He-3 polarization preservation in injectors

Kiel Hock

December 13, 2022

Brookhaven National Laboratory

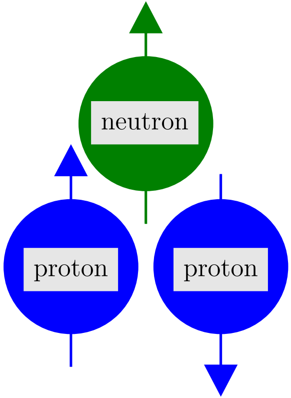
U.S. DEPARTMENT OF ENERGY

@BrookhavenLab

Table of Contents

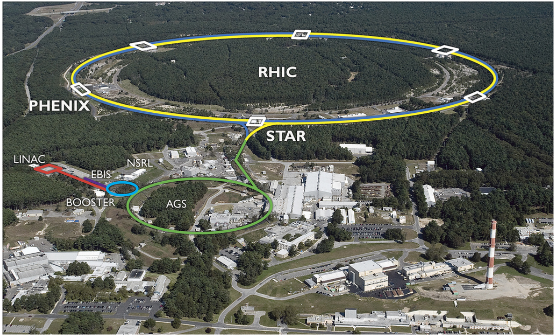
Why He-3?

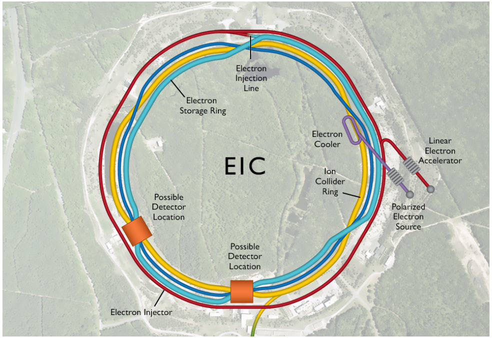
- Polarized neutron collisions are part of the EIC physics program (q=0).
- Polarized neutron collisions will be facilitated with collisions of polarized He-3, where up to 86% of the polarization is accounted for by the neutron.
- Polarization scheme of He-3 provides polarized neutrons paired with two unpolarized protons, q=2.



Brookhaven National Laboratory

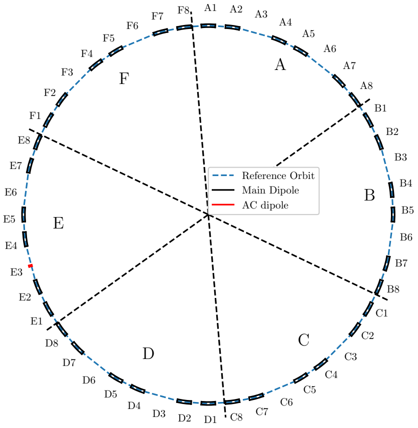
The RHIC and EIC Accelerator Complex





- 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.

Booster and AGS



The Booster will receive polarized He-3 from the EBIS at 2 MeV/u. The Booster:

- Has a superperiodicity of P=6, labelled A through F,
- Each superperiod contains 4 FODO cells and 6 main dipoles,
- Circumference of 201.78 m,
- $\nu_y < 4.5$ for polarized He-3 and $\nu_y > 4.5$ for polarized protons.
- Serves as the injector for the AGS.

The AGS is the injector for RHIC

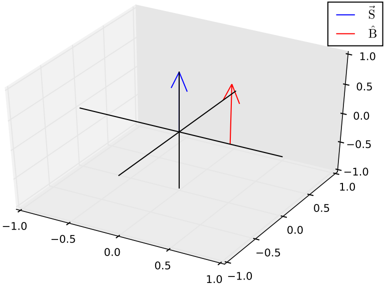
- Has a superperiodicity of 12 (labelled A through L) with a length of 807.12 m
- Tunes typically $\nu_y > 8.9$ for polarized protons.

Brookhaven National Laboratory

Spin Dynamics

Torque on the magnetic moment from a magnetic field: $\vec{\Gamma} \propto \vec{S} \times \vec{B}$

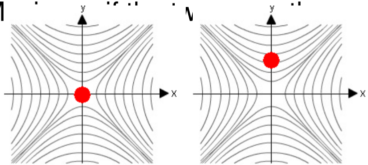
- No torque if the two are parallel
- Maximum if the two are orthogonal

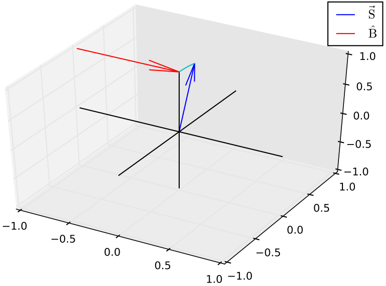


Spin Dynamics

Torque on the magnetic moment from a magnetic field: $\vec{\Gamma} \propto \vec{S} \times \vec{B}$

- No torque if the two are parallel
- M … al

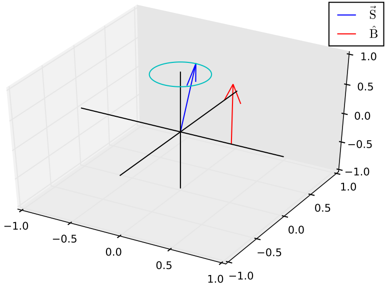




Spin Dynamics

Torque on the magnetic moment from a magnetic field: $\vec{\Gamma} \propto \vec{S} \times \vec{B}$

- No torque if the two are parallel
- Maximum if the two are orthogonal
- Beam now rotates in dipole field since they are no longer parallel.



Number of rotations the spin rotates in one turn is known as the spin tune: $\nu_s = G\gamma$, with G being the anomalous magnetic moment (G_{He-3}=-4.1842, $G_{protons}$=1.7928) and γ being the Lorentz factor.

Brookhaven National Laboratory

Thomas-BMT

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.

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

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

Brookhaven National Laboratory

Depolarizing Resonances and Polarization Preservation

Depolarizing resonances are primarily caused by particles sampling the horizontal fields of quadrupoles.

This causes depolarization when the spin precession is in phase with the sampling of the fields. This occurs when:

1. Imperfection Resonances: $\nu_s = n$
   - Result of non-zero vertical closed orbits
2. Intrinsic Resonances: $\nu_s = nP \pm \nu_d$
   - Where d is x or y, and the number of spin rotations in one turn of the ring is in phase with excursions into quadrupoles from betatron oscillations

where n is an integer and P is the superperiodicity.

Overview of polarization preservation techniques to be covered in detail:
In the AGS Booster

- Imperfection resonance crossing using orbit harmonic correction scheme
- Intrinsic resonance crossing using

In the AGS

- two partial snakes for overcoming imperfection and intrinsic depolarizing resonances.

The AGS snakes constrain our configurations and so will be covered first.

Brookhaven National Laboratory

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 rotate 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

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

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 $\nu_\mathrm{s} \neq \mathrm{G}\gamma$ with snakes.
The projection of the stable spin direction on the vertical axis is given by

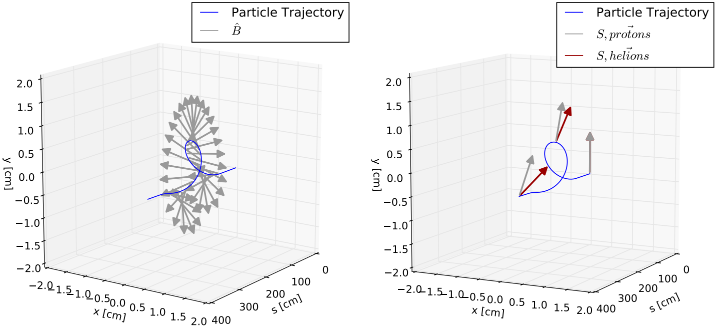
$$\cos\alpha_3 = \frac{1}{\sin\ \pi\nu_s}\left[\cos\frac{\chi_w}{2}\cos\frac{\chi_c}{2}\sin(G\gamma\pi) - \sin\frac{\chi_w}{2}\sin\frac{\chi_c}{2}\sin(G\gamma\frac{\pi}{3})\right] \tag{4}$$

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

$$G\gamma = 3n + 1.5. \tag{5}$$

Brookhaven National Laboratory

AGS Snakes

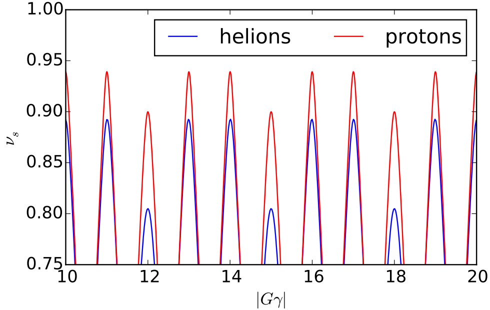


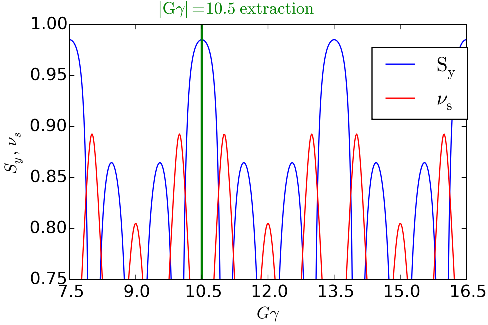
- This snake is a dipole magnet rolled into a helix.
- Direction of $\vec{B}$ sampled by particle and resulting spin rotation from vertical.
- The snakes are held at constant field.
- Due to horizontal component of stable spin direction, horizontal intrinsic resonances are present.
- With the same field strength snakes, He-3 will rotate G_h/G_p more than protons.
- This gives χ_c=25% and χ_w=14% (in units of % of π)

Brookhaven National Laboratory

ν_s and α_3 in the AGS

By having $\nu_s \neq G\gamma$, the criteria for imperfection resonance can no longer be satisfied.





This results in a substantial spin tune gap where both ν_x and ν_y can be placed.
Having both tunes inside the spin tune gap means the horizontal intrinsic resonances are also avoided.

- No emittance growth from many tune jumps.
- No polarization loss from crossing horizontal resonances.

Brookhaven National Laboratory

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]

$$CP = LL + UR \tag{6}$$

with

$$LL = m_{31}^2 + m_{32}^2 + m_{41}^2 + m_{42}^2 \tag{7}$$

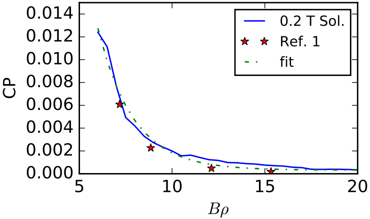
$$UR = m_{13}^2 + m_{14}^2 + m_{23}^2 + m_{24}^2. \tag{8}$$

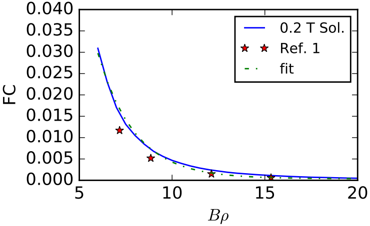
and

$$FC = m_{12}^2 + m_{34}^2 \tag{9}$$

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

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





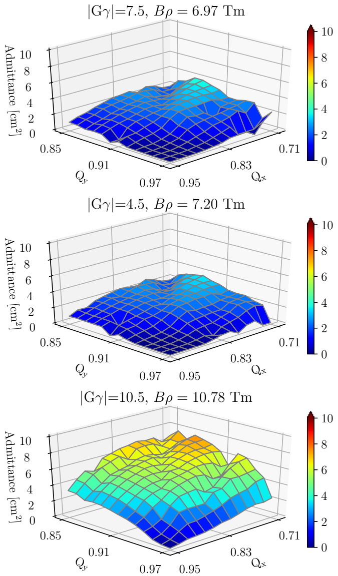
AGS Admittance Simulation Results

Protons cannot fit inside the spin tune gap at injection due to the snake optical defects limiting the admittance.
Simulations are performed at $B\rho = 6.968\ \mathrm{Tm}$, $B\rho = 7.203\ \mathrm{Tm}$, and $B\rho = 10.780\ \mathrm{Tm}$ as seen in figure.

- There are subtle differences in the admittance between He-3 at $B\rho = 6.968\ \mathrm{Tm}$ and protons at $B\rho = 7.203\ \mathrm{Tm}$
- A minimum factor of 2 gain in admittance in the $B\rho = 10.780\ \mathrm{Tm}$ case.

The admittance calculations are done for 1,000 turns to minimize computing time.

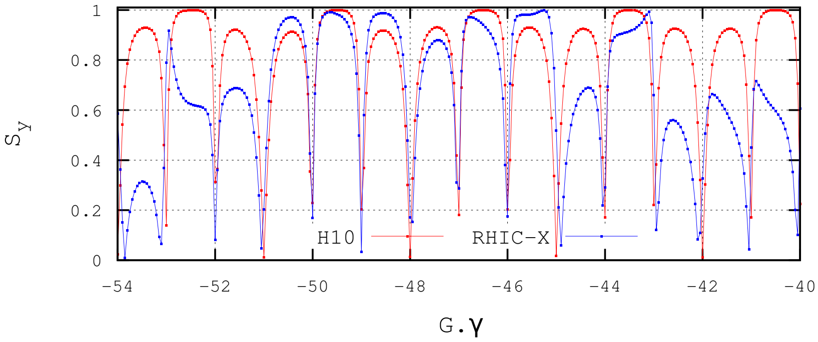
- Idealized admittance tracking would be for a number of turns equal to the time the particles are at injection energy.



Extraction from AGS

He-3 will be extracted from the AGS 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 $G\gamma = 45.5$ ($B\rho = 79.37\ Tm$).



Brookhaven National Laboratory

Introduction

- Booster and AGS
- Spin Dynamics

He-3 in the AGS

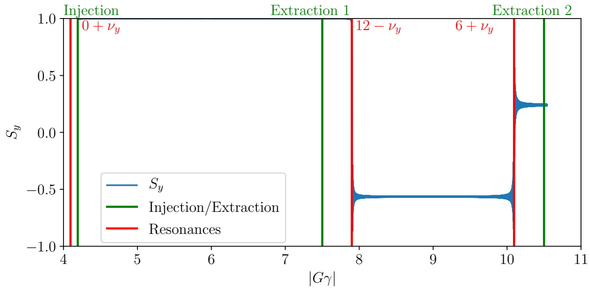
- The AGS Snakes
- AGS Admittance at Injection
- Extraction from AGS

He-3 in Booster

- Intrinsic Resonance Crossing with an AC Dipole
- 2021 AC Dipole Test Results
- Imperfection Resonance Crossing with Orbit Harmonics
- Additional Upgrades

Summary

Overview of He-3 in the Booster



- He-3 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

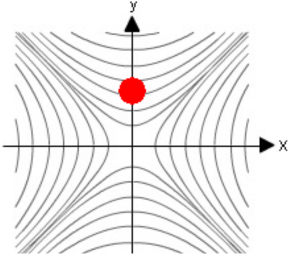
Intrinsic Resonance Crossing with an AC Dipole

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

$$Y_{coh} = \frac{B_m l}{4\pi B\rho\delta_m}\beta_y \tag{10}$$

  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.

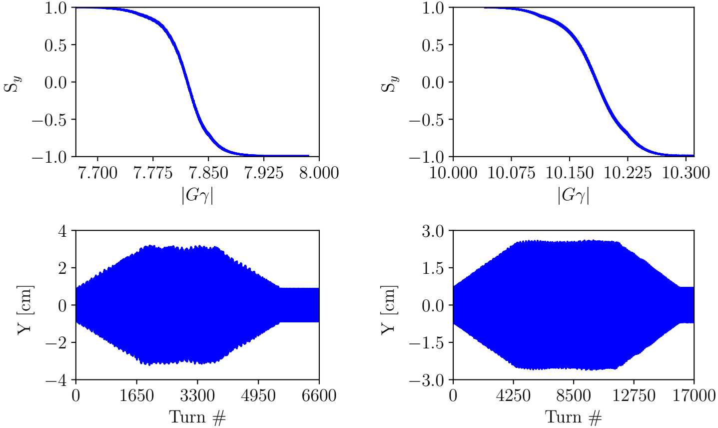


As f_m is fixed, ν_m can change as much as $\Delta\nu_m = 0.0028$ for He-3 crossing $|G\gamma| = 12 - \nu_y$ due to rapid change in f_{rev}

Brookhaven National Laboratory

Intrinsic Resonance Crossing with an AC Dipole

He-3 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 $\mathrm{B_m l} = 20.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 6 + \nu_y$).

Brookhaven National Laboratory

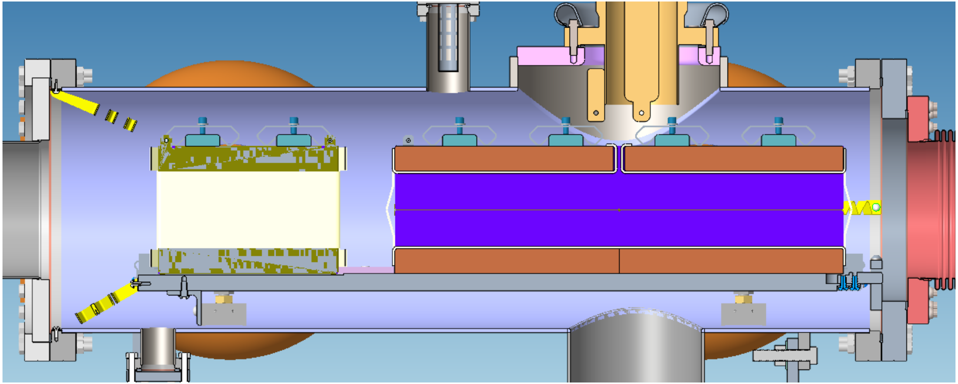
Summary of AC dipole Simulations

Resonance	Protons	He-3	
	$0+\nu_y$	$12-\nu_y$	$6+\nu_y$
ϵ_K	0.00246	0.00304	0.00440
σ_y [mm]	1.83	2.75	2.31
δ_m	0.01	0.01	0.01
$B_m l$ [Gm]	15.5	16.5	20.5
ν_y	4.809	4.192	4.174
ε_{ratio}	1.03	1.02	1.00
$N_{scraped}/N_{total}$[%]	0.0	1.2	0.0

where σ_y is the RMS width of the beam, ε_{ratio} is the comparison of σ_y at the start and end of the tracking, and $N_{scraped}/N_{total}$ monitors particle loss.

Brookhaven National Laboratory

AC Dipole upgrade



The AC dipole is powered as part of a resonant LC circuit

A drive frequency of $f_m = 250\ kHz$ is the maximum supported frequency for the power amplifier used in this beam test.

The design strength is $\mathrm{B_m l = 25\ G \cdot m}$ providing $\sim$ 25% margin from simulation.

Configuration for Proton Beam Tests

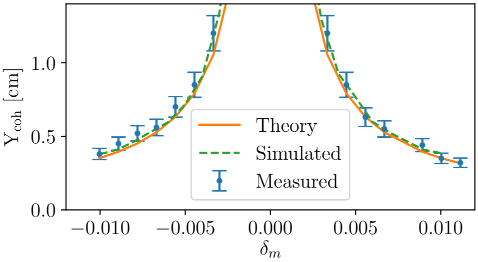
In preparation for He-3, the AC dipole was tested with protons.

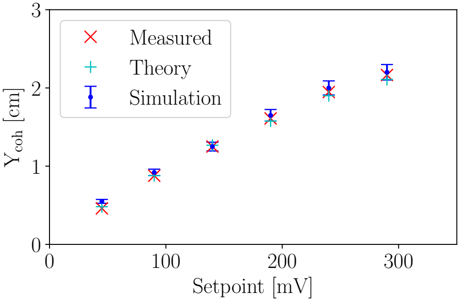
Protons are injected into the Booster from the 200 MeV LINAC

- $|G\gamma|_{injection} = 2.18$
- $\nu_y > 4.5$
- $|G\gamma_{extraction}| = 4.5$ avoids the $|G\gamma| = 0 + \nu_y$ intrinsic resonance.
- $|G\gamma|_{extraction}$ moved to $|G\gamma|_{extraction} = 4.93$ to cross $|G\gamma| = 0 + \nu_y = 4.81$.
  - Turn off AGS snakes so stable spin directions are matched.
  - Use AC dipole to preserve polarization across resonance.
- Cross the $|G\gamma| = 3,\ 4$ imperfection resonances.

Beam Dynamics with an AC dipole

Beam dynamics studies with unpolarized protons showed strong agreement between measurements, theory, and simulations.

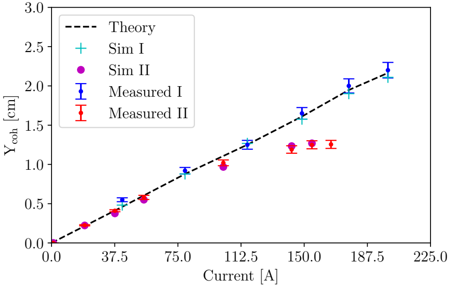




- Protons at this time were injected at 116 MeV, not nominal 200 MeV.

Results and Issues

BPM data shows reduced Y_{coh} vs I_m:



The RF operated in a fixed f_{rev} mode:

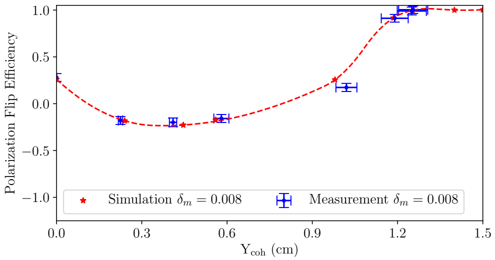
- which is the synchronization of RF for extraction from Booster to AGS (synchro) beginning 15 ms before extraction,
- it caused a change in radius to maintain the predetermined f_{rev},
- the change in radius caused feed-down in the sextupoles which resulted in a change of δ_m and a reduction of Y_{coh}.

The change in radius is

$$\Delta r = \frac{1}{2}\left\langle \frac{1+\alpha_y}{\beta_y} \right\rangle \frac{Y_{coh}^2}{2\beta_y} r. \tag{11}$$

This is implemented in Zgoubi with a radial change at turn 1200 to match experimental data.

Comparison of Experimental and Simulation Results



- Simulations show good agreement with measurements.
- Improvements between simulations and experimental data were achieved by mimicking the real beam conditions in detail.

Comparison of ϵ_k from simulation and experimental results:

	Simulation (2017)	Experiment
σ_y [mm]	1.83	1.23
$\epsilon_k(\sigma_y)$	0.002460	0.001905
$\epsilon_k(1.83\ mm)$	-	0.002324

Brookhaven National Laboratory

Reflection on He-3 with an AC dipole

- The model proved to accurately determine AC dipole requirements for polarized protons

He-3 crossing $|G\gamma| = 6 + \nu_y$ will occur 14.4 ms before extraction. To avoid interference with synchro, there are several options:

- Shorten the synchro process to occur outside the AC dipole pulse.
- Reduce the acceleration ramp rate after crossing the AC dipole pulse to further separate the synchro process.

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

$$B_{j,h} = a_h \sin(h\theta_j) + b_h \cos(h\theta_j) \tag{12}$$

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

$$I_j = \sum_h I_{h,S} \sin(h\theta_j) + I_{h,C} \cos(h\theta_j) \tag{13}$$

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

$$I_{max} = \max[|I_j|]. \tag{14}$$

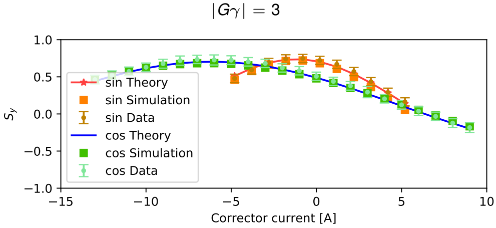
This is an important parameter so as to avoid exceeding the maximum current of the supplies, 25 A.

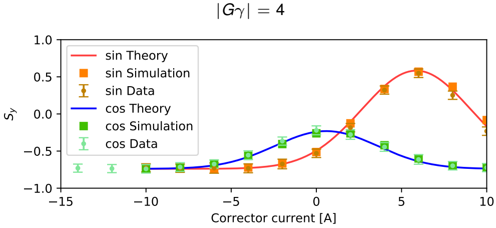
Protons Harmonic Scan at $|G\gamma|$=3,4

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

$$\frac{P_f}{P_i} = 2e^{-\frac{(I_{k,S}-I_{k,oS})^2}{2\sigma_{k,S}^2}} e^{-\frac{(I_{k,C}-I_{k,oC})^2}{2\sigma_{k,C}^2}} - 1 \tag{15}$$

where $I_{k,oS}$ and $I_{k,oC}$ are the optimal corrector currents, and $\sigma_{k,S}$ and $\sigma_{k,C}$ the widths.
Harmonic scan of protons crossing $|G\gamma| = 3,\ 4$ with a comparison between theory, simulations, and experimental data,

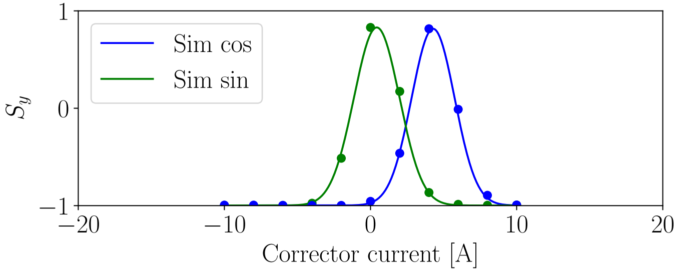




Brookhaven National Laboratory

He-3 Crossing $|G\gamma|$=5

With the experimental data of protons being well matched with simulation, the treatment is extended to He-3. Figure below shows a harmonic scan for He-3 crossing $|G\gamma| = 5$.



To correct the orbit harmonic h=4, $[I_{4,S}, I_{4,C}]$=[2.797 A, 0.669 A] and to spin-flip: h=5 currents are $[I_{5,S}, I_{5,C}]$=[10.0 A, -18.0 A] and I_{max}=23.086 A.
Harmonic scans for the remaining imperfection resonances and fit results are summarized in Table and corrector family currents and corresponding I_{max} on next slides.

Brookhaven National Laboratory

Summary of He-3 Corrector Strength Requirements

To allow all He-3 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

$$I(h=5, |G\gamma|=k) = I(|G\gamma|=5)\frac{B\rho(|G\gamma|=k)}{B\rho(|G\gamma|=5)} \tag{16}$$

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

- To improve the margin, the existing Booster Corrector supplies will be modified to allow 40 A of maximum current.

Additional Notes

The BtA transfer line is designed for a maximum $B\rho = 9.5\ Tm$ which is primarily limited by the kicker magnets.

- These will need to be upgraded to support higher extraction energy.

The Booster Main Magnet power supply only has two of six modules capable of going beyond $B\rho = 9.5\ Tm$

- The slower ramp rate from having lower voltage does not adversely effect polarization transmission in the booster.

Summary

- 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 to avoid polarization loss, and emittance growth, through horizontal resonances.
- 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.
- Extraction from the AGS at $|G\gamma| = 49.5$ provides the best spin match from AGS to RHIC.
- An intensity of 1.5×10^{11} ions/bunch with a polarization of 75-78% is expected at extraction.

Thank you

Thank you and questions.

Brookhaven National Laboratory