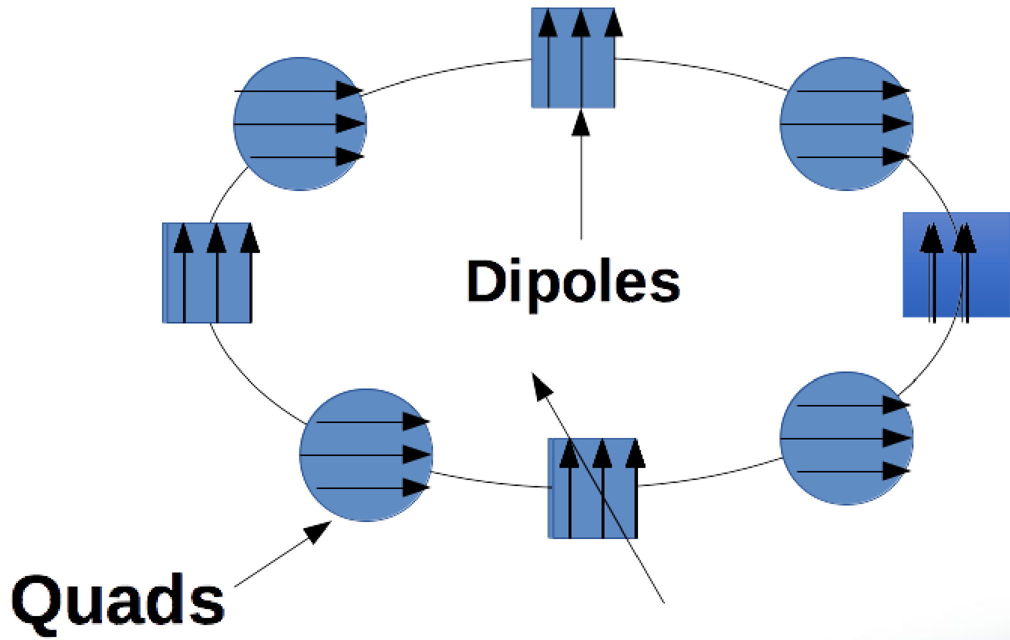
Backup Slides

Spin Resonance Review

Spinor Form

T-BMT Equation: $$\frac{d\vec{S}}{dt} = \frac{q}{\gamma m}\vec{S} \times \left((1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right) \longrightarrow \frac{d\Psi}{d\theta} = -\frac{i}{2}\begin{pmatrix} f_3 & -\xi \\ \xi^* & -f_3 \end{pmatrix}\Psi.$$





Spin Resonance: Spin Tune = Rate of Horizontal field kicks
(vertical motion through Quads)

$G\gamma$ = N +/- Qz Intrinsic or **$G\gamma$ = N** Imperfection
Due to vertical betatron Due to vertical closed orbit error

Polarization Evolution

Synchrotron radiation determines the polarization evolution through Sokolov-Ternov spin-flip emission and spin diffusion caused by quantum emission of S photons. Both processes combined define the equilibrium polarization P_{eq} and polarization relaxation time t.

$$P(t) = (P_0 - P_{eq})\,e^{-t/\tau} + P_{eq}$$

Derbenev-Kondratenko: (1973)

$$P_{eq} = -\frac{8}{5\sqrt{3}}\frac{\alpha_-}{\alpha_+}$$

$$\tau^{-1} = \frac{5\sqrt{3}}{8}\frac{\hbar r_0}{m}\gamma^5 \alpha_+$$

$$\alpha_- = \left\langle \oint \frac{d\theta}{|\rho|^3}\,\hat{\boldsymbol{b}}(\boldsymbol{n}-\boldsymbol{d}) \right\rangle$$

$$\alpha_+ = \left\langle \oint \frac{d\theta}{|\rho|^3}\left[1 - \frac{2}{9}(\boldsymbol{n}\hat{\boldsymbol{v}})^2 + \frac{11}{18}|\boldsymbol{d}|^2\right] \right\rangle$$

Depolarization caused by spin diffusion is defined by a derivative of invariant spin field over $d = \frac{\Delta E}{E} = \frac{\Delta g}{g}$:

$$\boldsymbol{d} = \gamma \frac{\partial \boldsymbol{n}}{\partial \gamma}$$ (taken at const x, x′, y, y′)

$$\left(\frac{\partial \mathbf{n}}{\partial d}\right)_{A_x, A_y} \qquad \frac{\partial \mathbf{n}}{\partial A_x}$$

Derivation of Spin Matching Conditions

Spin matched spin rotator system:

the spin invariant field (alpha_0) dependence on horizontal betatron amplitude A_x and energy deviation δ is not allowed outside the rotator system.

$\longrightarrow$ $\partial n / \partial \delta = 0 \quad \partial n / \partial A_x = 0$

Thus avoiding any spin dynamics distortion by synchrotron radiation in the arc bends.

The following integral over the whole spin rotator system must be made 0 for terms proportional to A_x and δ:

$$\int_{s_{in}}^{s_{out}} \left(w_x k_{0x} + w_s k_{0s} + w_y k_{0y} \right) ds = 0$$

The orbital motion is considered in a standard form through components of betatron motion eigen-vectors f_I *and* f_{II} and dispersion functions D_x, D_y:

$$x = f_{Ix} A_x + f_{Ix}^* A_x^* + f_{IIx} A_y + f_{IIx}^* A_y^* + D_x \delta$$

$$y = f_{Iy} A_x + f_{Ix}^* A_x^* + f_{IIy} A_y + f_{IIy}^* A_y^* + D_y \delta$$

Spin Matching Conditions for Solenoidal Rotators

We assume the following reasonable optics conditions:

- Betatron coupling is fully compensated individually for each of the four solenoidal insertions by dividing each solenoid in two parts and using sets of quadrupoles/skew quadrupoles between and around them
- The vertical dispersion function D_y does not leak into the horizontal bends

Then, using integration by parts one gets the following set of spin matching conditions:

$$\sum_{rot: j=1,4} H_j\left(f_I\right) = 0; \quad \sum_{rot: j=1,4} H_j\left(f_I^*\right) = 0;$$

Betatron matching conditions

$$a\gamma \sum_{rot: j=1,4} H_j\left(D\right) + \sum_{rot: j=1,4} \varphi_j k_{sj} - \sum_{bends: i=1,4} \psi_j k_{yi} = 0$$

Longitudinal matching condition

where:

$$H_j\left(F\right) = \frac{\varphi_j}{2}\left[\left(k_x\left(F_x' + \frac{K_s}{2}F_y\right) + k_y\left(F_y' - \frac{K_s}{2}F_x\right)\right)_{j,entrance} + \left(k_x\left(F_x' + \frac{K_s}{2}F_y\right) + k_y\left(F_y' - \frac{K_s}{2}F_x\right)\right)_{j,exit}\right]$$

F is either f_I or *D*

Longitudinal Spin Matching

$$a\gamma \sum_{rot:j=1,4} H_j(D) + \sum_{rot:j=1,4} \varphi_j \kappa_{sj} - \sum_{bends:i=1,4} \psi_j \kappa_{yi} = 0$$

This term can be nullified either by forcing dispersion function to be zero in solenoids or by proper optics

This combination is completely defined by the choice of bending angles of the rotator dipoles and solenoidal fields.

For JLEIC S-type bending configuration and spin-up to spin-up transformation through the whole rotator system, this is automatically zero.

For eRHIC C-type bending configuration this can be nullified at a particular energy with the following choice of rotator parameters:

$\varphi_1 = \varphi_4 = 0.524$ rad, $\varphi_2 = \varphi_3 = 2.094$ rad

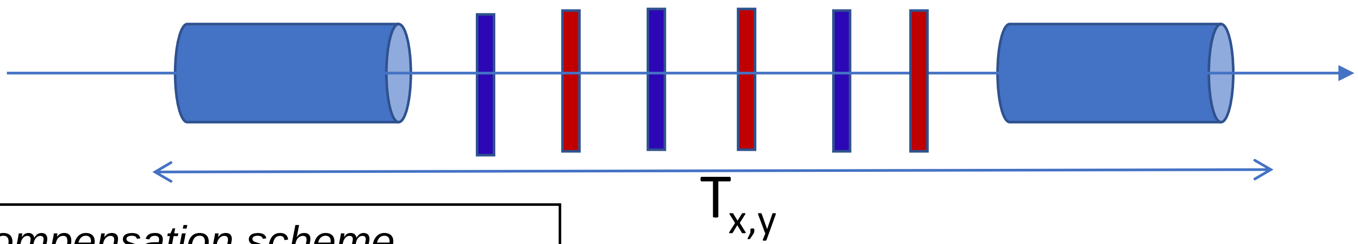
$\psi_1 = \psi_4 = \pi$ rad, $\psi_2 = \psi_3 = \pi/2$ rad

It makes sense to fully match the rotators at eRHIC highest energy, 18 GeV.

Solenoidal Insertion with Betatron Spin Matching

Spin matching conditions related with betatron motion can be satisfied for each individual solenoidal insertion, using two solenoid halves and (at least) 6 quadrupoles between them.

For each j : $H_j(f_I) = 0 \quad \text{and} \quad H_j(f_I^*) = 0$



Coupling compensation scheme by A. Zholents and V. Litvinenko (1984)

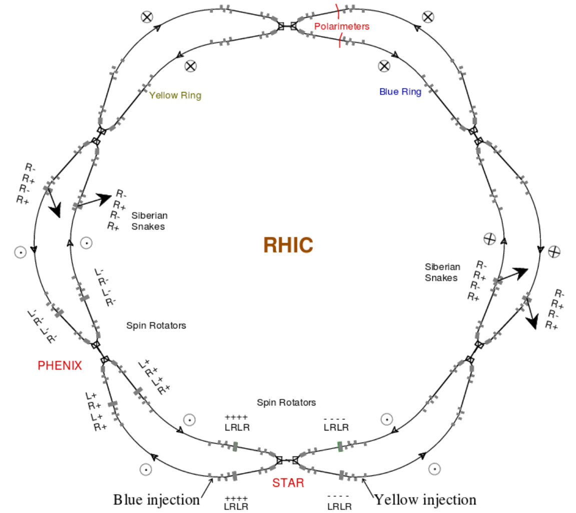
For a betatron spin-matched and fully decoupled solenoidal insertion the horizontal and vertical transport matrices must have the following forms:

$$T_X = \begin{pmatrix} -\cos(\varphi) & -\frac{2}{K_s}\sin(\varphi) \\ \frac{K_s}{2}\sin(\varphi) & -\cos(\varphi) \end{pmatrix}; \quad T_Y = -T_X = \begin{pmatrix} \cos(\varphi) & \frac{2}{K_s}\sin(\varphi) \\ -\frac{K_s}{2}\sin(\varphi) & \cos(\varphi) \end{pmatrix}$$

$$K_s = \frac{B_s}{B\rho} \qquad \varphi = (1+a)K_s$$

Using Spin Rotators as Partial Snakes

As an alternative to strong solenoidal snakes (see slide 21), it may be feasible to use spin rotators around an IR as partial snake. In this case, the spin is naturally longitudinal at Gγ=int. At the other IR π/3 away, spin will be longitudinal at Gγ=3*int.



$\theta=0$ at 1st IR, $\theta=10\pi/6$ at 2nd IR

Stable spin direction for a partial snake with longitudinal rotating axis is:

Vertical

$$\cos\alpha_3 = \frac{1}{\sin\pi\nu_s}\sin(\pi G\gamma)\cos\left(\frac{S}{2}\right),$$

Horizontal

$$\cos\alpha_1 = -\frac{1}{\sin\pi\nu_s}\sin G\gamma(\pi-\theta)\sin\left(\frac{S}{2}\right),$$

Longitudinal

$$\cos\alpha_2 = \frac{1}{\sin\pi\nu_s}\cos G\gamma(\pi-\theta)\sin\left(\frac{S}{2}\right).$$