Hadron polarization for the EIC

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Brookhaven National Laboratory
U.S. DEPARTMENT of ENERGY

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The Electron Ion Collider

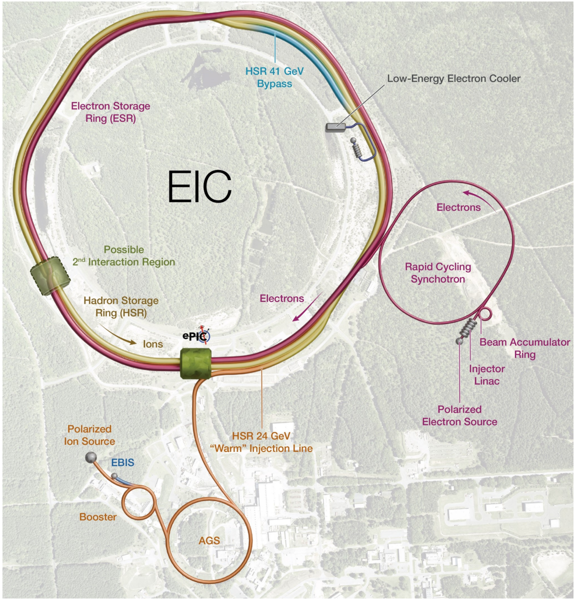
The Electron Ion Collider will be built on the existing RHIC accelerator complex.

→ The Hadron Storage Ring (HSR) will repurpose many RHIC components.

→ The HSR will utilize the existing hadron sources and injectors.

- The Electron Beam Ion Source (EBIS) will provide polarized helions.
- The Optically Pumped Polarized Ion Source (OPPIS) will provide polarized protons.
- Booster and AGS are the injector synchrotrons to pre-accelerate beams for the HSR.
- HSR will accelerate beams from their injection energy (∼24 GeV q/n) up to the desired store energy.

The EIC physics program calls for various collisions energies, with HSR ring energies of 41 GeV, and 100 GeV to 275 GeV$\frac{q}{n}$.



The RHIC Accelerator Complex for spin

The RHIC complex is show on the right.

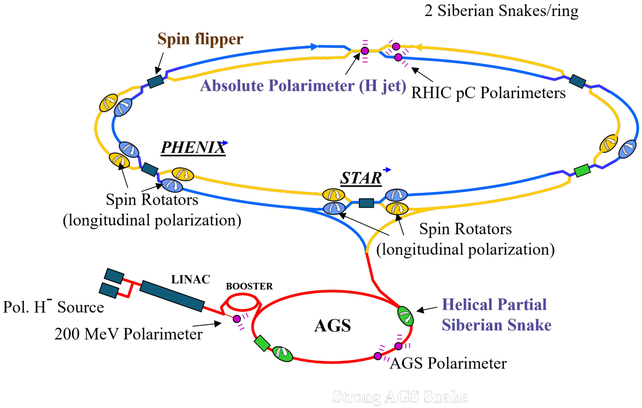
→ IR6 and IR8 each have four rotator magnets, two for blue and two for yellow. 8 in total.

→ Each ring has two snakes. 4 in total.

→ RHIC and the HSR are named according to a clock, with arcs labelled from 1 to 12, with half-cells labelled 1-20/21, and an i or o to denote inner and outer arcs.

→ The snakes are located at: yo9-b7, yo3-b7 and bi9-b7, bi3-b7.

→ The rotators are located at the b3's of each IR.



→ All existing snakes have right-handed helicity (R) and alternate current through the coils (R+R-R+R- or R-R+R-R+).

→ All existing rotator magnets have alternating right and left-handed helicity (L) and have the same current (L+R+L+R+ or L-R-L-R-).

The helical magnets

The amount of rotation from a single coil is defined as:

$$\phi = \sqrt{1+\chi^2}, \chi = (G + 1/\gamma)\frac{qB_o}{m\beta c|k|}. \tag{1}$$

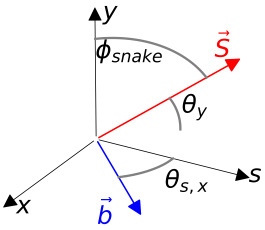
This is weakly dependent on the energy but strongly dependent on: G, q, m, and the chosen field, B_o. The rotation after transiting all four coils, the final rotation angle is ϕ_k. The purpose of these helical magnets is to rotate the spin, $\vec{S}$, by ϕ_k=180°, about the axis $\vec{b}$ which lies in the horizontal plane with an angle $\theta_{s,x}$ from the longitudinal axis.

→ Defining θ_y as the remnant angle of $\vec{S}$ after exiting the snake or rotator is convenient.

→ For the snakes, $\theta_y = -90$ degrees corresponds to a full spin-flip.

→ For the rotator, $\theta_y = 0$ degrees corresponds to the spin being in the horizontal plane.

The snake magnet assemblies contain four helical magnets that rotate $\vec{S}$ by 180° each pass.

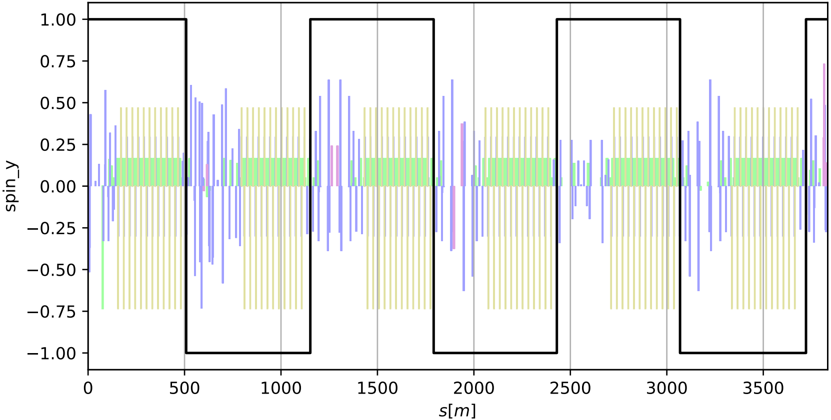


HSR Snake Placement

To support polarization transmission up to the highest energies, six snakes will be installed, evenly spaced around the ring.

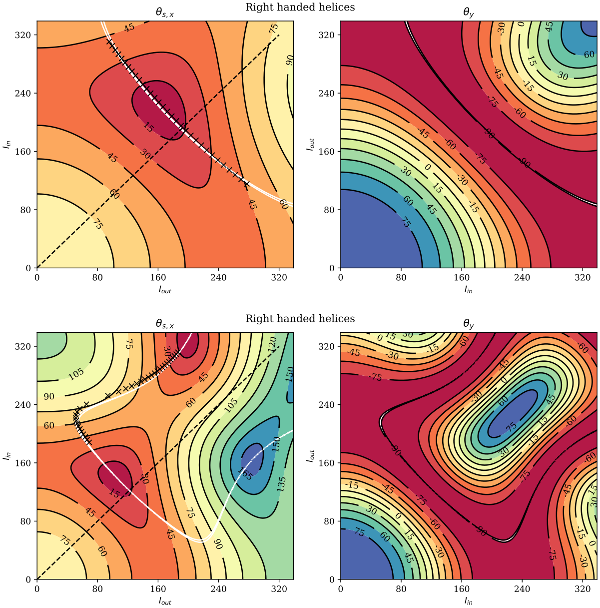
A ring with six equally spaced snakes with precession axis of $\theta_{s,x}(k)$ has a spin-tune that follows:

$$\nu_s = \frac{1}{\pi}\sum_{k=1}^{6}(-1)^k\theta_{s,x}(k),$$



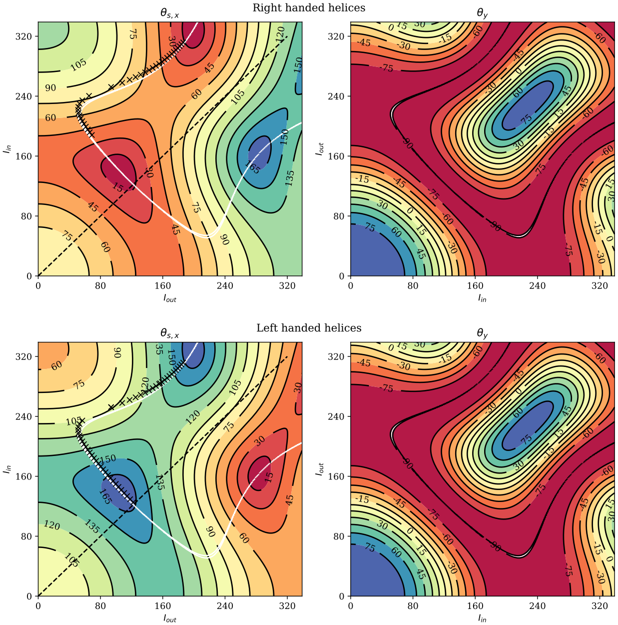
The HSR snakes

- → As in RHIC, protons can have a precession axis of ±45 which will use the maximum range of the power supplies (322 A) and magnets (4 T).
- → Values of interest to support $\nu_s = 0.5$ include ± 15, ± 45, $\{0, 90\}$.
- → Different ϕ_k sets were explored with mixed results.
- → E. Hamwi proposed the {0,90} set and also performed an exhaustive search for the optimal axes.
- → Helions can satisfy all angles and is primarily constrained by aperture at injection, limited to $\theta_{s,x}$ =73° at $B\rho = 55$ Tm.



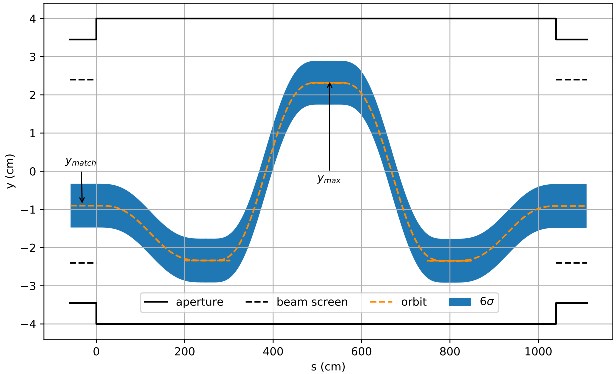
A Left-Handed Snake

- Four snakes will be repurposed from RHIC. The additional two snakes need to be constructed from unused rotator magnets.
- To maximize the number of spare coils, one snake will be made with all left-handed helicity.
- The left handed snake behaves the same as the right-handed snake, but with the opposite precession axis for the same current (L+L-L+L-=R-R+R-R+) and an opposite rotation.



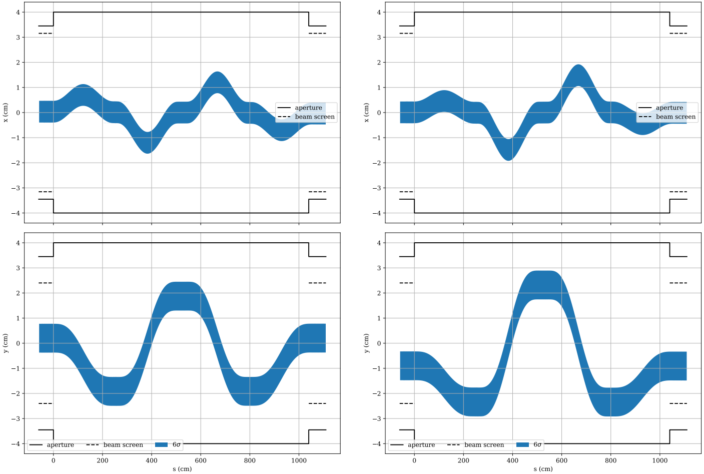
The Snake Aperture

- → The aperture in the snakes and rotators are a concern at lower energies, primarily for snakes at injection energy.
- → As the beam accelerates, the beam size and the orbit in the helix are reduced.
- → It is ideal to have the orbit centered in the aperture, which would result in a maximum orbit excursion of $\pm y_{max}$.
- → In this ideal case, there is a matching requirement on the accelerator outside of the helix, y_{match}.
- → The envelope of the beam at each snake is dependent on the local $\beta_{x,y}$ at each snake.



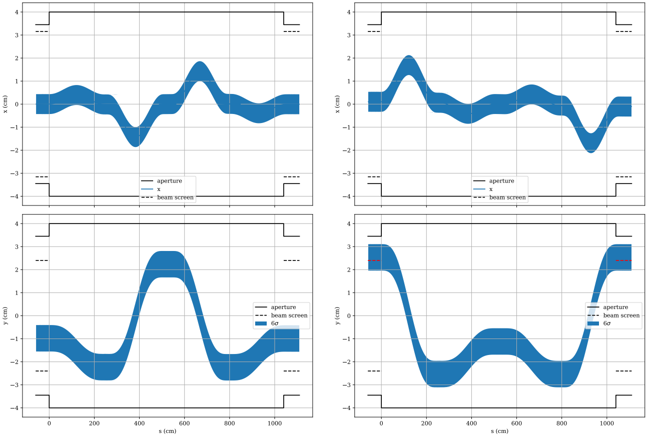
Proton Aperture at Injection

- The horizontal (top) and vertical (bottom) orbits for protons as they transit the snake with 15° (left) and 45° (right) precession axes.
- Both trajectories allow have sufficient aperture inside the helix and have a minimal matching requirement to the accelerator.
- The 15° snake has improved matching requirements over the 45° case.



Helion Aperture at Injection

- The horizontal (top) and vertical (bottom) orbits for helions as they transit the snake with 45° (left) and 90° (right) precession axes.
- Although helions can satisfy almost all possible precession axes, there is insufficient aperture at injection for an angle above 73°.
- The 90° snake has matching requirements outside of the beam screen aperture at the intended injection energy.



Snake Configuration Summary

→ Although some configurations are more favorable for aperture, they may not be optimal for polarization transmission.

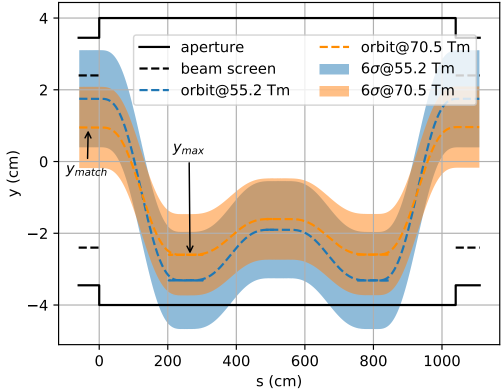
→ Current simulations show protons with ±45 and helions at ±45 or 0,90 (unattainable at injection) have optimal polarization transmission. (See E. Hamwi 2025)

$\theta_{s,x}$	species	I_{out} (A)	I_{in} (A)	y_{max} (cm)	y_{match} (cm)	max β_y (m)
± 15	p	136	247	1.897	-0.222	118.8
± 45	p	100	322	2.331	-0.888	74.8
0	h	103	137	1.540	-0.785	162.5
± 15	h	86	156	1.751	-0.198	135.9
± 45	h	59	193	2.237	-0.979	83.4
90	h	229	62	2.534	2.534	0.0

The $\theta_{s,x}$=90° is not supported at injection so there is no supported max β_y.

- This axis can be realized with an increase of the injection energy, or by ramping the snake configuration at an intermediate energy.

The HSR Limitations at injection



- → Aperture of helions at injection $B\rho = 55.2$ and 70.5 Tm with $\theta_{s,x}$=90°.
- → A minimum injection energy to support the 90° snake corresponds to $B\rho = 61.4$ Tm.
- → Injection at $B\rho = 55.2$ Tm corresponds to $|G\gamma| = 49.5$ and avoids the strong AGS resonance at $|G\gamma| = 60 - \nu_y$.

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Relevant Parameters

- → The EIC calls for polarized electron collisions on both polarized protons and polarized helions
- → The maximum collision energy for protons is 275 GeV, where for helions it is 183 GeV/u.
- → For cooling, protons will be cooled at injection. Helions will be ramped to a porch above transition (above $|G\gamma| = 96$) and cooled.
- → The source polarization is 80-83% (protons) and 80% (expected, helions), with a required store polarization of 72%.
- → Near lossless polarization transmission required from source to store.

	Protons	Helions
m (GeV/c^2)	0.938272	2.808392
q	1	2
G	1.7928474	-4.1841536
$\lvert G\gamma \rvert$(injection)	45.5	49.5
$B\rho$(injection, Tm)	79.4	55.2
$\lvert G\gamma \rvert$(max)	525	820
$B\rho$(max, Tm)	916.5	917.9

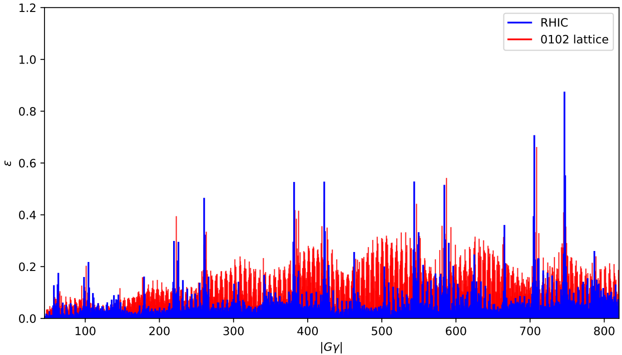
- → Injection of helions at higher energy would require crossing the $|G\gamma| = 60 - \nu_y$ resonance.
- → Studies to support this are ongoing and indicate requiring a second cold snake in the AGS.

Intrinsic and Imperfection Resonance Strengths

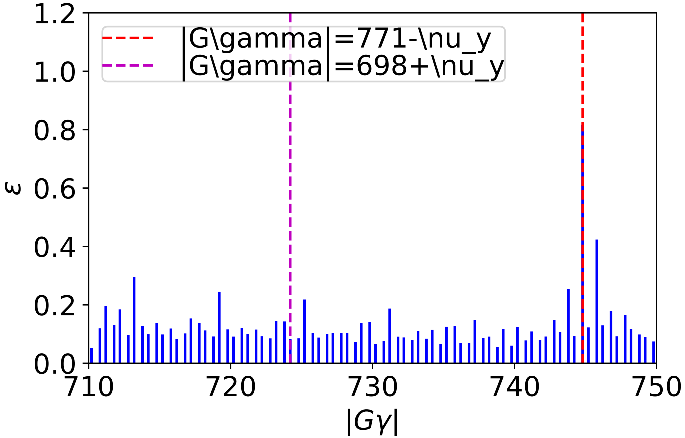
The spin resonance strength follows [1],

$$\epsilon_K = \frac{1}{2\pi} \oint \left[(1 + G\gamma) \frac{\partial B_x / \partial y}{B\rho} \right] y e^{iK\theta} ds \qquad (2)$$

Calculated for helions using the January 2, 2024 lattice release showed large non-systematic resonances when compared to the RHIC lattice

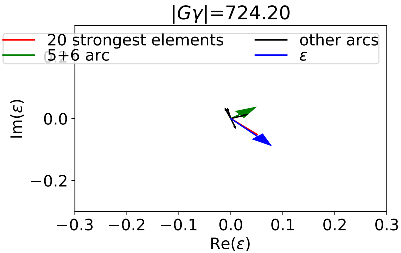


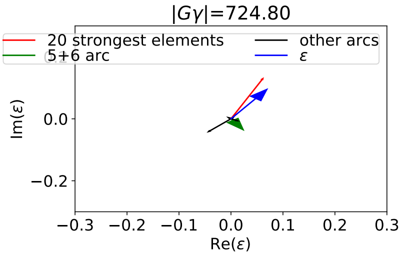
Non-systematic resonances

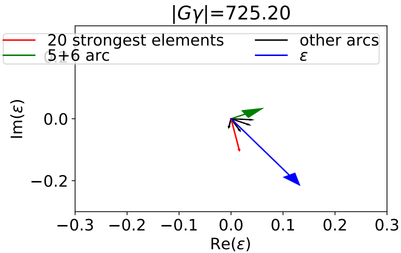


Let's look at $|G\gamma| = 698 + \nu_y$ and the 2 subsequent resonances

Non-systemmatic resonances near $|G\gamma| = 698 + \nu_y$



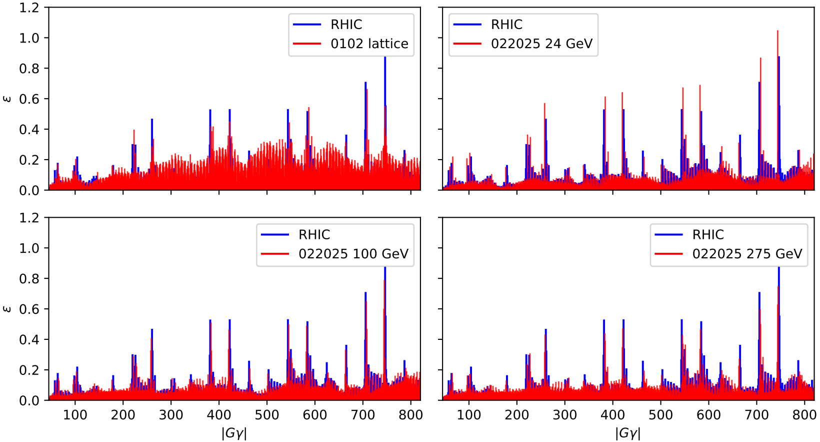




$\rightarrow$ Non-systematic intrinsic resonances largely driven by the low-β insertions (20 strongest elements).

$\rightarrow$ To make the HSR more RHIC like, subsequent lattice iterations utilize all yellow arcs.

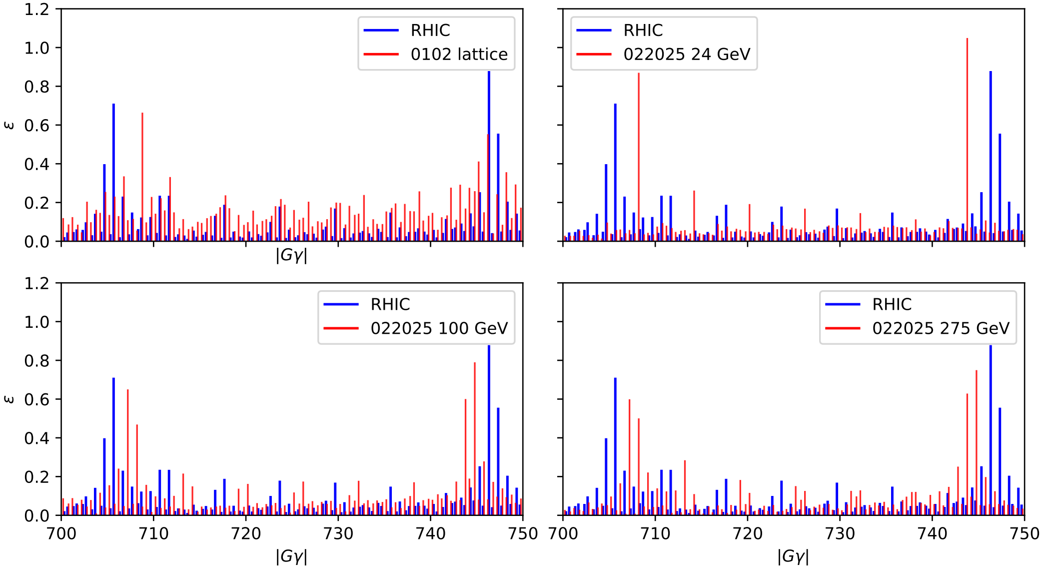
Resonance Strength comparison



→ Significant reduction in non-systematic resonances with the February 20, 2025 lattice pre-releases.

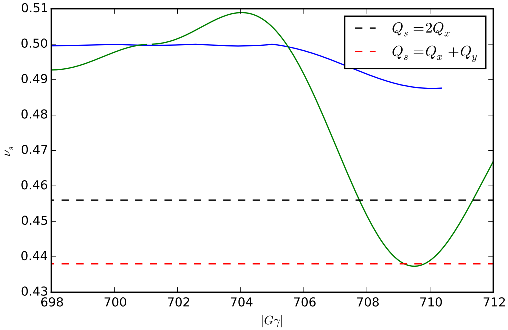
→ As the IRs are squeezed more at higher energies, the non-systemmatic resonance strengths increase, and the stronger resonances are reduced.

Resonance Strengths, zoom-in



Tracking

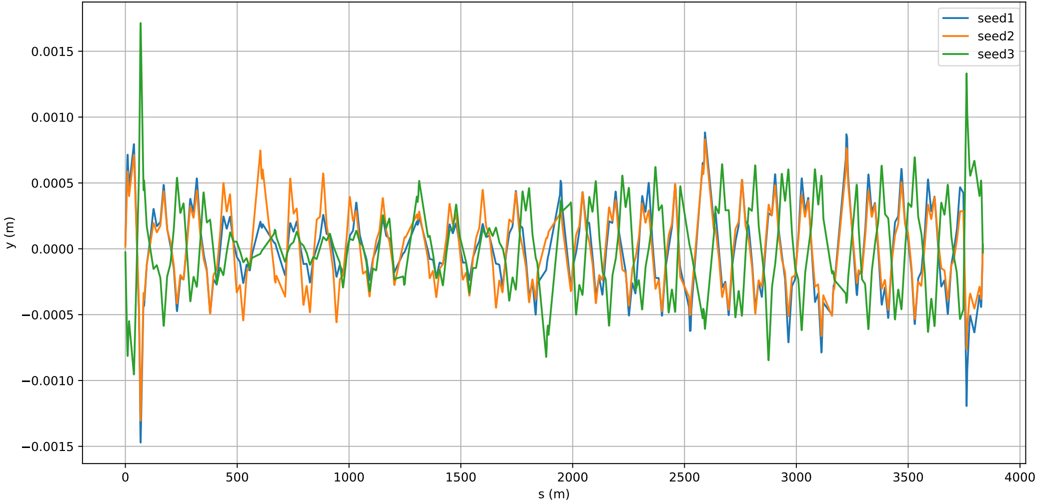
From studies on the previous lattices, we know polarization loss is from a perturbation of ν_s in the vicinity of the strong intrinsic resonances, resulting in $\nu_s = n \pm \nu_x \pm \nu_y$ or $\nu_s = 2\nu_x$. Zero polarization loss when $\varepsilon_x = 0$.



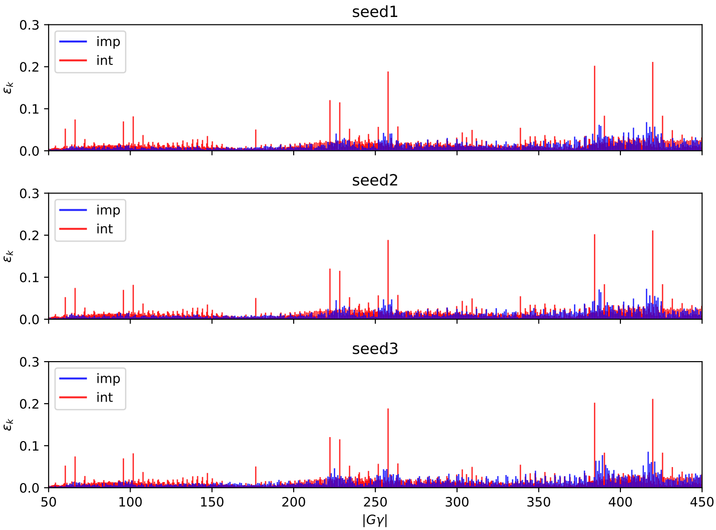
Simulations results show:

1) Bunch tracked across many units of $G\gamma$ with cooled emittances and no orbit error.
2) Bunch tracked across many units of $G\gamma$ with cooled and orbit errors, with the average over all seeds shown.

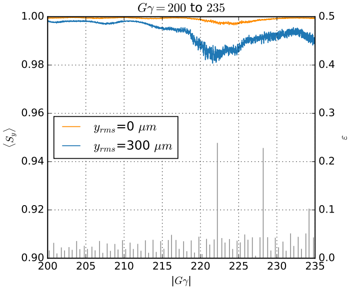
ϵ_k evaluation for different seeds

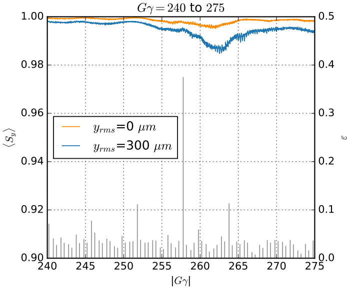


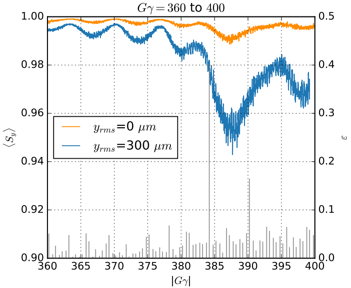
Imperfection Resonances

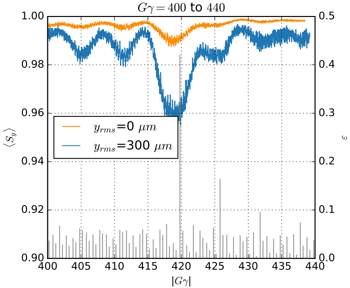


Resonance crossing with protons





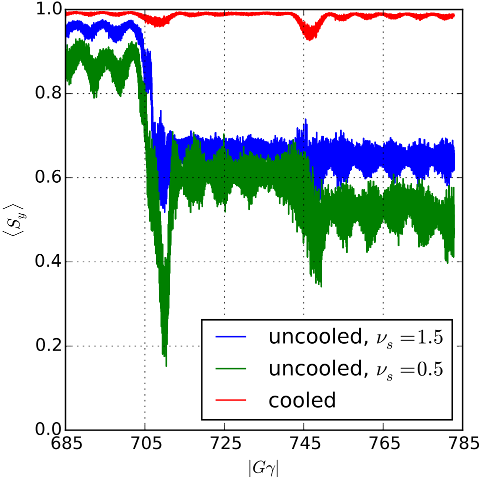




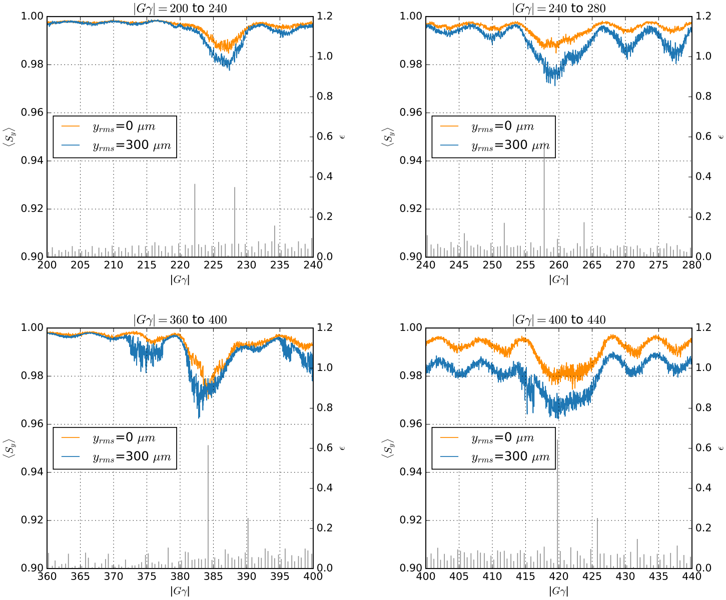
- Spin tracking across the strong intrinsic resonances, located at: G =196+ν_y, 284-ν_y, 358+ν_y, and 446-ν_y.
- Simulation results comparing a zero vertical RMS orbit with the average of several randomly seeded errors to produce yco,RMS = 300 μm.
- The polarization transmission efficiency from injection to store at G = 275 GeV is 97% without additional mitigation, to be compared to 92% achievable at 250 GeV in the RHIC configuration.

2024 lattice tracking results

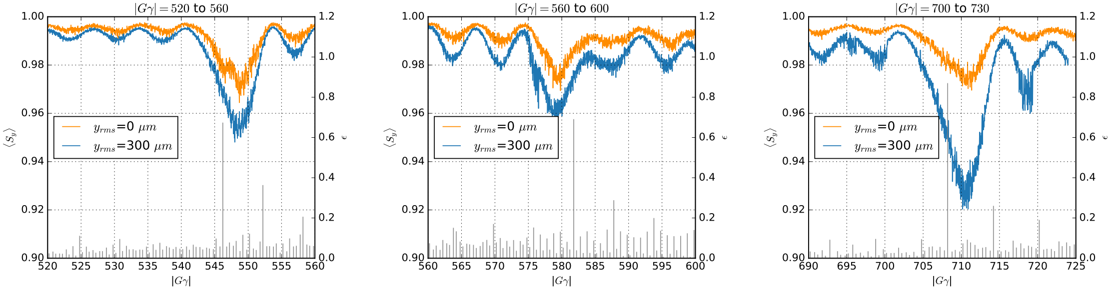
- $\rightarrow$ Tracking against the two strongest resonances
- $\rightarrow$ No polarization loss with cooled emittances.
- $\rightarrow$ Significant polarization loss with un-cooled emittances.
- $\rightarrow$ Notable difference in ± 45 ($\nu_s = 1.5$) and ± 15 precession axes.
- $\rightarrow$ These simulations did not include orbit errors.

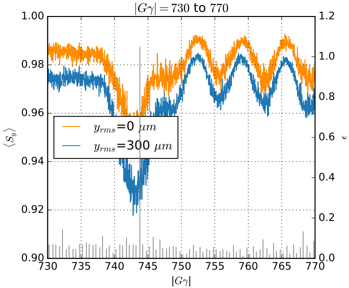


Resonance crossing with helions I



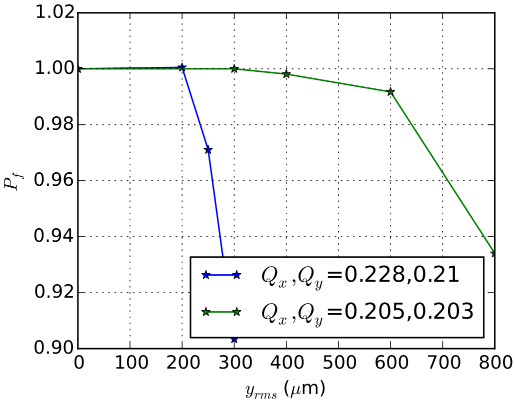
Resonance crossing with helions II





- Spin tracking across strong depolarizing resonances which are located at $|G\gamma|$= 196+ν_y, 284-ν_y, 358+ν_y, 446-ν_y, 520+ν_y, 608-ν_y, 682+ν_y, and 770-ν_y.
- Simulation results comparing a zero vertical RMS orbit with the average of several randomly seeded errors to produce $y_{co,RMS}$ =300 μm.
- The total polarization loss across all of these resonances is less than 1%.

Simulation Summary, helions III

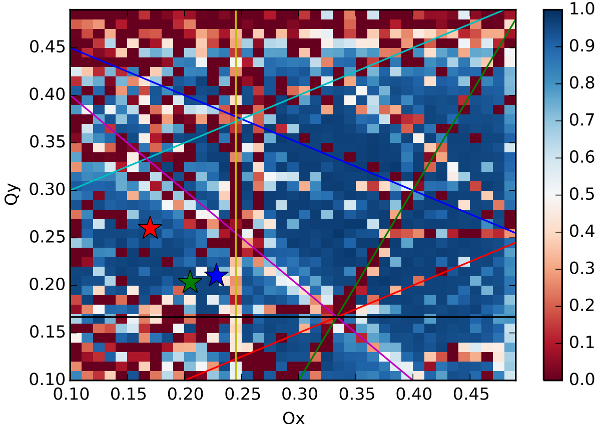


- With the tunes of $Q_x, Q_y = 0.228, 0.21$, polarization transmission starts to drop above 200 μm.
- With the tunes of $Q_x, Q_y = 0.205, 0.203$, polarization transmission starts to drop around 600 μm

Moving Q_x lower, moved the operating tunes further away from the $Q_s = 2Qx$ and $Qx + Qy$ resonance and giving improved polarization transmission.

On the fractional tunes

Tunes of $Q_x, Q_y = 0.228, 0.21$ improve polarization transmission but are not ideal for maintaining flat beam, which sets a minimum $\Delta Q \sim 0.02$.



- Several higher order resonances are present, with the $Q_s = 2Q_x$ and the $Q_s = Q_x + Q_y$ being the most prevalent.

A search for an improved working point is ongoing.

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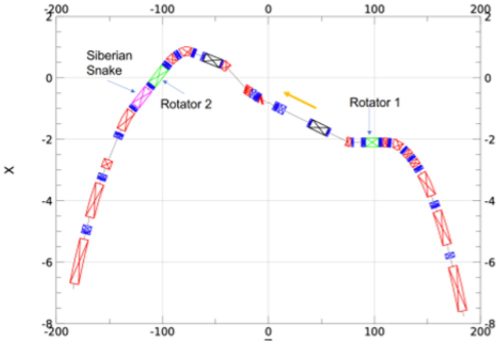
The EIC Rotators

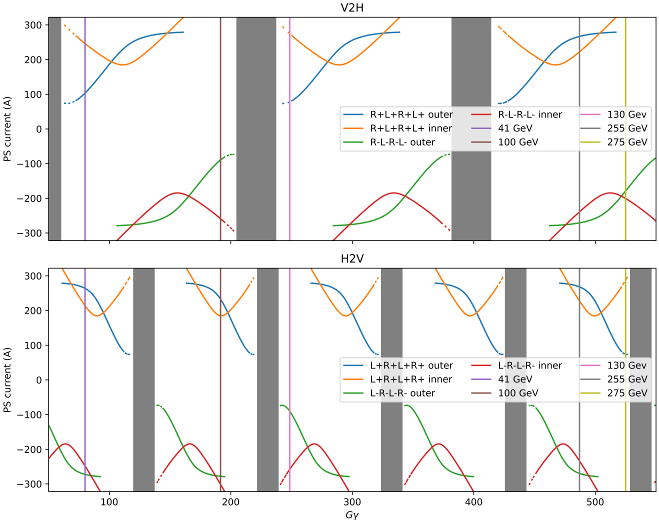
The electrons have a relatively straight trajectory through the interaction region to minimize the synchrotron radiation produced. This follows what was established in V. Pitsyn and S. Berg, ”EIC Hadron Spin Rotators” 2022.

- → To accommodate the electron trajectory, the rotators are placed at 32.58 mrad (rotator 1, July 2025 lattice) and 61.35 mrad (rotator 2) away from the IP.
- → RHIC rotators are placed symmetrically at 3.675 mrad away from the IP.
- → The asymmetry in the rotator placement results in a deviation of ν_s from $\frac{1}{2}$.
- → The rotator 2 must be changed from the RLRL to LRLR helicity pattern.



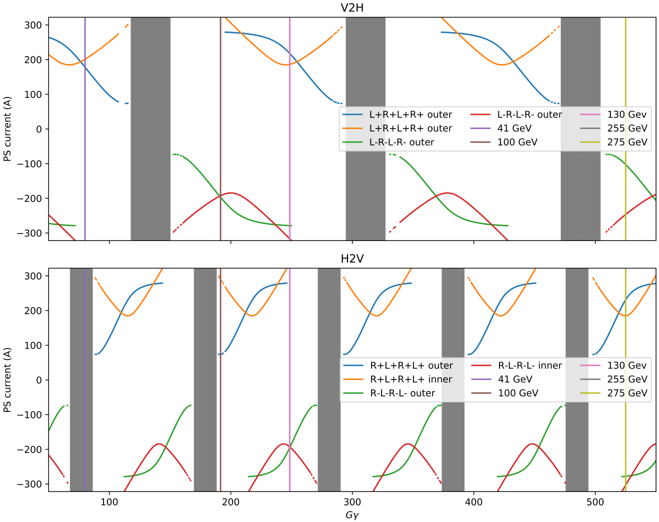
The HSR rotators with protons

- → Due to PS and magnet limitations, the rotator magnets cannot satisfy all rotation angles of protons.
- → Energies where longitudinal polarization cannot be satisfied is a grey void in the right plot.
- → The voids for rotator2 (H2V) are 42% smaller than the rotator 1 voids, but are 74% more frequent.
- → Void spacing for rotator 2 has a width of ∼18 units of $G\gamma$ and occur every 102 units of $G\gamma$.
- → Void spacing for rotator 1 has a width of 32 units of $G\gamma$ and occurs every 177 units of $G\gamma$.



The HSR rotators with protons

- → Plots show a V2H rotator in LRLR configuration (top) and the H2V in RLRL configuration (bottom).
- → Order matters, leaving the H2V rotator as RLRL would make longitudinal polarization at 41 GeV inaccessible.
- → The H2V rotator must be reconfigured to LRLR sequence to satisfy longitudinal polarization at the primary energies of interest.



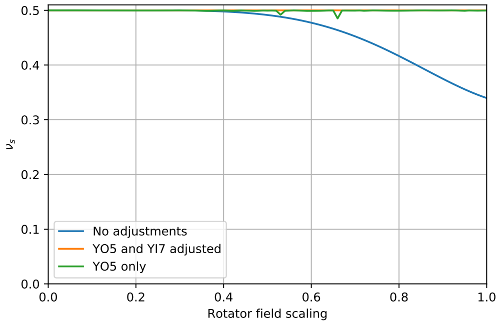
Rotator ramp and ν_s compensation

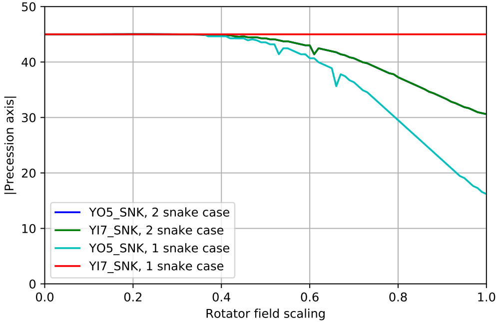
→ Different lattice and a larger gap between rotators.

→ Simulations done with rotator field maps comparing solutions with the downstream snake (YO5) and using both YO5 and YI7 snakes.

→ Both snakes is under constrained leading to jumps in precession axis.

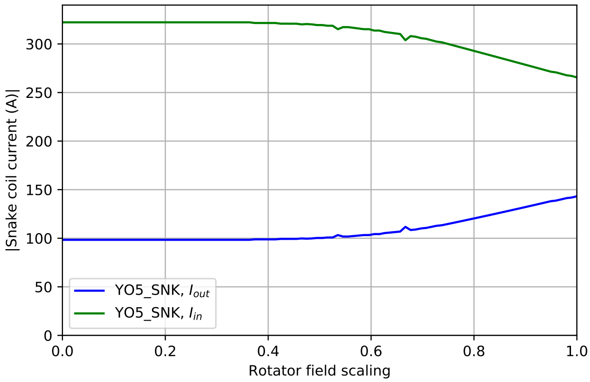
→ YO5-only has a precession axis change from -45° to -16.2°.

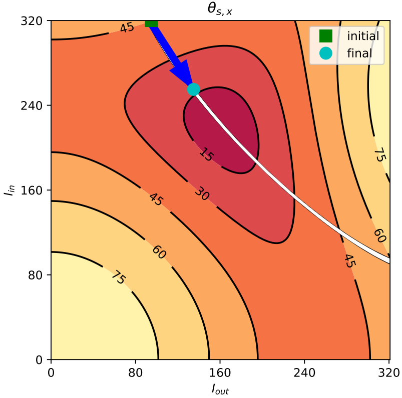




Snake ramp for compensation

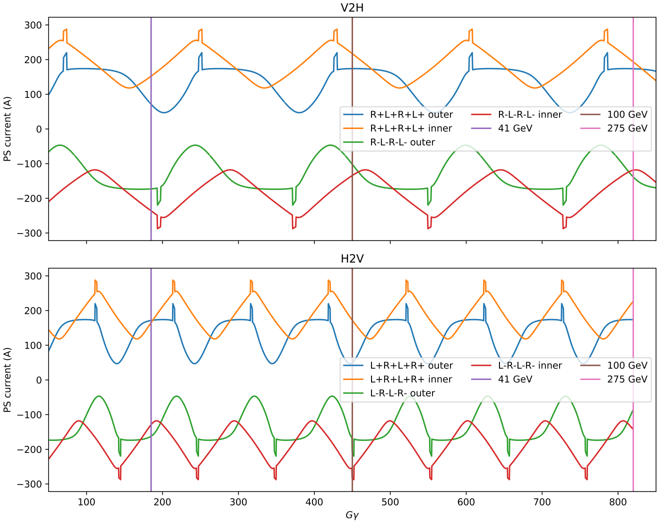
To compensate for the $\Delta\nu_s$ from the rotator ramp, the snake currents can follow the ramp below.





The EIC Rotators with helions

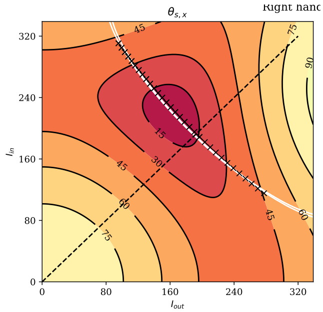
→ The rotators can satisfy all possible angles for helions.

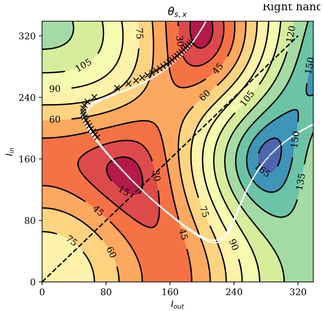


Rotator Summary

Species	Energy	$\Delta\nu_y$	Snakes used	$\Delta\theta_{s,x}$
p	41	0.107	1	-38.9°
	100	0.346	4	-20.8°
	275	0.169	1	-28.8°
h	41	0.392	4	+13.2°
	100	0.294	4	+30.8°
	183	0.217	4	+19.4°

- $\rightarrow$ For protons, $\theta_{s,x} = 0 \rightarrow 45$ is suitable for ramping the snakes.
- $\rightarrow$ If the snakes with protons need a precession axis beyond 45, up to 60 can be supported with $I_{out} > I_{in}$.
- $\rightarrow$ For helions, $\theta_{s,x} = 0 \rightarrow 75$ is suitable for ramping the snakes.
- $\rightarrow$ If the snakes with helions need a precession axis beyond 75, up to 180 can be supported with $I_{out} > I_{in}$.





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Summary

- $\rightarrow$ The available precession axis range is set by polarization transmission needs and aperture at injection.
- $\rightarrow$ Polarized helions can have a change of precession axis on the cooling porch or raise injection energy to support 90° precession axis.
- $\rightarrow$ Polarization transmission studies are ongoing.
- $\rightarrow$ Cooled emittances have suitable polarization transmission.
- $\rightarrow$ Loss mitigation studies are ongoing.
  - E. Hamwi had nice results mitigating polarization loss from intrinsic resonances by tuning the betatron phase advance with the 2024 lattice.
- $\rightarrow$ Longitudinal polarization can be satisfied with the current rotator arrangement for energies of interest.

Thank you

Thank you and questions.