Maximizing He-3 polarization

Kiel Hock for Team

C-AD Machine Advisory Committee
December 17-19, 2025

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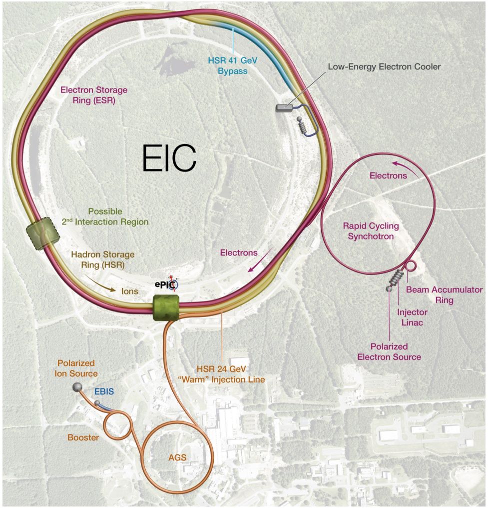
Brookhaven National Laboratory

Polarized He-3 at the EIC

Polarized He-3 will facilitate polarized neutron collisions for the Electron Ion Collider.

- Polarized He-3 beams will be produced at the Electron Beam Ion Source (EBIS) with an expected intensity of 2.5×10^{11} ions/pulse and 85% polarization.
- EBIS accelerates the beam to 2 MeV/u ($|G\gamma|$ =4.1932).
- Booster accelerates up to $|G\gamma| = 7.5$ or 10.5 to match stable spin directions with AGS.
- AGS accelerates up to $|G\gamma|$ =49.5, avoiding the strong $|G\gamma| = 60 - \nu_y$ intrinsic resonances.
- HSR will accelerate and store the beam up to $|G\gamma| = 820$.
- This is significantly higher than polarized protons with $G\gamma = 487$ (RHIC, achieved) and $G\gamma = 525$ (HSR, planned).
- The EIC requires He-3 with a store intensity of 0.8×10^{11} ions/bunch and 70% polarization.

Parameter	Value	Unit
Mass	2808.39	MeV/c^2
q	2	e
G	-4.1842	-



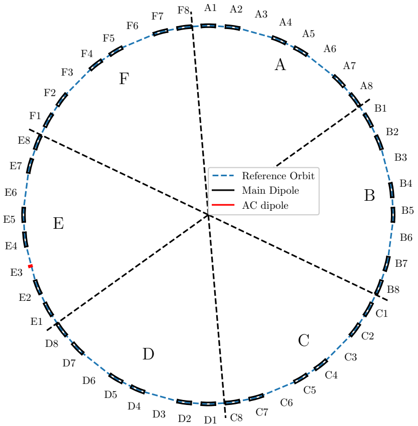
Spin Dynamics in Accelerators

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

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

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

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.
- Injecting at $\nu_y < 4.09$, the $|G\gamma| = 0 + \nu_y$ is avoided.
- There are three imperfection resonances up to $|G\gamma| = 7.5$.
- There are six imperfection resonances and two intrinsic resonances up to $|G\gamma| = 10.5$.

The AGS is the injector for HSR

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

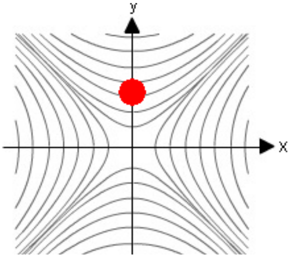
Booster Intrinsic Resonance Crossing with an AC Dipole

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

$$Y_{coh} = \frac{B_m l}{4\pi B\rho\delta_m}\beta_y \qquad (2)$$

  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.

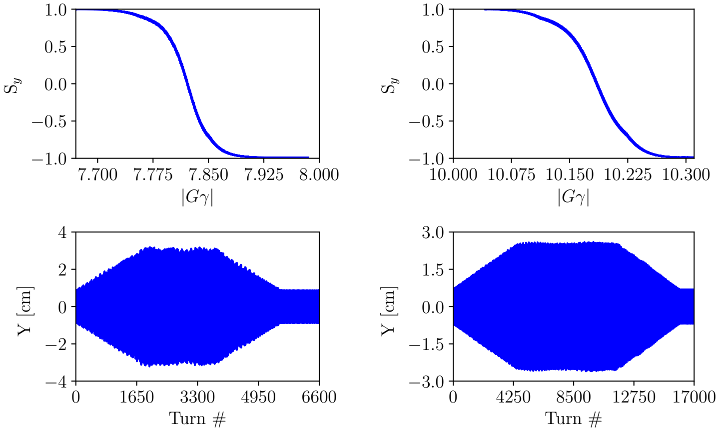


As f_m is fixed, ν_m can change as much as $\Delta\nu_m = 0.0028$ for He-3 crossing $|G\gamma| = 12 - \nu_y$ due to rapid change in f_{rev}

- The current configuration for the AC dipole supports up to 16.1 $\mathrm{G \cdot m}$.
- The design is 25 $\mathrm{G \cdot m}$ which requires two power amplifiers connected to the magnet. This approach is still being investigated.

Booster 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 $\mathrm{B_m l} = 20.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 6 + \nu_y$), with $\delta_m = 0.01$.

Booster 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

$$B_{j,h} = a_h \sin(h\theta_j) + b_h \cos(h\theta_j) \tag{3}$$

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

$$I_j = \sum_h I_{h,S} \sin(h\theta_j) + I_{h,C} \cos(h\theta_j) \tag{4}$$

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

$$I_{max} = \max[|I_j|]. \tag{5}$$

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

Summary of He-3 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,

$$\frac{P_f}{P_i} = 2e^{-\frac{(I_{k,S}-I_{k,oS})^2}{2\sigma^2_{k,S}}} e^{-\frac{(I_{k,C}-I_{k,oC})^2}{2\sigma^2_{k,C}}} - 1 \quad (6)$$

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

$$I(h=5, |G\gamma|=k) = I(|G\gamma|=5)\frac{B\rho(|G\gamma|=k)}{B\rho(|G\gamma|=5)} \quad (7)$$

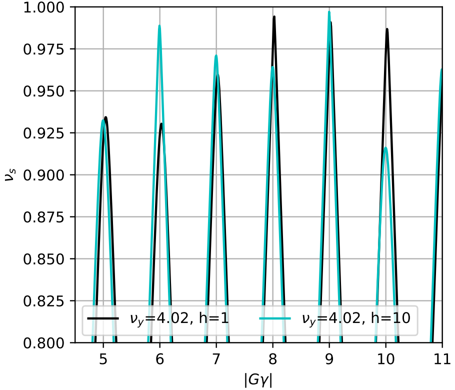
These corrector currents are [$I_{4,S}$, $I_{4,C}$, $I_{5,S}$, $I_{5,C}$]=[2.797 A, 0.669 A, 0.520 A, 4.296 A]

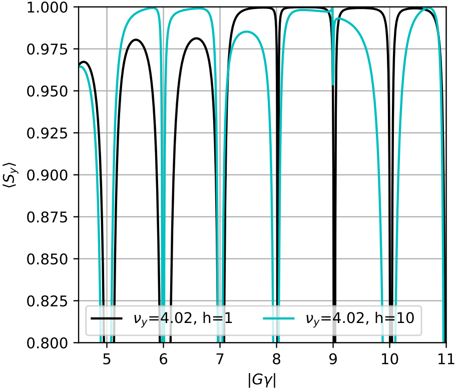
K	$I_{k,oS}$ (A)	$I_{k,oC}$ (A)	$I_{K,S}$ (A)	$I_{K,C}$ (A)	$\boldsymbol{I_{M,F}}$ (A)	$\boldsymbol{I_{M,C}}$ (A)
5	0.322	2.105	0.35	-1.71	**4.33**	6.44
6	0.567	-0.189	1.78	9.65	**17.77**	9.19
7	1.425	0.847	10.02	-8.14	**22.4**	13.95
8	-2.463	5.242	2.75	-9.39	**21.98**	22.37
9	-0.614	-0.222	-1.17	-14.35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

Polarized He-3 in the Booster, Possible Upgrades

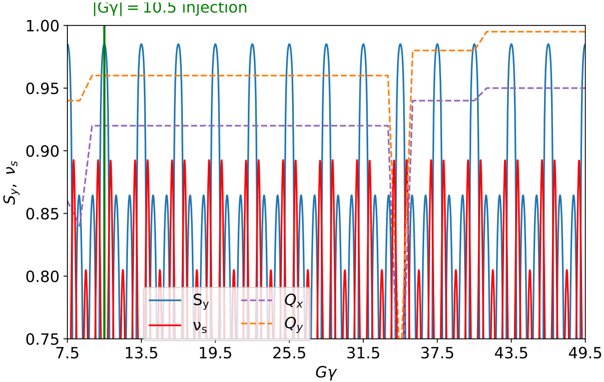
Ongoing studies: corrector upgrades to produce sufficiently strong imperfection resonances to produce a ν_s gap to avoid the $|G\gamma| = 12 - \nu_y$ and $6 + \nu_y$ resonances.

- The 24 existing vertical Booster corrector magnets have a maximum strength of 24.4 $\mathrm{G \cdot m}$.
- To produce the 0.08 ν_s-gap at h=10, a strength of 406 $\mathrm{G \cdot m}$ is needed.
- This would require an overhaul of the Booster corrector packages.





Polarized He-3 in the 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.
- Below $|G\gamma| = 10.5$, simulations show a trade off between intensity and polarization.
- Simulations show no polarization loss above $|G\gamma| = 10.5$.

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]

$$CP = LL + UR \tag{8}$$

with

$$LL = m_{31}^2 + m_{32}^2 + m_{41}^2 + m_{42}^2 \tag{9}$$

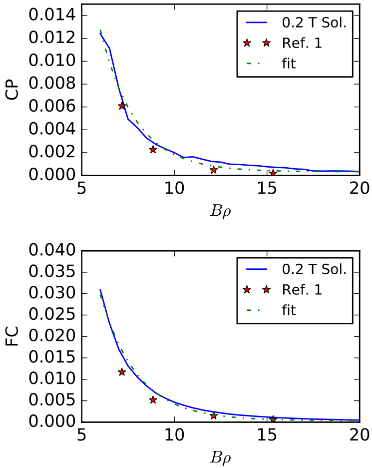
$$UR = m_{13}^2 + m_{14}^2 + m_{23}^2 + m_{24}^2. \tag{10}$$

and

$$FC = m_{12}^2 + m_{34}^2 \tag{11}$$

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

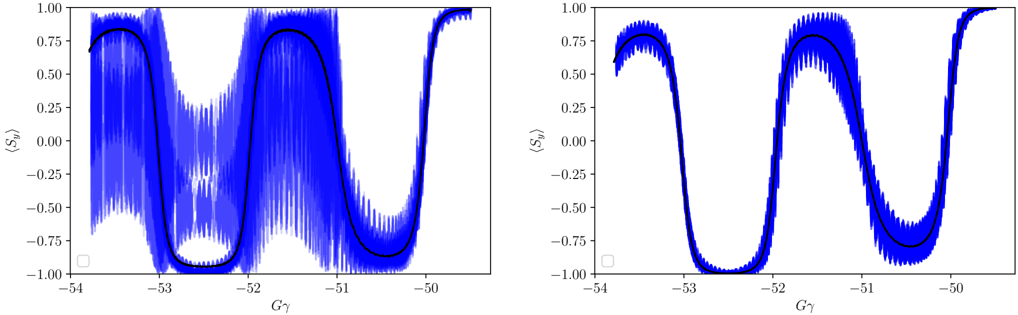
These optical distortions reduce exponentially with $B\rho$.



Polarized He-3 in the AGS, Possible Upgrades

In the current configuration, no polarization loss is expected in AGS above $|G\gamma| = 10.5$. **Adding a second cold snake would allow extraction above $|G\gamma| = 49.5$.** Crossing the $|G\gamma| = 60 - \nu_y$ resonance with 6D distributions

- Left: χ_c, χ_w =25, 14%, results in 4.4% polarization loss with $Q_x, Q_y = 0.95,\ 0.995$.
- Right: $\chi_w = \chi_c = 25\%$, results in 0.43% polarization loss with the same tunes of $Q_x, Q_y = 0.95,\ 0.995$.



The optics distortions from two cold snakes would necessitate higher Booster-to-AGS transfer energy.

- Studies of polarized He-3 in the spin-tune gap can also inform upgrades for polarized protons.

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Commissioning Plan

The commissioning plan spans to 2030. In that time there are several objectives and priorities. The research is also broken into two components, before and after the A5 kicker upgrade.
Objectives:

1. Commission polarized He-3 up to $|G\gamma| = 7.5$ in Booster.
2. Commission polarized He-3 up to $|G\gamma| = 49.5$ in AGS.
3. Commission polarized He-3 up to $|G\gamma| = 10.5$ in Booster after A5 upgrade.

Priorities:

1. Identify the maximum achievable efficiency to determine the number of bunch merges required to satisfy EIC intensity requirements.
2. Identify the maximum achievable polarization transmission with the proposed techniques and ensure the EIC polarization requirements can be satisfied.
3. Fully study the proposed alternatives in Booster and AGS if Priority #2 cannot be satisfied.
4. Identify and propose upgrades as needed to satisfy EIC requirements.

Booster Commissioning Plan

1. Low energy injection of He-3 into the Booster at high intensity.
2. Orbit harmonic corrections through six imperfection spin resonances.
   - $|G\gamma|$=5 to 7 with $|G\gamma|$ = 7.5 extraction prior to A5 kicker upgrade
   - Studies up to $|G\gamma|$ = 9 without A5 upgrade, no AGS snakes
   - Up to $|G\gamma|$=10 after A5 kicker upgrade
3. AC dipole studies through two intrinsic spin resonances.
   - Not used at $|G\gamma|$ = 7.5 extraction
   - Study $|G\gamma|$ = 12-ν_y resonance, no AGS snake
   - Study and optimize $|G\gamma|$ = 12-ν_y and $|G\gamma|$ = 6 + ν_y after A5 kicker upgrade
4. Maximize overall performance.

The time given as estimates on the next slides is derived from measurements with polarized protons and assuming a reduction in intensity (1×10^{11} ions/bunch). A reduction in intensity will further increase the time requirements or reduce the available statistics.

Booster Commissioning Plan, time requirements

1. Low energy injection of He-3 into the Booster at high intensity.
2. Orbit harmonic corrections through six imperfection spin resonances.
    - Single day for two harmonic scans
    - To study in detail, 4 days per resonance. Effects of tune changes, effects from other harmonics, etc.
3. AC dipole studies through two intrinsic spin resonances
    - From Booster AC dipole experiment, 6 days to study in detail for each resonance.
4. Maximize overall performance.

Notes

- General optimizations and initial setup will take three days (items 1 and 4).
- Resuming each year will require 6 days to re-establish polarization to $|G\gamma| = 7.5$, 10 days to re-establish polarization to $|G\gamma| = 10.5$. This is aside from nominal setup time.
- AGS injection is needed for all polarization studies to utilize the AGS polarimeter
- All times assume two 8-hour shifts/day.

AGS Commissioning Plan

1. Spin-tune gap studies:
   1.1 Polarized He-3 in the spin-tune gap at injection $|G\gamma|$ = 7.5 to 9.5 without A5 kicker upgrade.
      - Prior to A5 kicker upgrade, use jump/skew quads for $|G\gamma|$ = 8, 9, and 10, optimize transmission across $|G\gamma| = 0 + \nu_y = 8.9$ resonance.

   1.2 Study both tunes inside the spin-tune gap (38 imperfection resonances, 6 strong intrinsic resonances)
      - General polarization transmission.
      - How high does Qy need to be?
      - How high does Qx need to be?
      - Minimum separation of Qx to Qy for good transmission?
      - Can polarization be preserved across the $|G\gamma| = 60 - \nu_y$ (maximum supported by magnets is $|G\gamma| = 70.5$)?
2. Maximize overall performance.

AGS Commissioning Plan, time requirements

1. Spin-tune gap studies:
   1.1 Polarized He-3 in the spin-tune gap at injection $|G\gamma|$ = 7.5 to 9.5 without A5 kicker upgrade.
   - 2 days

   1.2 Study both tunes inside the spin-tune gap (38 imperfection resonances, 6 strong intrinsic resonances)
   - Scan of Q_x and Q_y in the spin-tune gap using ramp polarization measurements. 2 days per scan. 20 days total.
   - Scan of Q_y at $|G\gamma|$ =0+ν_y, 12+ν_y, 36-ν_y, 24+ν_y, 48-ν_y, and 36+ν_y. Standard polarization measurements 2 days/scan. 12 days.
   - Different snake strengths. Repeat scan of Q_x and Q_y in spin-tune gap. 20 days total.
   - Polarization transmission up to $|G\gamma|$=55.5. Study Q_y at $|G\gamma|$=60-ν_y, 4 days.
2. Maximize overall performance.
   - 7 days

He-3 Commissioning time summary I

Booster commissioning Item	Duration (days)
Low energy injection with higher intensity*	1
Imperfection resonance crossings $\|G\gamma\| = 5$ to 7*	12
Imperfection resonance crossing $\|G\gamma\| = 8$ and 9	8
AC dipole at $\|G\gamma\| = 12 - \nu_y$	6
Maximize performance*	3
TOTAL	30

Booster annual restart items	Duration (days)
Low energy injection with higher intensity*	1
Imperfection resonance crossings $\|G\gamma\| = 5$ to 7*	3-6
Maximize performance*	3
TOTAL	7-10

After A5 kicker upgrade	Duration (days)
Reoptimize to $\|G\gamma\| = 7.5$	7-10
Imperfection resonance crossings $\|G\gamma\| = 10$	4
AC dipole at $\|G\gamma\| = 12 - \nu_y$ and $\|G\gamma\| = 6 + \nu_y$	8
Maximize performance	3
TOTAL	22-25

He-3 Commissioning time summary II

AGS commissioning Item	Duration (days)
Optimize injection, study transmission from |Gγ| = 7.5 to 10.5	2
Study polarization transmission up to |Gγ| = 48.5	52
Study polarization transmission up to |Gγ| = 55.5	4
Maximize performance	7
TOTAL	65

AGS after A5 kicker upgrade	Duration (days)
Establish injection into the spin-tune gap	1
Re establish polarization transmission up to |Gγ| = 48.5	14
Further investigate different snake strengths	32
Maximize performance	7
TOTAL	22-54

Year	Commissioning activity	Time (days)
2027	Commission helium-3 in Booster up to |Gγ| = 7.5, study intrinsic and imperfection resonances above |Gγ| = 7.5 , and commission low energy injection into AGS.	30
2028	Reestablish polarized helium-3 in Booster. Optimize low energy in AGS, study transmission from |Gγ| = 7.5 to 10.5 to determine need for higher energy injection. Begin studies of Qx and Qy in spin-tune gap up to |Gγ| = 49.5.	28-48
2029	Determine maximum efficiency in Booster and AGS and number of merges to satisfy EIC intensity requirements. Study |Gγ| = 60- in detail.	18-32
2030	Study and optimize the transmission along the ramp. Finish incomplete studies.	30-44 days

Summary

Charge question: Are the accelerator R&D effort well executed, and future work well planned?

- To support the EIC requirements, polarized He-3 need near lossless transmission of both intensity and polarization in the injectors.
- The optimal configurations for the Booster and AGS have been identified for commissioning, and a commissioning timeline and goals out to 2030 has been given.
- Possible upgrades have been identified if the intended configurations fall short of EIC requirements.
- Polarized He-3 are currently requested at the EIC within the first five years of physics/commissioning. Additional upgrades will need to be identified, installed, and recommissioned before this time.
- Polarized protons began development over 30 years ago, has been a driver for upgrades to the injectors, and has been a primary focus of studies in the injectors.
- Having longer but less frequent study periods, such as two-months every other year vs. one month every year, will not improve the efficiency of studies.
    - More frequent study periods allows for more focused studies and time to analyze data ahead of the next period.
- Improvements to the AGS polarimetry will reduce time needed for polarization studies, see F. Rathmann ”Plans for EIC Polarimetry”.

Recommendation #10: Improved modeling below transition

From

V. Schoefer

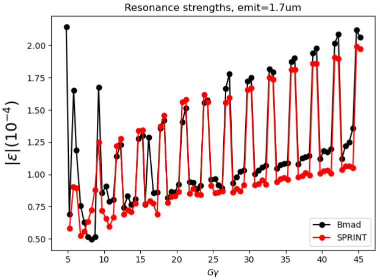
Model error at low energies in AGS driven largely by snake optical defects and large orbit excursions (feed-down).

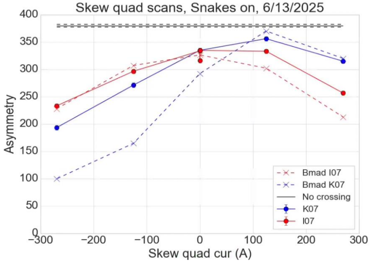
Horizontal resonance calculated via SPRINT (snakes=matrix) vs Bmad (snakes=full-field maps) show large discrepancies at low energy

- Single resonance crossing study at low energy (Gɣ=7.24) indicate:
  Bmad predicts resonance correction more accurately than SPRINT
  Feed-down from vertical offset in sextupoles is likely contributing to depolarization (via coupling)
- Orbit response studies
  AGS ORM measurements in various configurations (main magnets only, high and low energy), ongoing to characterize optics
  Bayesian methods successfully applied to Booster[1] ORM data to be applied in AGS
- Model Studies
  Bmad model refinement: imported as-measured survey errors and realistic orbits into model to estimate and correct for feed-down depolarization. Assess impact on resonance structure.

Accelerator improvements (planned)

- BPM upgrade (~2 yrs): TBT capability at all locations (72x2 planes), currently single location. Significantly increases ability to characterize optics and *coupling sources*
- Realignment of AGS: Full survey of AGS (combined function+tune/chrom control mags).
  - Towards full general orbit correction of AGS orbit (currently limits to few harmonics by weak correctors)
  - Consider upgrade of orbit steerers based on assessment after survey (increase number and/or strength of correctors)





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[1] Machine-Learning–Accelerated Bayesian Uncertainty Quantification for Digital Twin Modeling and Control of the AGS Booster, C. Kelly et al,AI4EIC, Boston, MA 2025

Thank you

Thank you and questions.

Extra slides

Polarization measurement times

The AGS has a CNI polarimeter with a carbon target that can take several different types of measurements with different timing and motor control. The types of measurements and the time to collect the data are:

Measurement type	Intensity	Time (m)
Core	2×10^{11}	5
Core	1×10^{11}	10
Core	0.5×10^{11}	18
Ramp	2×10^{11}	300
Profile	2×10^{11}	400

For the AGS storage cell-based polarimeter of t$\sim$22 s. For a measurement of the total polarization similar to the ”core” measurement:

- Beam is at the maximum energy of the AGS for 0.7 s/cycle.
- 22 cycles are needed for the 22 s data collection time.
- One cycle is as short as 4 s$\Rightarrow$2.1 minutes for $\Delta P/P \sim 3\%$, 40% of our normal measurement time.

As an example, the initial Booster commissioning that totals 30 days would be reduced to 14 days with this polarimeter. Further improvements on time could be gained with increased gas density or extended data collection times/cycle.