An Overview of Helions in the HSR and its Injectors

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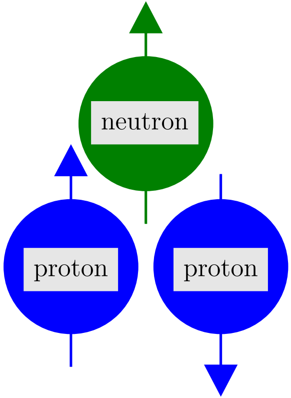
Why helions?

- Polarized neutron collisions are part of the EIC physics program (q=0).
- 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.



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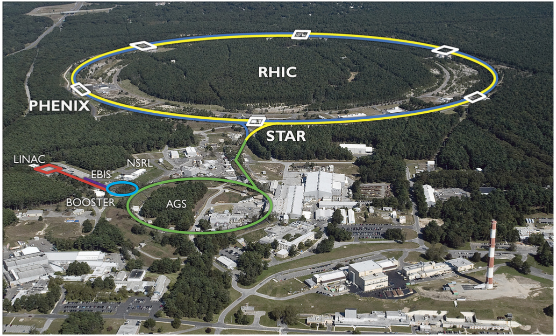
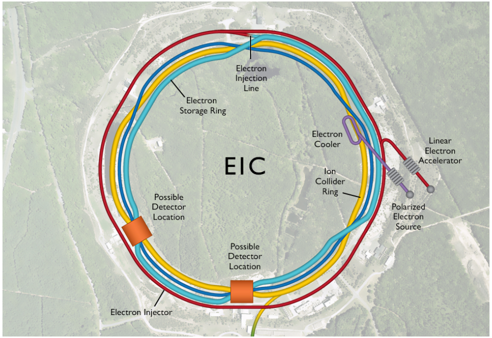
The RHIC and EIC Accelerator Complex





- RHIC scheduled to run until 2025.
- 2025 through 2032 is construction of EIC.
  - ► Installation of electron collider ring inside RHIC tunnel.
- EIC commissioning and physics program to follow.

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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 $\vec{E}$)

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

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

From this, the resonance strength can be calculated with the Fourier transform of spin perturbing fields

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

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 betatron tune.

Introduction

Polarized Helions in the AGS Booster
- Intrinsic Resonance Crossing
- Imperfection Resonance Crossings

Polarized Helions in the AGS
- AGS Admittance at Injection
- Extraction from AGS

Polarized Helions in the HSR
- HSR Resonance Strengths
- HSR Rotators

Summary

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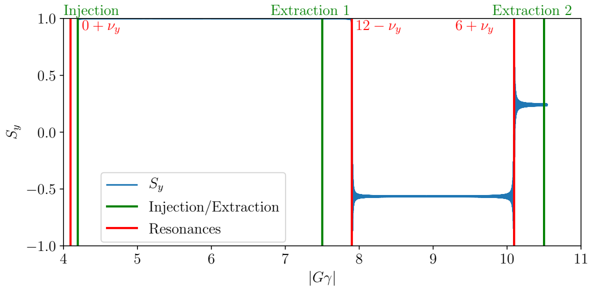
Overview of helions in the Booster



- helions are injected into the Booster at $|G\gamma| = 4.19$
- The injected intensity from EBIS is expected to be 2×10^{11} with a polarization of 80%.
- At injection, $\nu_y < 4.1$ to avoid the $|G\gamma| = 0 + \nu_y$ resonance
- Extraction possible at $|G\gamma| = 7.5$ and $|G\gamma| = 10.5$

Extraction at $|G\gamma| = 10.5$

- Crossing $|G\gamma| = 5$ through 10 imperfection resonances
- Crosses $|G\gamma| = 12 - \nu_y$ and $|G\gamma| = 6 + \nu_y$
- Allows stronger snakes for
- Minimizes optical defects from AGS cold snake
- Vertical tune can be placed inside spin tune gap in AGS at injection

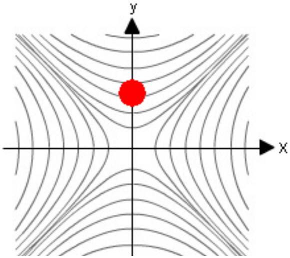
Intrinsic Resonance Crossing with an AC Dipole

An AC dipole works by forcing all particles to undergo large amplitude vertical betatron oscillations.

- This is done with a horizontal magnetic field that oscillates in phase with the vertical betatron motion, at tune $\nu_m = f_m/f_{rev}$.
- The amplitude of these coherent oscillations is

$$Y_{coh} = \frac{B_m l}{4\pi B\rho\delta_m}\beta_y \tag{3}$$

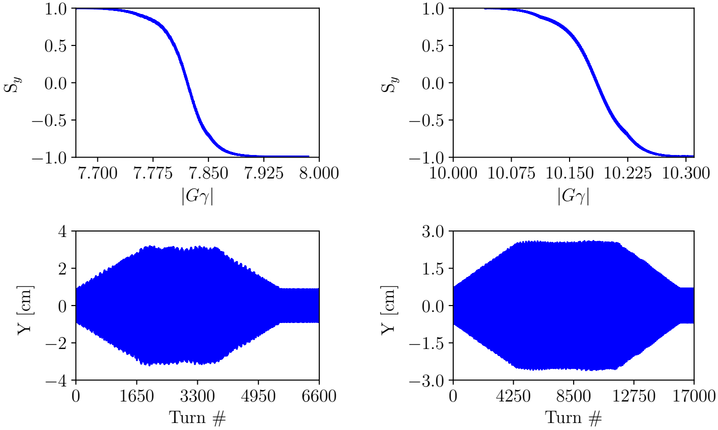
  where $B_m l$ is the integrated strength of the dipole kick.
- The separation between the tune of the AC dipole, ν_m, and ν_y is the resonance proximity parameter, $\delta_m = \nu_y - (n + \nu_m)$.
- This creates a driven resonance at ν_m.



As f_m is fixed, ν_m can change as much as $\Delta\nu_m = 0.0028$ for helions crossing $|G\gamma| = 12 - \nu_y$ due to rapid change in f_{rev}

Intrinsic Resonance Crossing with an AC Dipole

helions crossing the $|G\gamma| = 12 - \nu_y$ (left) and $|G\gamma| = 6 + \nu_y$ (right)



Full spin-flip achieved with $\mathrm{B_m l} = 16.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 12 - \nu_y$) and $\mathrm{B_m l} = 20.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 6 + \nu_y$).

Details in K. Hock "Transport of Polarized helions in Injector Synchrotrons for the future electron-ion collider project at the Brookhaven National Laboratory" PhD Thesis, 2021.

Imperfection Resonances: Harmonic Orbit Correction

For correcting the $|G\gamma| = k$ resonance, the h=k harmonic of the corrector dipoles is used. Harmonic h=k can be:

- corrected so no polarization is lost,
- or enhanced to induce a full spin-flip.

The Booster has 24 vertical orbit correctors placed adjacent to vertically focusing quadrupoles, and are used for creating and correcting orbit harmonics. These correctors are powered according to

$$B_{j,h} = a_h \sin(h\theta_j) + b_h \cos(h\theta_j) \tag{4}$$

where j is corrector number, θ_j is the location in the ring, a_h and b_h are the amplitudes for harmonic h. The total current on corrector j is

$$I_j = \sum_h I_{h,S} \sin(h\theta_j) + I_{h,C} \cos(h\theta_j) \tag{5}$$

where $I_{h,S}$ and $I_{h,C}$ are the corrector currents for the Sine and Cosine components. The maximum current of all correctors is

$$I_{max} = \max[|I_j|]. \tag{6}$$

This is an important parameter so as to avoid exceeding the maximum current of the supplies, 25 A.

Summary of helions Corrector Strength Requirements

The Froissart-Stora formula at a given resonance k, and harmonic h=k, as a function of corrector current is given by,

$$\frac{P_f}{P_i} = 2e^{-\frac{(I_{k,S}-I_{k,oS})^2}{2\sigma^2_{k,S}}} e^{-\frac{(I_{k,C}-I_{k,oC})^2}{2\sigma^2_{k,C}}} - 1 \quad (7)$$

To allow all helions imperfection resonances to be studied with the same orbit, the h=4 and h=5 harmonic corrections are scaled to all higher order resonances by the ratio of rigidity. That is

$$I(h=5, |G\gamma| = k) = I(|G\gamma| = 5)\frac{B\rho(|G\gamma| = k)}{B\rho(|G\gamma| = 5)} \quad (8)$$

These corrector currents are [$I_{4,S}$, $I_{4,C}$, $I_{5,S}$, $I_{5,C}$]=[2.797 A, 0.669 A, 0.520 A, 4.296 A]

K	μ_S [A]	μ_C [A]	$I_{S,K}$	$I_{C,K}$	$I_{M,F}$	$I_{M,C}$
5	0.322	2.105	0.35	-1.71	4.33	6.44
6	0.567	-0.189	1.78	9.65	17.77	9.19
7	1.425	0.847	10.02	-8.14	22.4	13.95
8	-2.463	5.242	2.75	-9.39	21.98	22.37
9	-0.614	-0.222	-1.17	-14.35	29.71	17.59
10	-23.669	-0.477	-3.67	-0.477	22.86	39.43

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AGS Snakes, optical distortions

To quantify the optical defects, particles are tracked through only the cold snake to calculate the transport matrix.
From the transport matrix, the total coupling (CP) and focusing (FC) are calculated from transport matrix elements m_{ij},[a]

$$CP = LL + UR \tag{9}$$

with

$$LL = m_{31}^2 + m_{32}^2 + m_{41}^2 + m_{42}^2 \tag{10}$$

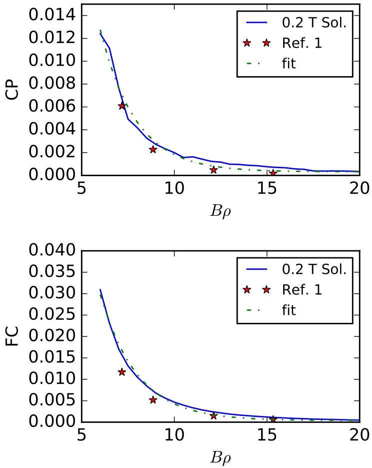
$$UR = m_{13}^2 + m_{14}^2 + m_{23}^2 + m_{24}^2. \tag{11}$$

and

$$FC = m_{12}^2 + m_{34}^2 \tag{12}$$

[a] Ref 1: C-A/AP 128, Cold Snake Optimization by Modelling

These optical distortions reduce exponentially with $B\rho$.



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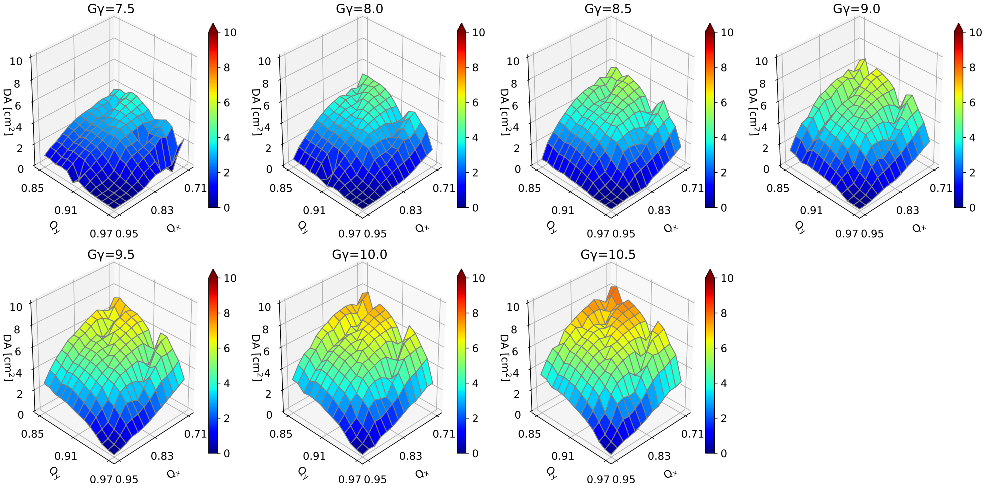
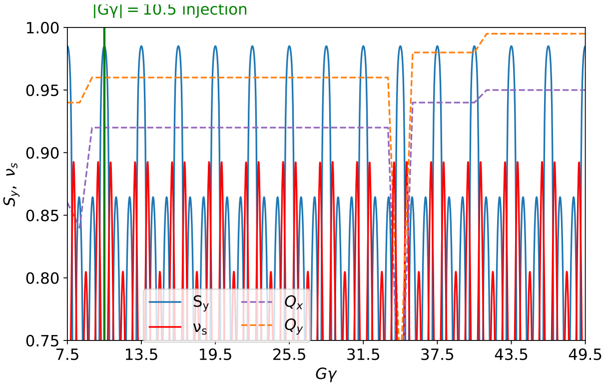
AGS admittance at injection



- Substantial increase in admittance with changes in $B\rho$
- Next slide has a closer look at the admittance in the region of $Q_x, Q_y > 0.88$.

Helions in AGS



Example horizontal and vertical tunes, along with spin tune and the projection of the stable spin direction on the vertical axis.

- At $G\gamma$=8, the $G\gamma = 8 \pm \nu_x$ and $G\gamma = 8 \pm \nu_y$ are potentially crossed.

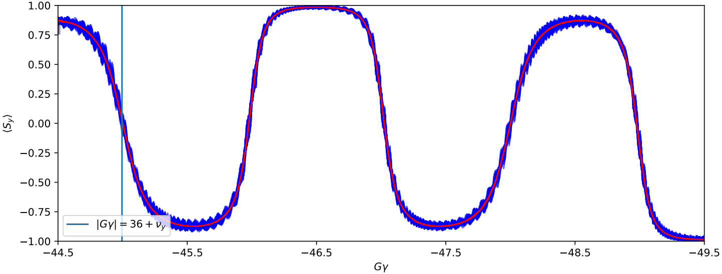
AGS resonance crossings

Due to the reduced admittance at $|G\gamma| = 7.5$, excessive beam loss will necessitate additional bunch merges compared to the $|G\gamma| = 10.5$ case.

$\lvert G\gamma\rvert$	ν_x	ν_y	Beam loss	Polarization
7.5 to 8.5	8.88	8.94	76.7%	98.7%
8.5 to 9.5	8.82	8.94	0.2%	99.0%
9.5 to 10.5	8.92	8.96	14.7%	99.7%

To support $|G\gamma| = 10.5$ injection, the Booster Main Magnet PS and AGS injection kicker need upgrades.

Crossing the $|G\gamma| = 36 + \nu_y$



Extraction from AGS

helions will be extracted from the AGS to the HSR at $|G\gamma| = 49.5$.

- Due to mismatch in stable spin direction between RHIC and AGS, extraction cannot occur above $|G\gamma| = 51.5$.
- This is lower in rigidity ($B\rho = 55.21\ Tm$) than protons which extract at $G\gamma = 45.5$ ($B\rho = 79.37\ Tm$).

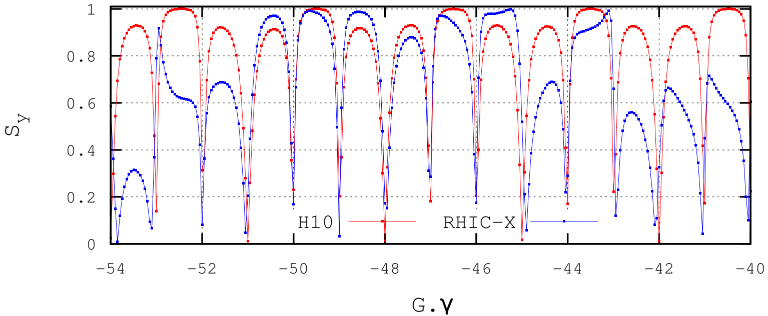


Image from F. Méot et al. "On the Image of AGS 3He2+ n0 , in the Blue" C-AD tech note, 2015.

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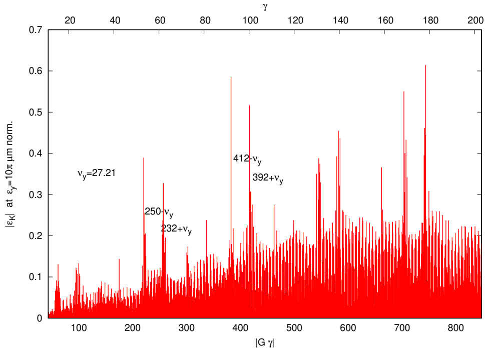
HSR resonance strengths



- The baseline resonance strength for the $|G\gamma| = 400$ region is comparable to the $|G\gamma| = 700$ region.
- At $|G\gamma| = 412 - \nu_y$, the resonance is strong but well isolated
- At $|G\gamma| = 718 + \nu_y$, the nearby 715+, 716+, and 717+ are all stronger than the strongest proton resonance.
- The 734- region is similar, albeit with slightly more spacing.
- The $|G\gamma|$=500 region may give insight into the stronger resonances (several strong resonances packed together).

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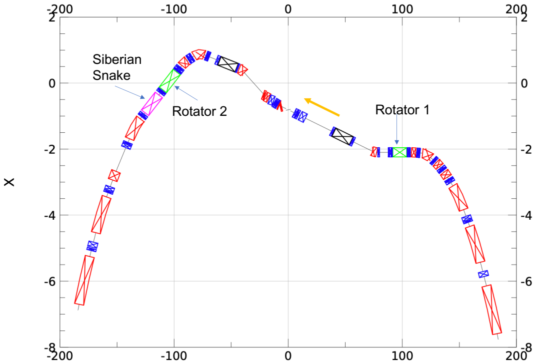
HSR rotators

The HSR rotators are at θ=61.35 mrad and θ=-17 mrad away from IP6, where RHIC Rotators are at θ =3.675 and -3.675 mrad, with θ being the bending angle. For the angle to be longitudinal at IP6, the angle at each rotator in the horizontal plane is

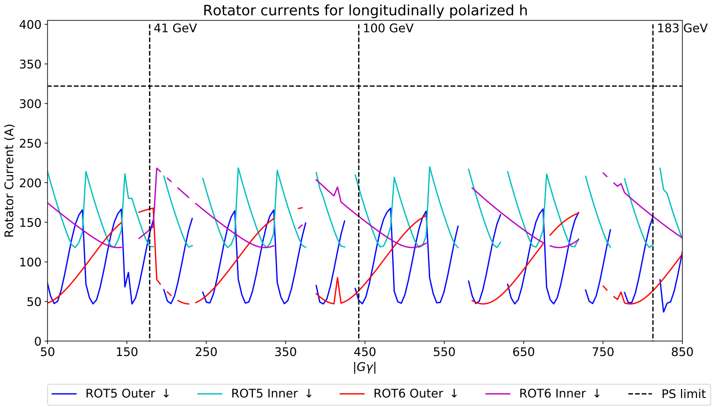
$$\phi = G\gamma\theta \tag{13}$$



- the rotators consist of four helical dipoles
- The outer coils are powered separately from the two inner coils.
- the PS limit is 322 A.

Image from V. Ptitsyn et al. ”EIC Hadron Spin Rotators” IPAC, 2022

Polarized helion energy scan



- Because of the higher G, the current requirements are well below the $\pm 322\ A$
- Regions with hole values correspond to where the fit routine failed and need to be investigated further

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- The AC dipole is able to spin-flip through the two intrinsic resonances in Booster. The harmonic correction method allows for 100% polarization transmission through the six imperfection resonances.
- The higher injection $|G\gamma|$ into AGS allows for stronger snake settings.
- These stronger snakes allow both horizontal and vertical tunes to be placed inside the spin tune gap. This precludes the need of tune jumps and emittance growth associated with it.
- Extraction from the AGS at $|G\gamma| = 49.5$ provides the best spin match from AGS to RHIC and avoids the $|G\gamma| = 60 - \nu_y$ resonance.
- An intensity of 1.5×10^{11} ions/bunch with a polarization of 75-78% is expected at extraction.
- Current RHIC rotators and their PS can be reused and will operate below their PS limits.
- HSR resonance crossing simulations are ongoing.

Thank you

Thank you and questions.