Snakes in AGS and EIC

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Polarized Ion Sources and Beams at EIC
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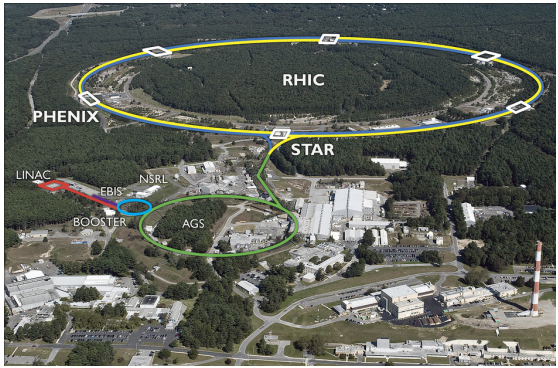
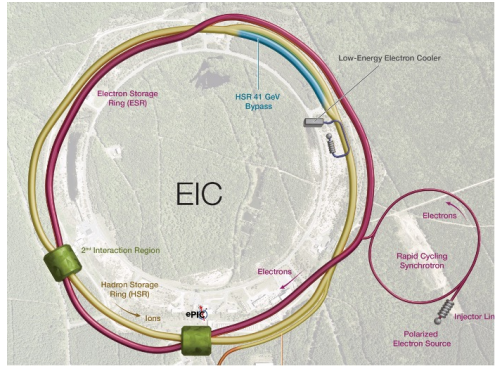
The RHIC and EIC Accelerator Complex





- RHIC scheduled to run through 2025.
- 2026 through 2032 is construction of EIC.
  - Installation of electron storage ring in the existing RHIC tunnel, with adjacent supporting facilities.
  - Modification of existing RHIC components into the Hadron Storage Ring (HSR).

Thomas-BMT Equation

The Thomas-BMT equation is the equation of motion for a particle's spin vector, $\vec{S}$, in a synchrotron (neglecting effects of $\vec{E}$)

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

- Term $\propto \vec{B}_\perp$ is strongest due to presence of strong focusing quadrupoles
- Terms $\propto \vec{B}_\parallel$ is small.

The number of precessions in one turn is the spin-tune $\nu_s = G\gamma$. From this, the resonance strength can be calculated with the Fourier transform of spin perturbing fields

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

which is satisfied when $\nu_s = n$ and $\nu_s = nP \pm \nu_D$, where n is an integer, P is the superperiodicity, and ν_D is the D=x,y betatron tune.

What is a snake

A snake is a dipole magnet that has been rolled into a helix.
The spin rotation angle from a single snake is

$$\phi_{snake} = 2\pi\sqrt{1+\chi^2} \tag{3}$$

where

$$\chi = (G+1/\gamma)\frac{qB_0}{m\beta c|k|} \tag{4}$$

which is rotated about the axis

$$\mathbf{b} = \begin{pmatrix} 0 & \frac{-H}{\sqrt{1+\chi^2}} & \frac{-\chi}{\sqrt{1+\chi^2}} \end{pmatrix}$$

with H being the helicity (either R or L), and B_0 being the dipole field of the helix.
The AGS has two ”partial” snakes, which rotate the spin less than 180 degrees.
The EIC will have six ”full” snakes, each of which consists of four helical dipoles, which rotate the spin 180 degrees.

The AGS Snakes

The AGS has two partial helical dipoles (snakes) to preserve polarization through the vertical imperfection resonances. The two snakes are referred to as Cold and Warm, each rotates the spin a fixed amount (χ_C and χ_W) as particles transit the snakes on every turn.
The spin tune in this dual partial snake configuration is

$$\nu_s = \frac{1}{\pi}\cos^{-1}\left[\cos\frac{\chi_c}{2}\cos\frac{\chi_w}{2}\cos(G\gamma\pi) - \sin\frac{\chi_c}{2}\sin\frac{\chi_w}{2}\cos(G\gamma\frac{\pi}{3})\right] \tag{5}$$

where the $\pi/3$ term is from the relative separation of the two snakes being one third of the ring. It is also important to note that $\nu_s \neq G\gamma$ with snakes.
The projection of the stable spin direction on the vertical axis is given by

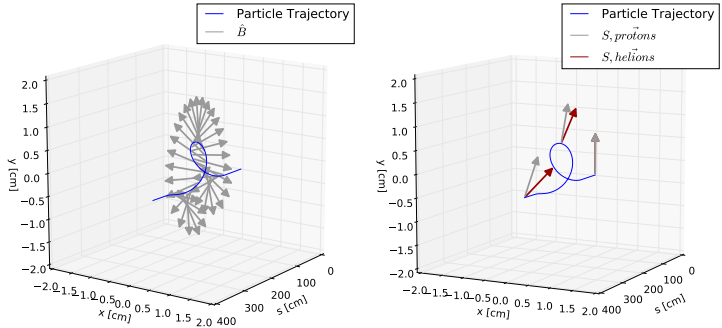
$$\cos\alpha_3 = \frac{1}{\sin\ \pi\nu_s}\left[\cos\frac{\chi_w}{2}\cos\frac{\chi_c}{2}\sin(G\gamma\pi) - \sin\frac{\chi_w}{2}\sin\frac{\chi_c}{2}\sin(G\gamma\frac{\pi}{3})\right] \tag{6}$$

The vertical component of the stable spin direction, $\cos\alpha_3$, will be nearest vertical every

$$G\gamma = 3n + 1.5. \tag{7}$$

With snakes, $\nu_s \neq G\gamma$, avoiding imperfection resonances and the possibility of avoiding intrinsic resonances.

AGS Snakes

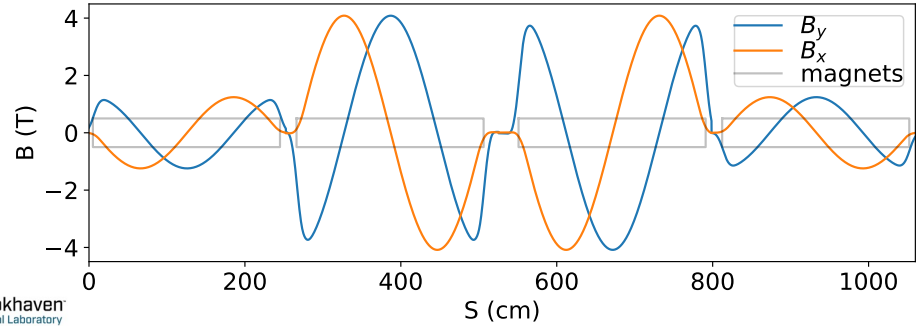


- Direction of $\vec{B}$ sampled by particle and resulting spin rotation from vertical.
- The snakes are held at constant field and the superconducting magnets have a long ramp time of several minutes.
- Due to the horizontal component of stable spin direction, horizontal intrinsic resonances are present.
- With the same field strength snakes, He-3 will rotate G_h/G_p more than protons.
- For helions χ_c=25% and χ_w=14% (in units of % of π) is equivalent to protons χ_c=14% and χ_w=9%.

The EIC Snakes

The EIC will have six full snakes, equally spaced. Each of which is comprised of 4 full helical dipoles.

- 2 snakes from the existing yellow RHIC ring, and 2 snakes from the existing blue RHIC ring, all have right-handed helicity
- 1 snake constructed from right handed helix rotator magnets, and 1 snake constructed from left handed helix rotator magnets



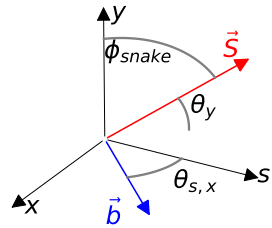
Snakes in the EIC

By alternating the sign of B_0 of each magnet, the orbit through the dipole is symmetric and manageable (such as R+R-R+R-).
By alternating the sign of B_0 from each full snake to each full snake, the precession axis alternates. The six snakes will be placed symmetrically around the ring and have

$$\nu_s = \frac{1}{\pi}\sum_{k=1}^{6}(-1)^k\theta_{x,s}(k) \tag{8}$$

where $\theta_{x,s}(k)$ can be set to achieve the desired spin tune. With 6 snakes, $\nu_s = 0.5$ with $\theta_{x,s}(k) = \pm\pi/12$.

- Defining θ_y as the remant 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.



Species of Interest

Initial polarized collisions will be carried out with polarized protons, followed by polarized helions. Other possible polarized species are deuteron, lithium-6, and lithium-7.

	p	d	h	Li^6	Li^7
m (MeV/c^2)	938.27	1875.61	2808.92	5601.52	6533.83
μ/μ_N	2.7928	0.8574	-2.1275	0.8220	3.2564
S	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{3}{2}$
G	1.793	-0.143	-4.184	-0.178	1.532
mc^2/G (GeV)	0.523	13.116	0.671	31.466	4.264
χ_c, χ_w (%)	14, 9	-	21.8, 14	-	5.2, 3.3

Species in the Booster, AGS, and HSR

The corresponding energy ranges from injection into the Booster, up to the maximum energy of the EIC.

		p	d	h	Li^6	Li^7
Booster range	$\lvert G\gamma \rvert$	2.19→4.5	0.144→0.25	4.193→10.5	0.178→0.3	1.35→2.5
AGS range	$\lvert G\gamma \rvert$	4.5→45.5	0.25→1.82	10.5→49.5	0.3→2.25	2.5→16.5
HSR range	$\lvert G\gamma \rvert$	45.5→524	1.82→21	49.5→820	2.25→26.2	16.5→193.5

- Due to the low G of deuterons and Li6, a solenoid will be used instead of helical dipoles.

The commissioning order of these species would follow:

- Protons commissioned to reach EIC intensity and polarization.
- Helions commissioning after source completion in 2026. Develop an entirely new configuration with an estimated time in AGS of 4-6 months, 24/7 of dedicated studies.
- Deuteron commissioning →Lithium commissioning, as sources become available.

Introduction

Snakes with Protons

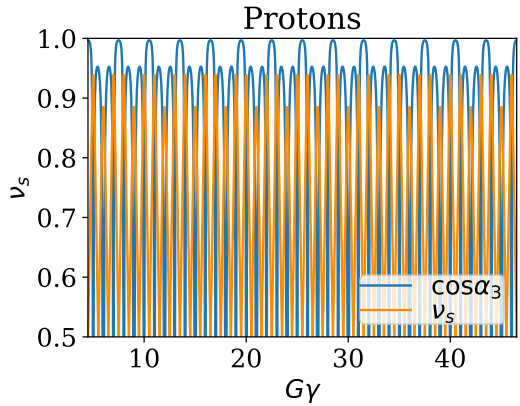
Snakes with helions

Snakes with deuteron

Snakes with lithium

Snakes in the AGS

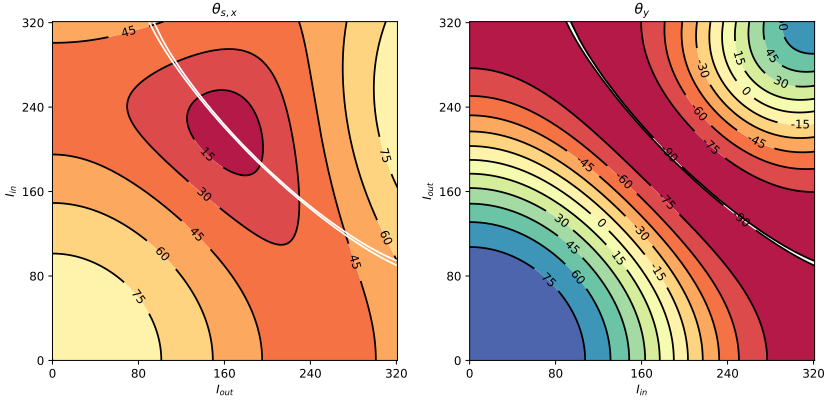
- Current configuration in the AGS with protons
- The spin-tune gap is the area where of tune-space above $\nu > 0.95$.
- For protons, $\nu_y \sim 0.95 - 0.99$ to avoid crossing $\nu_s = \nu_y$.
- Horizontal intrinsic resonanaces occur every $n \pm \nu_x$, and utilizes a fast tune-jump to minimize polarization loss.



- Full correction of snake resonance driving terms is being commissioned to improve polarization transmission.[a]

[a] V. Schoefer "Using betatron coupling to suppress horizontal intrinsic spin resonances driven by partial snakes" 2021.

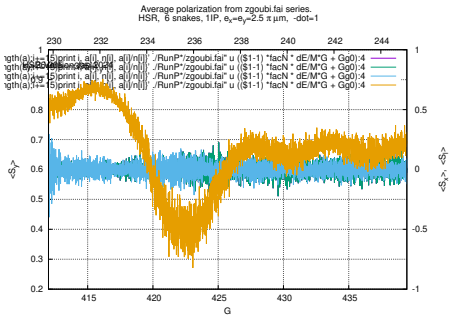
Snakes in the EIC with protons



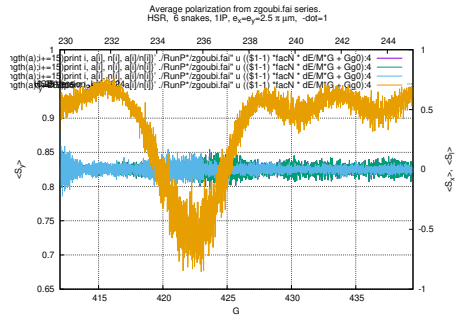
- To minimize the orbit matching requirements to the snake, $l_{out} < l_{in}$ is preferential.
- A snake precession axes angle of $\theta_{s,x}$=0 to 60 degrees can be supported.

Polarization Transmission with Protons

VKICK .2, $\sigma_y = 1.3\,\text{mm}$
$P_i = 0.875 \quad P_f = 0.685 \quad P_f/P_i = 0.783$



VKIC .1, $\sigma_y = 0.65\,\text{mm}$
$P_i = 0.945 \quad P_f = 0.935 \quad P_f/P_i = 0.989$



- Including randomly misaligned elements, there is sensitivity to the phase and amplitude [1].
- This warrants further study to find the optimal snake axes.
- Simulations were performed with the January 2024 lattice.

[1] F. Mèot, "EIC HSR beam polarization vs. jeopardized 3-periodicity", 2024.

Brookhaven National Laboratory

Introduction

Snakes with Protons

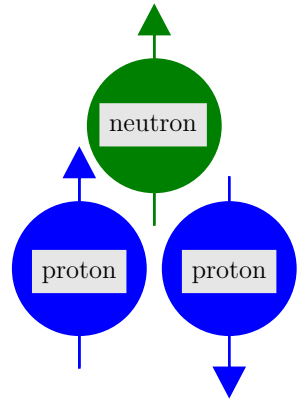
Snakes with helions

Snakes with deuteron

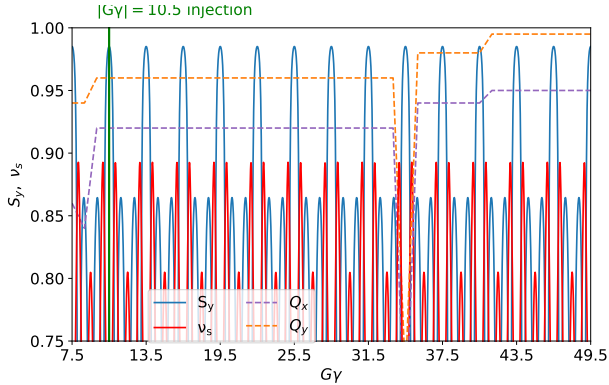
Snakes with lithium

Polarized helions

- Polarized neutron collisions will be facilitated with collisions of polarized helions, where up to 86% of the polarization is accounted for by the neutron.
- Polarization scheme of helions provides polarized neutrons paired with two unpolarized protons, q=2.
- The source is being developed as an upgrade to the EBIS preinjector and is expected in 2026.

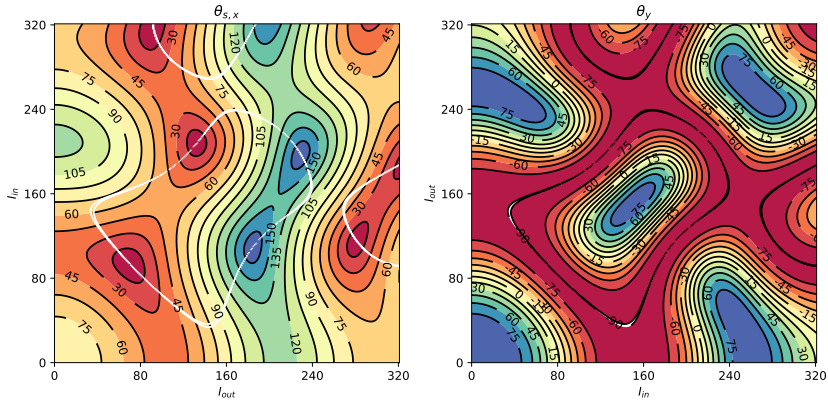


Snakes in the AGS, helions



- Intended configuration will have both ν_x and ν_y inside the spin-tune gap.
- Possibility of crossing some resonances early in the acceleration cycle if there is insufficient admittance to move both tunes inside the spin-tune gap.

Snakes in the EIC, helions

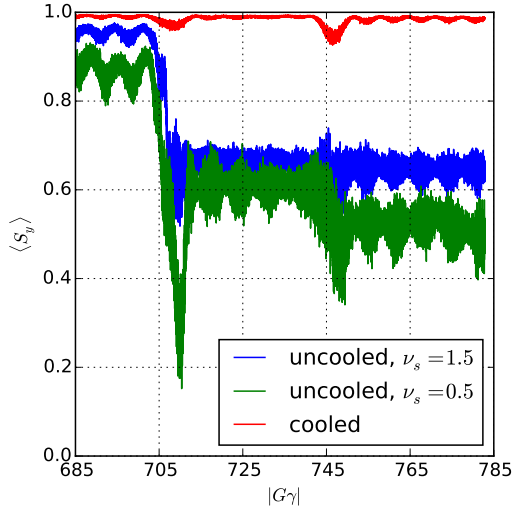


- Due to the higher G of helions, the snakes can accommodate all possible angles.

Polarization Transmission with Helions

In the presence of strong resonances, the ν_s set by the snakes can be perturbed, risking polarization loss.

- Due to the higher $|G\gamma|$ reached by helions, the snake precession axes need to be optimized to minimize these losses.
- With cooled beams ($\varepsilon_x = 2.0\ \mu m$, $_y = 0.5\ \mu m$), polarization transmission is near 100% across the strongest resonances.
- With uncooled beams ($\varepsilon_x = 2.5\ \mu m$, $_y = 2.5\ \mu m$), one can observe the transmission efficiency of bunched beam with ν_s=0.5 ($\phi_k = \pm 15$) and ν_s=1.5 ($\phi_k = \pm 45$) .
- Simulations performed with lattice from January 2024.



Introduction

Snakes with Protons

Snakes with helions

Snakes with deuteron

Snakes with lithium

Polarized deuteron in EIC

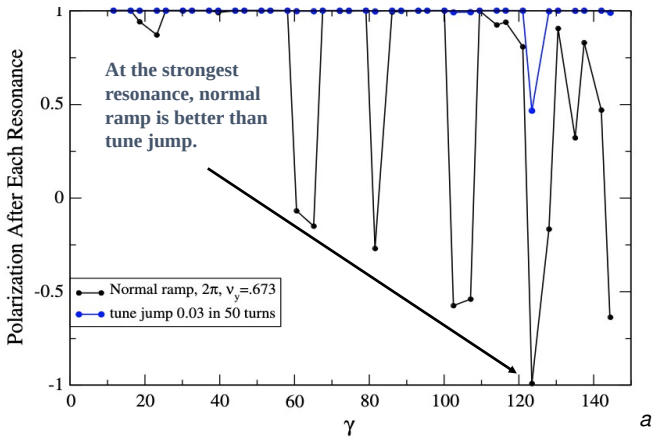
Unpolarized dueteron beam has been used in RHIC during ion physics program[a].

- $G\gamma$ range: -1.6 to -20.9. 19 imperfection resonances. With an rms orbit error of 0.3 mm, 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/dt=90/220 s$\Rightarrow$resonance crossing rate =1.2×10^{-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. 15 Tm warm solenoid (0.45% partial snake) should work. AGS Solenoid: 4.7 Tm and 2.4 m long.
- There are 38 intrinsic resonances in the energy range. They can be overcome by a modest vertical tune jump system (0.03 unit in 50 turns). For the strongest one, full spin flip can be achieved (2 m rms emittance assumed).

Presently, the EIC physics program does not include polarized deuterons.

[a] From H. Huang "Hadron Polarization for EIC" 2024

Polarization Transmission with deuterons



Polarization is largely preserved with the use of the weak tune jump.

a From H. Huang "Hadron Polarization for EIC" 2024

Introduction

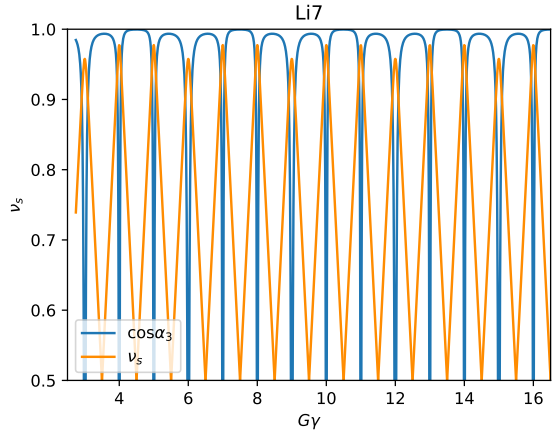
Snakes with Protons

Snakes with helions

Snakes with deuteron

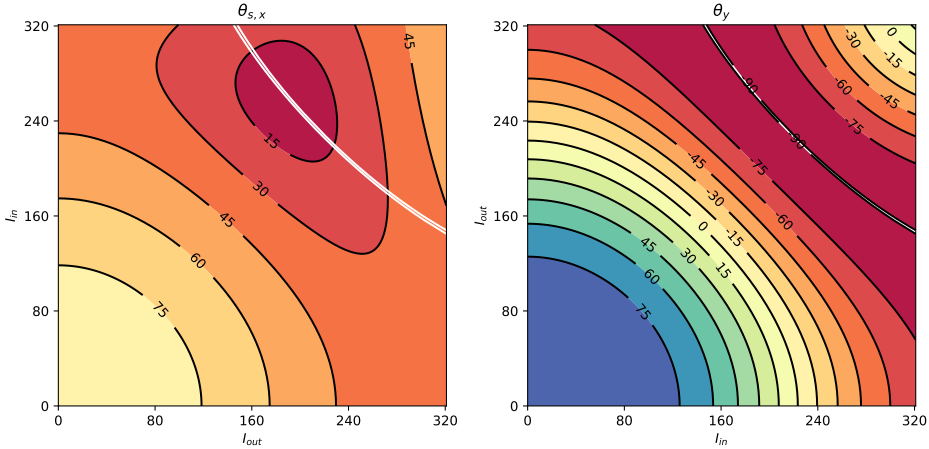
Snakes with lithium

Snakes in the AGS with Li7, preliminary



- Li7 has a smaller spin-tune gap, although is extracted before the stronger resonances.
- Li7 would need tune-jump to cross resonances faster or skew quads for resonance correction.

Snakes in the EIC with Li7, preliminary



- Li7 has a limited snake axis range of $\theta_{s,x}$ =0 to 30.
- Confirmed with field maps that full spin-flip is possible.

Summmary

On protons:

- In the AGS, the partial snake configuration leaves polarization loss to external systems.
- In the HSR, the six snakes will allow polarization transmission up to the maximum energy.
- Care must be taken when considering the snake axes, and optimization studies are ongoing.

On helions:

- In the AGS and the HSR, the snakes should allow for high polarization transmission.
- Having buth ν_x and ν_y inside the spin-tune gap avoids all resonances in the AGS.
- Attention must be paid to the snake axes in the EIC to see high polarization transmission.
- The rotators can place the spin in the vertical plane at all energies.

On Deuteron:

- Deuterons can use a solenoid as a partial snake and will need a tune jump system to overcome intrinsic resonances.
- This configuration allows for high polarization transmission.

On Lithium:

- Preliminary analysis indicate: Li7 can likely use the same techniques as protons where Li6 can use the same techniques as deuteron.
- Identifying upgrades for Li6 and Li7 in the injectors would likely benefit the transmission other polarized species.

Thank you & questions.