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U.S. DEPARTMENT of ENERGY

Polarization status at the Electron Ion Collider

Kiel Hock

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Overview

Introduction

Electron Polarization

- Polarization in the Rapid Cycling Synchrotron
- Polarization in the Electron Storage Ring

Hadron Polarization

- Polarization in the Alternating Gradient Synchrotron
- Polarization in the Hadron Storage Ring

Summary

Introduction

The Electron Ion Collider

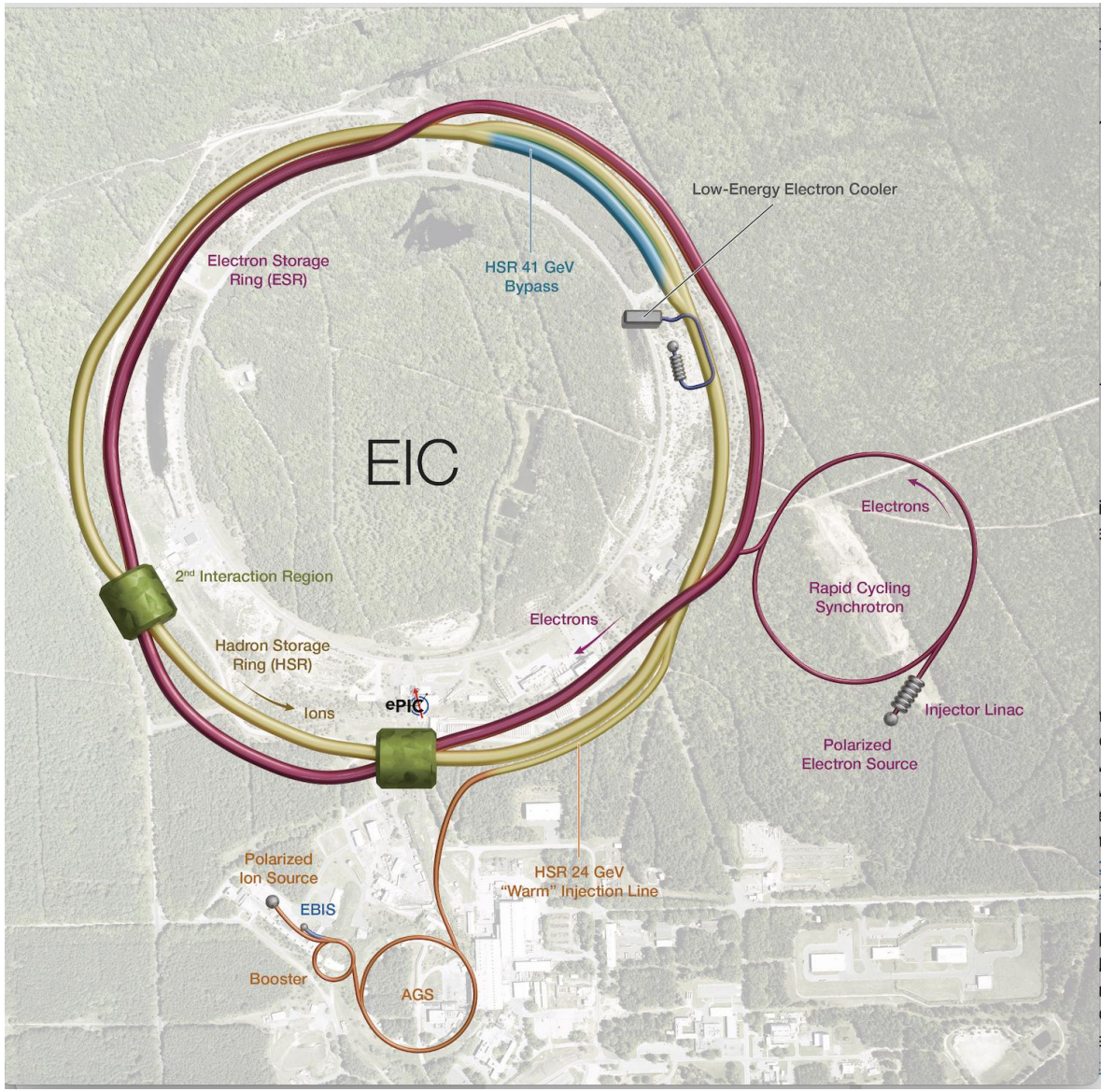
The Electron Ion Collider will be the first polarized electron-hadron (proton and light ion) collider.

The EIC will be built at the existing RHIC accelerator complex

- Hadrons will use the existing infrastructure (ion sources, Booster and Alternating Gradient Synchrotron(AGS)).
- The new polarized electron source and the Rapid Cycling Synchrotron (RCS) will be external, and the Electron Storage Ring (ESR) will be installed inside the existing RHIC tunnel.

Convergence to a final design

- The Rapid Cycling synchrotron has been moved outside of the existing RHIC tunnel.
- The Hadron storage ring (HSR) now consists of only the yellow RHIC ring
  - Except for the 41 GeV bypass, an inner blue arc to match revolution frequencies of electrons and hadrons at low energy.



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Spin Dynamics

The motion of a particles spin, $\vec{S}$, is given by the Thomas-BMT equation (neglecting effects from $\vec{E}$)

$$\frac{d\vec{S}}{dt} = \frac{q}{\gamma m}\,\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right]$$

- When the spin precession in the dipoles is in phase with the particle's sampling of the horizontal fields of a quadrupole, a resonance condition exists. These occur at:
  - $G\gamma = nP \pm \nu_y$, intrinsic resonance from vertical betatron motion
  - $G\gamma = n$, imperfection resonance due to vertical closed orbit
- The spacing between these resonances per unit change in energy is mc^2/G

	G	mc^2/G (GeV)	Energy range (source to storage)	$\lvert G\gamma \rvert$ range
Electron	1.15965×10^{-3}	0.441	750 MeV→18 GeV	1.7→41
Proton	1.79285	0.523	200 MeV→275 GeV	2.2→525
Helion	-4.18415	0.671	2 MeV/u→183 GeV/u	4.2→820

Electron Polarization

- Electron polarization overview
- RCS polarization
- ESR polarization

Electron Polarization Overview

V. Ranjbar

Pre-injector: Front End → delivers up 1 nC of bunch charge with 88% polarization

- Source already exists need to build buncher and transport line to LINAC

Pre-injector: S-Band LINAC → accelerates 1 bunch to 750 MeV

- Capable of being cycled up to 28 times per acceleration cycle (30Hz):

BAR (Beam Accumulator Ring)→ to achieve 28 nC/bunch in the RCS we will use an accumulator ring

RCS will accelerate from 750 MeV to 5 and 10 GeV energy delivering one bunch of 7 nC every second. This will fill ESR in under 20 mins.

Path to 18 GeV :

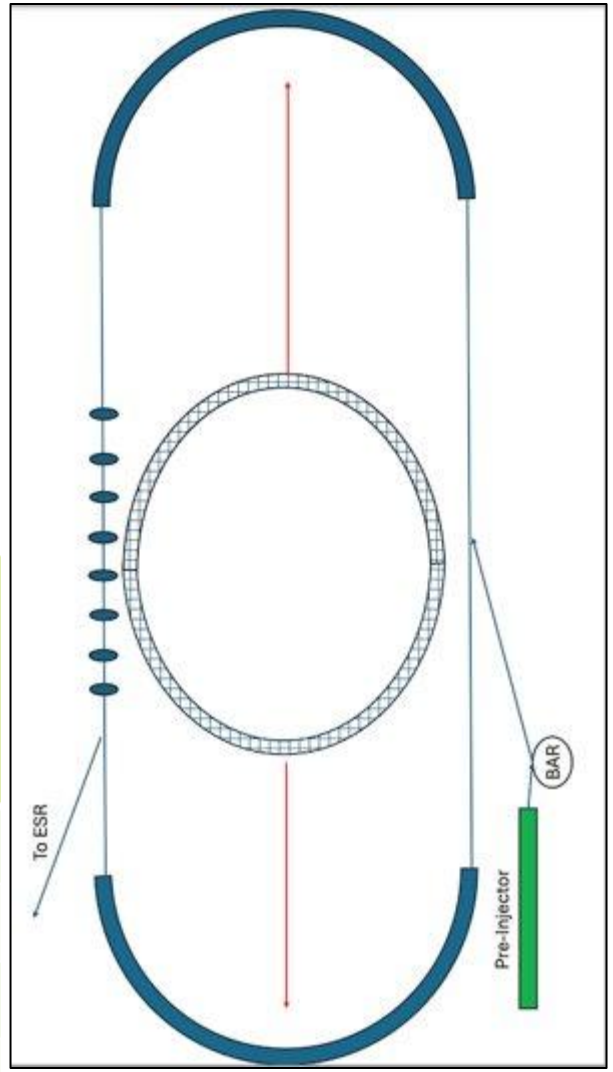
6 additional RF installation

RCS Polarization

V. Ranjbar

The RCS will accelerate from the pre-injector (750 MeV) up to the top storage energy of the ESR (18 GeV)

- Long straight section supports up to 130 MV of RF with vertical spin phase advance of 4π.
- To avoid any strong depolarizing resonances, the periodicity is pushed to P=160 with ν_y =58.
- A 100 ms ramp to 18 GeV, and a vertical RMS orbit of 0.4 mm supports polarization of 85% for the ESR, assuming 88% from source.



Avg. Orbit RMS (mm)	Avg. Max Orbit (mm)	Pol. at 5 GeV (%)	Pol. at 10 GeV (%)	Pol. Eff. to 18 GeV (%)	Pol. at 18 GeV (%)
0.423	1.22	87	87	96.7	85
0.635	1.83	87	87	92.8	81.6
0.848	2.44	87	87	87.7	77.2
1.277	3.68	87	87	74.4	65.4

See V. Ranjbar et al. “Spin resonance free electron ring injector” PRAB, 2018.

ESR Polarization

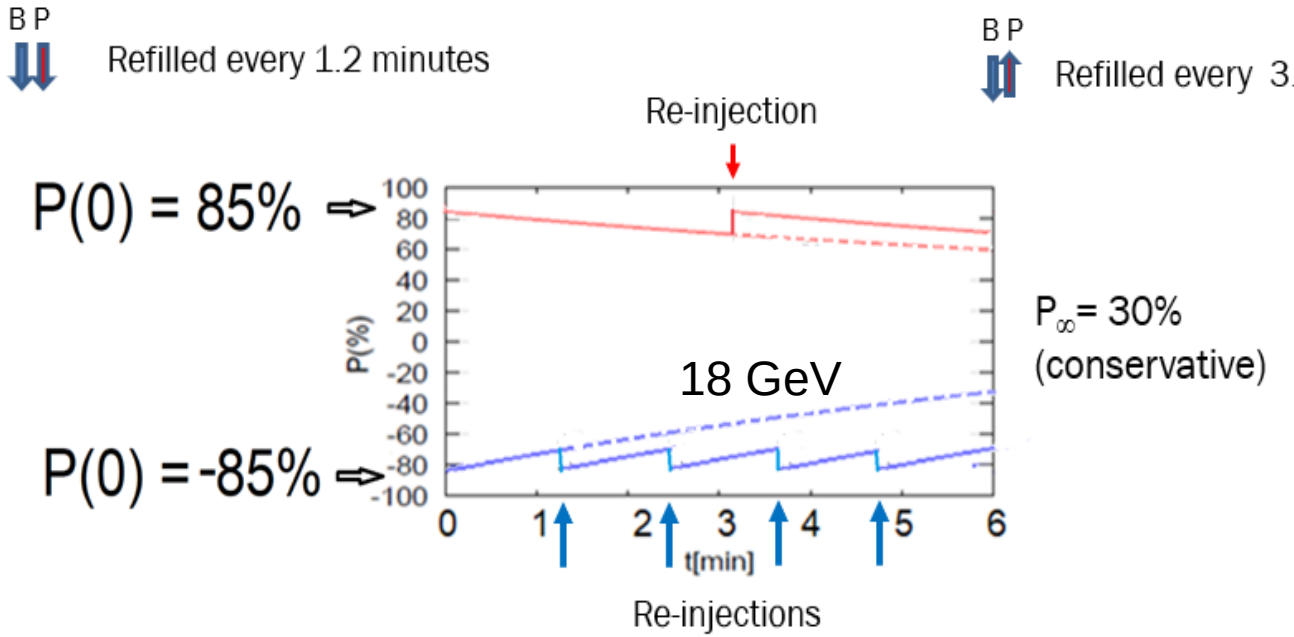
To maintain high polarization of 70%, the ESR will require frequent re-injections.

Desired energies at 5, 10, and 18 GeV.

The ESR will have spin in both directions (↑↓) to help with systematic uncertainties at the detector.

- Sokolov-Ternov effect: polarizes beam opposite the main dipole field.
- Spin diffusion: quantum excitation can be minimized through lattice optimization.

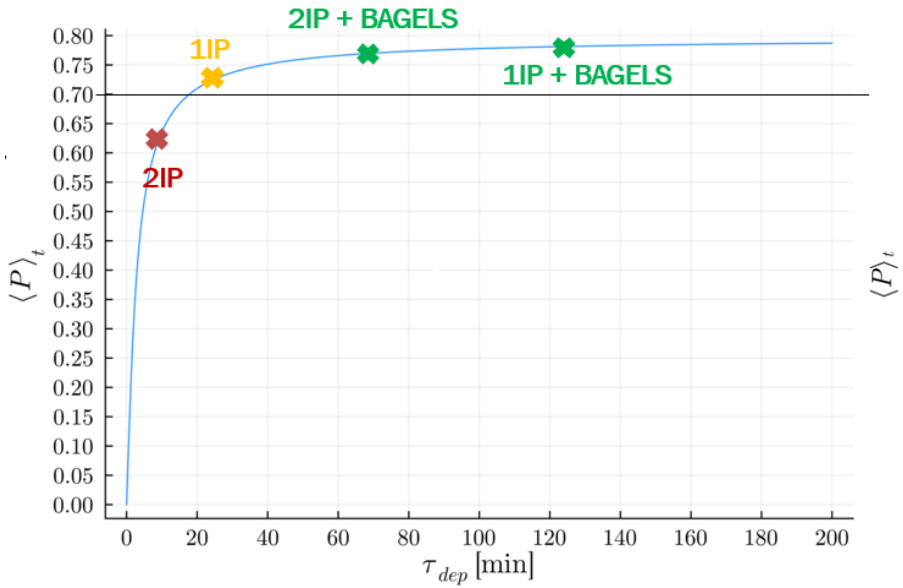
Polarization lifetime affected by above effects, resulting in different lifetimes for spin ↑ and ↓.

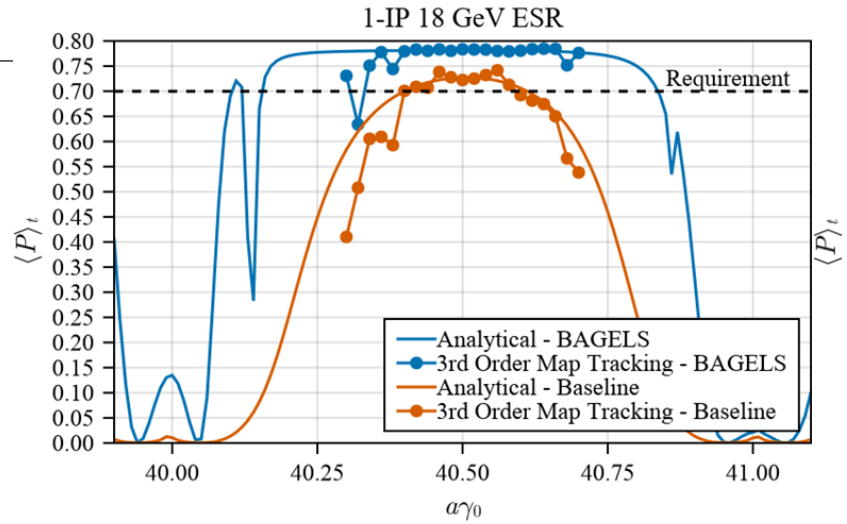


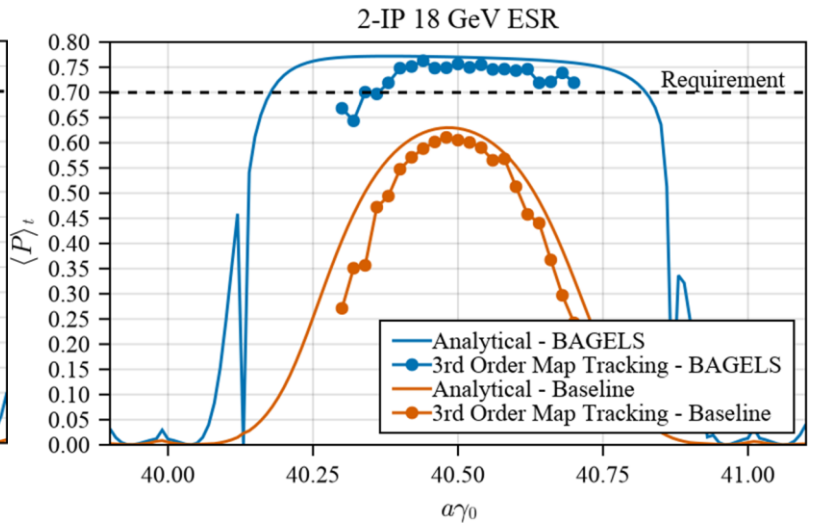
ESR Polarization

M. Signorelli

- Choice of unit bump: “Opposing $2\pi n$-bumps” for no delocalized coupling & no delocalized vertical dispersion
- Best Adjustment Groups for ELectron Spin (BAGELS) algorithm developed to minimize $\partial\hat{n}/\partial\delta$ around the ring.
- Turning only 4 knobs until polarization is maximal**:**







- Max orbit excursion < 1.4 mm
- **Polarization requirements now exceeded for both 1- and 2-IP 18 GeV lattices**

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See M. Signorelli and G. Hoffstaetter, “BAGELS for simultaneous polarization, orbit, and optics control in electron storage rings. PRAB, 2025

Hadron Polarization

- Hadron polarization overview
- AGS polarization
- HSR polarization

Hadron polarization overview

Polarization preserving devices:

- Booster: harmonic correctors (imperfection resonance correction) and an AC dipole (intrinsic resonances)
- AGS: a superconducting and normal conducting helical dipole that rotate proton spin 10+6% of 180^{o}
- HSR: will have six snakes (where RHIC has two in each ring).

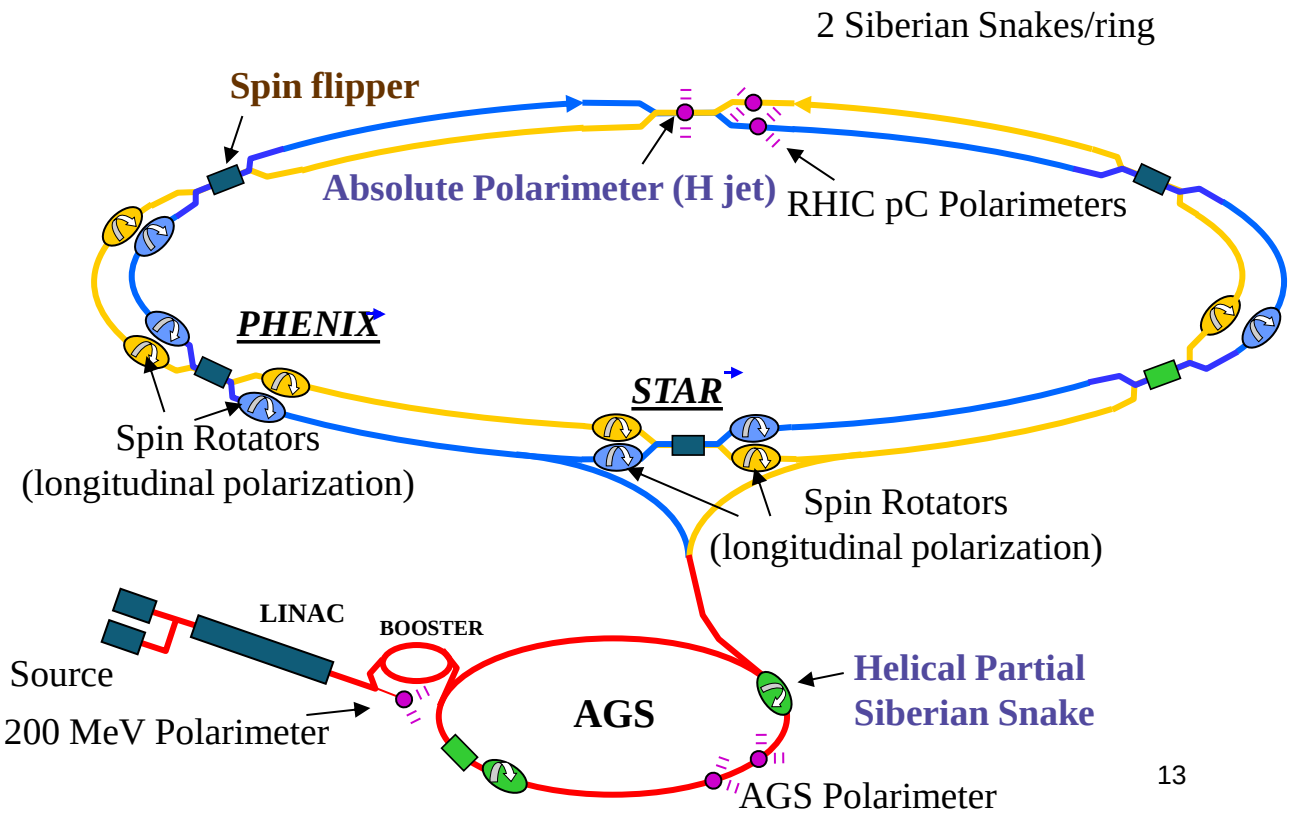
Polarized protons:

- The polarized proton source provides polarization up to 7×10^{11} at 80% polarization.
- In the Booster, the bunch is shaped through scraping to optimize polarization transmission.
- The AGS will need to provide 3×10^{11} protons/bunch with 75-80% polarization, assuming zero loss in the HSR.
- Currently, the AGS can provide 3×10^{11} protons/bunch with 65% polarization.

Polarized helions:

- Polarized helions are expected to be available in 2026
- The source is expected to provide up 2×10^{11} ions/pulse with 80% polarization.

Both protons and helions need near 100% polarization transmission in the injectors and HSR to support EIC requirements.



AGS Polarization, protons

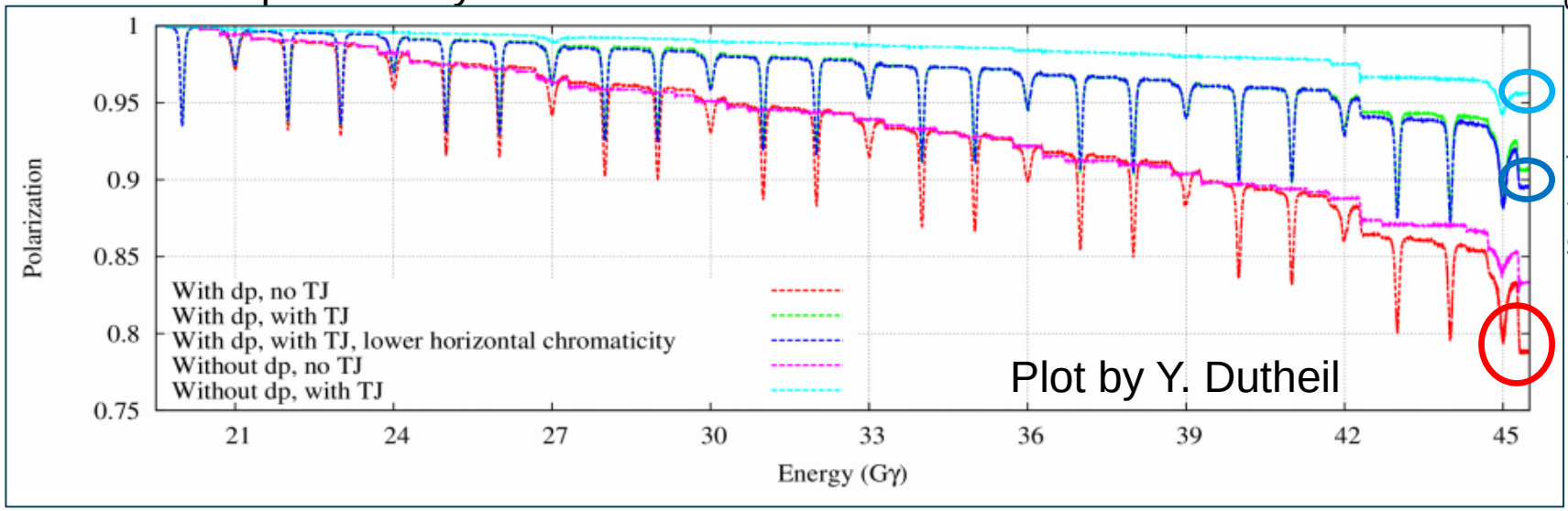
V. Schoefer

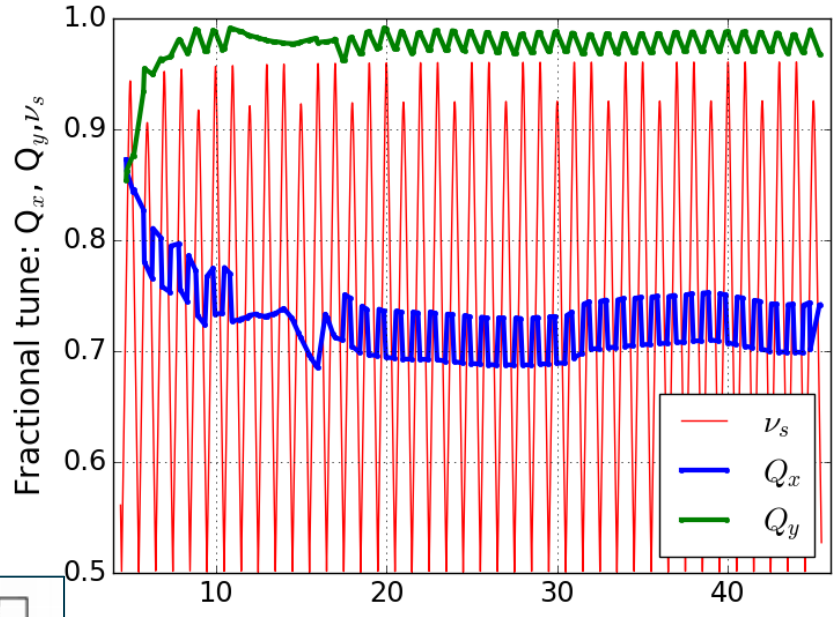
With the two partial snakes, protons have a small spin-tune gap for the vertical betatron tune to be placed in, avoiding vertical depolarizing resonances.

- A total of 82 weak horizontal resonances are crossed.
- A fast tune jump to cross these resonances faster, minimize the polarization loss, an 8-10% gain over baseline polarization.

For direct correction of the snake resonance driving term, 15 skew quadrupoles have been installed.

- A total of 82 weak horizontal resonances are crossed.
- Up to 15% gain over baseline polarization.
- Used operationally for RHIC Run24.

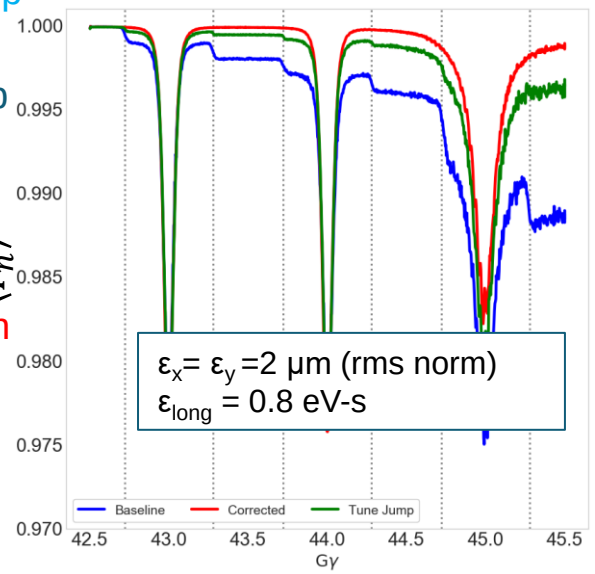




Tune jump 0 dp/p

tune jump +dp/p spread

No mitigation



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See V. Schoefer, “Using betatron coupling to suppress horizontal intrinsic spin resonances driven by partial snakes” PRAB, 2021

AGS Polarization, helions

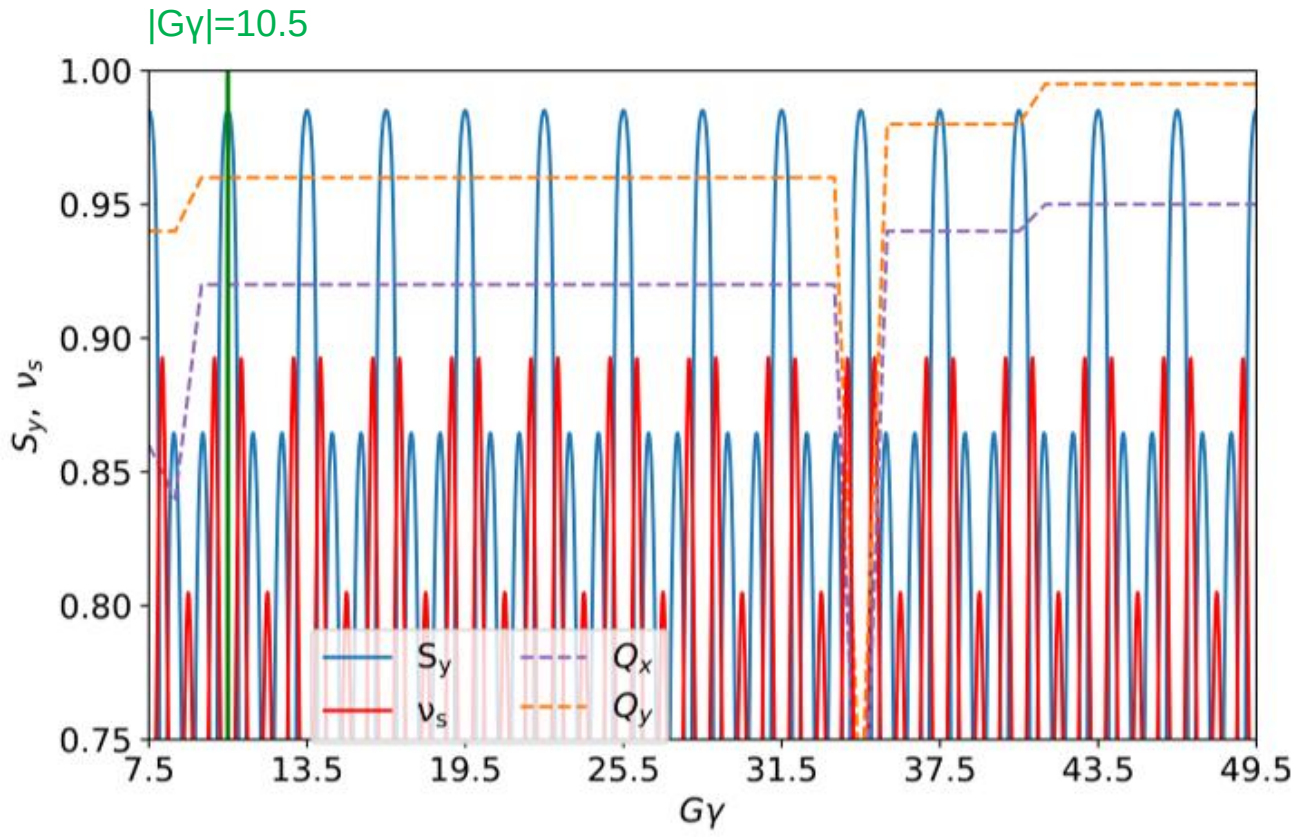
Due to the higher G of helions, the rotation from each snake is more, allowing both tunes to be placed inside the spin-tune gap

- To maximize the polarization and intensity transmission early in the AGS cycle, beam will be extracted from Booster at |Gγ|=10.5.
- This is due to greatly reduced optical defects from the snakes, which decay exponentially with energy.

• Polarization transmission is expected to be near 100% with both betatron tunes inside the spin-tune-gap.

•This is only supported above |Gγ|=10.5.

•Studies following the source completion can give insight on additional upgrade for protons.



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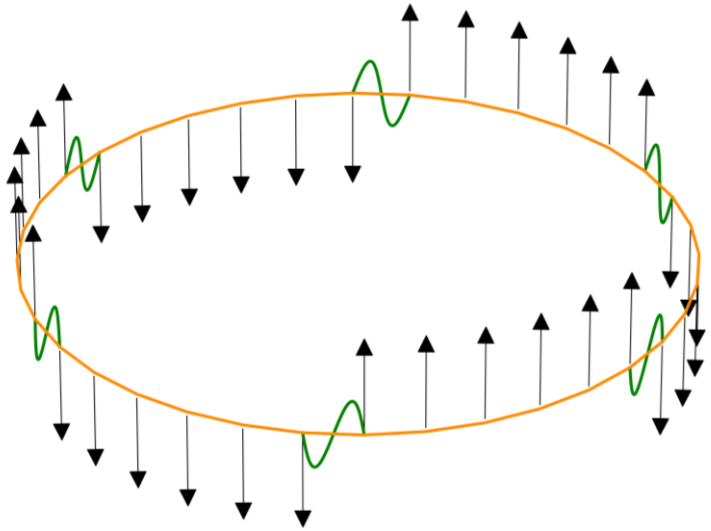
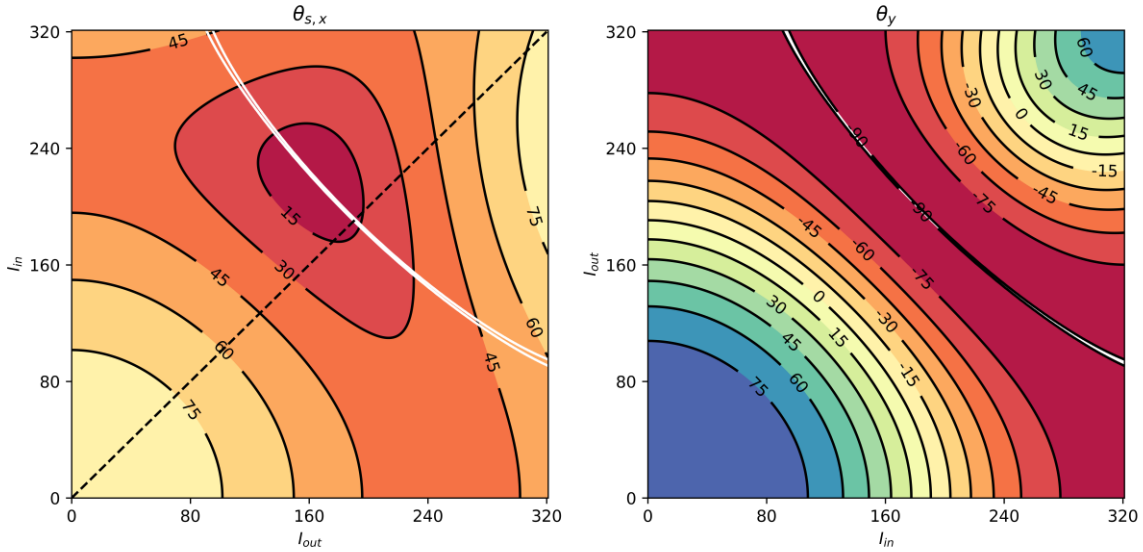
HSR Snakes

To preserve polarization of protons and light ions up to their maximum energy, there will be 6 full snakes

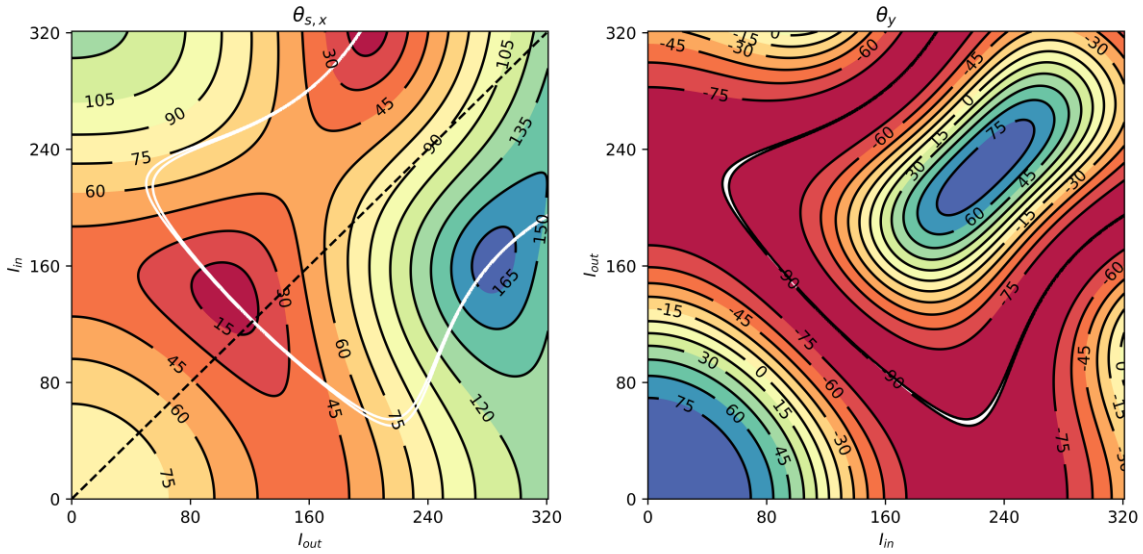
- Each snake consists of four dipoles, with the outer and inner coils powered independently, I_{out} and I_{in}.
- To minimize the orbit matching requirements, $I_{out}<I_{in}$.
- Protons can satisfy a precession axis from 0 to 45 degrees.
- Helions can satisfy all possible angles, due to its higher G.



Protons



Helions



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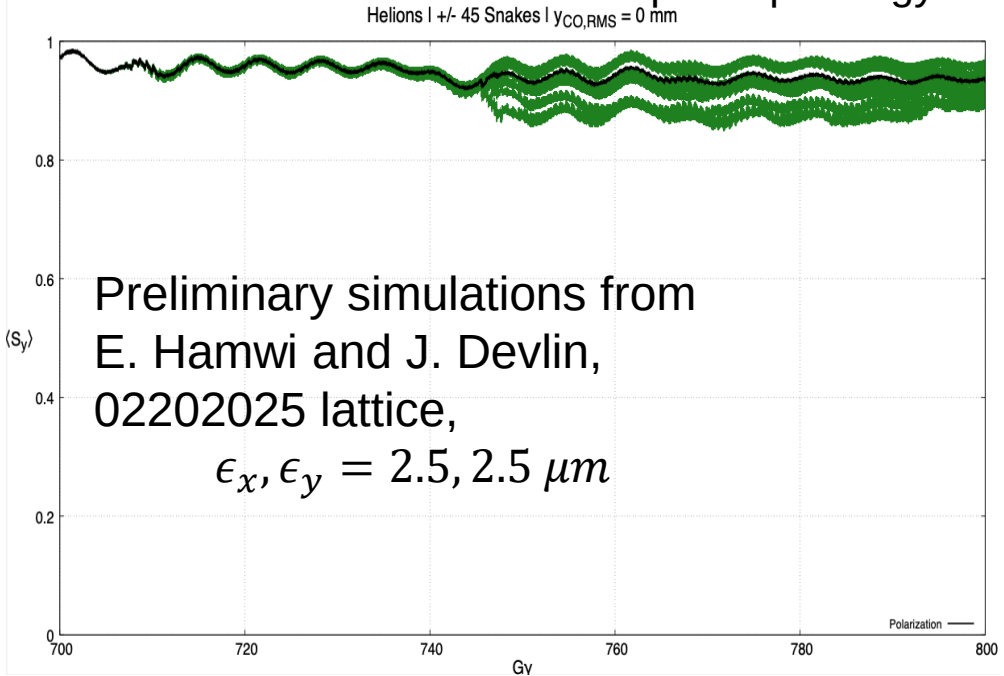
HSR polarization transmission

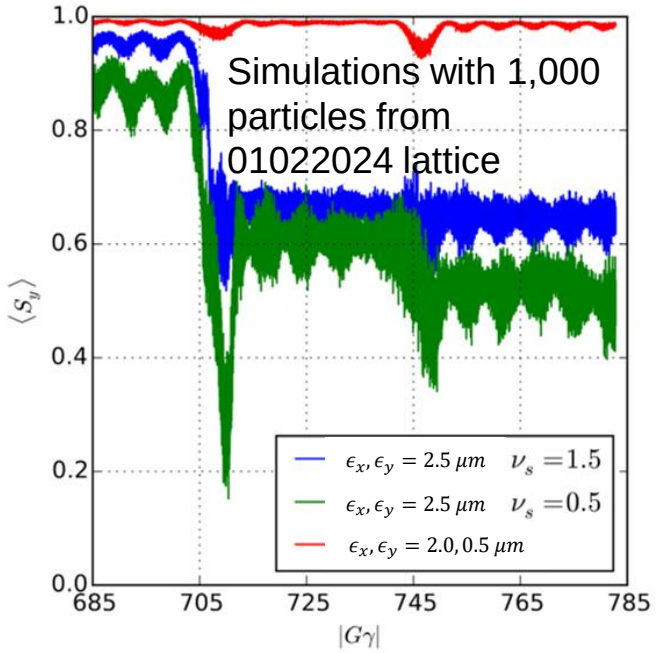
Polarized protons at E=275 GeV→Gγ=525

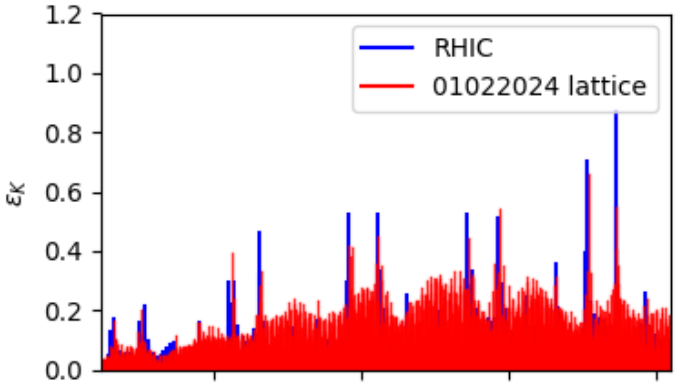
- •Good polarization transmission from 23.8 to 275 GeV.

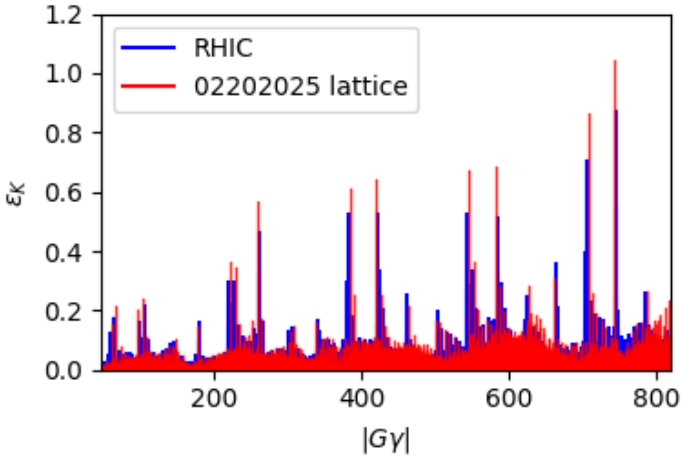
Polarized helions at the equivalent E=183 GeV/u →|Gγ|=820

- •Simulations with the 01022024 lattice showed pre-cooling necessary for good polarization transmission up to top energy.
  - •Uncooled polarization transport showed a strong dependence on the chosen snake precession axis.
  - •Phase trombone to improve spin match with IP improved performance with uncooled emittances.
- •New lattice shows reduced resonance strengths for non-systematic resonances.
- •Preliminary simulations for the 02202025 lattice show good transmission up with uncooled emittances up to top energy.





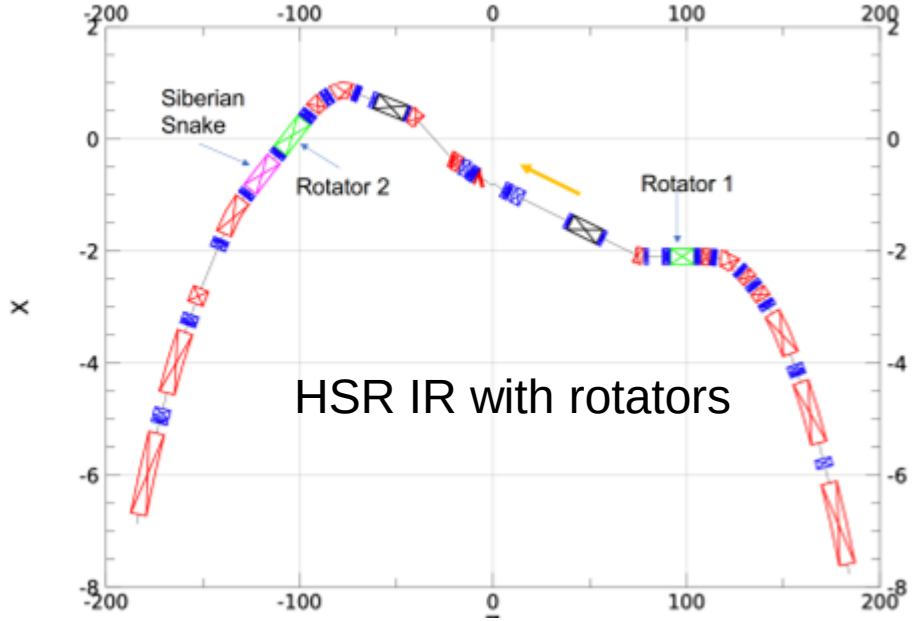




IR Design and Rotators

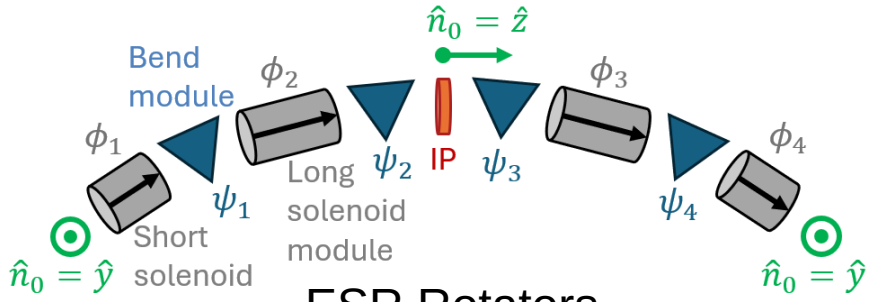
In the HSR:

- To minimize synchrotron radiation in the IR, the ESR lacks bends near the IP.
- To accommodate the straight electron trajectory, the HSR has several strong bends near the IP.
- As a result, the rotator magnets are placed 17 mrad and 61.35 mrad from the IP (compared to RHIC at 3.675).
- The RHIC rotator magnets can satisfy longitudinal polarization for protons at 41, 100, and 275 GeV.



In the ESR:

- Longitudinal polarization at the IP is satisfied at 5 and 10 GeV.
- The BAGELS algorithm satisfies the longitudinal spin-match at 18 GeV.



ESR Rotators

	Solenoids		Bends	
	$\phi_{1,4}$	$\phi_{2,3}$	$\psi_{1,4}$	$\psi_{2,3}$
17.846 GeV 1-IP/2-IP	0°	−90°	N/A	−90°
9.781 GeV 1-IP	−52.2°	−126.0°	−124.4°	−49.3°
9.650 GeV 2-IP	−51.7°	−124.4°	−122.7°	−48.7°
5.068 GeV 1-IP/2-IP	−90°	0°	−64.4°	−25.6°

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See V. Ptitsyn and J. Berg, “EIC Hadron Spin Rotators”, IPAC2022, 2022

Summary

Electron polarization

- The RCS has been moved outside the RHIC tunnel and still supports the spin-transparent design.
- The RCS will deliver highly polarized beam to the ESR to satisfy the EIC's requirements
- The ESR will need frequent replacement of bunches to maintain high polarization.
- The BAGELS optimization maximizes polarization lifetime

Hadron polarization

- Polarized protons
  - In the AGS, efforts to improve polarization transmission are ongoing. The skew quads for horizontal intrinsic resonance correction show promise and are being commissioned.
  - In the HSR, polarization transmission supports the EIC requirements up to $G\gamma = 525$
- Polarized helions
  - Will be available for study in 2026.
  - In the AGS, near lossless transmission is expected between $|G\gamma| = 10.5$ to $|G\gamma| = 49.5$.
  - In the HSR, polarization transmission studies up to $|G\gamma| = 820$ are ongoing.

Thank you

Questions?