



The AGS Booster: History and Upgrades

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@BrookhavenLab

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Summary

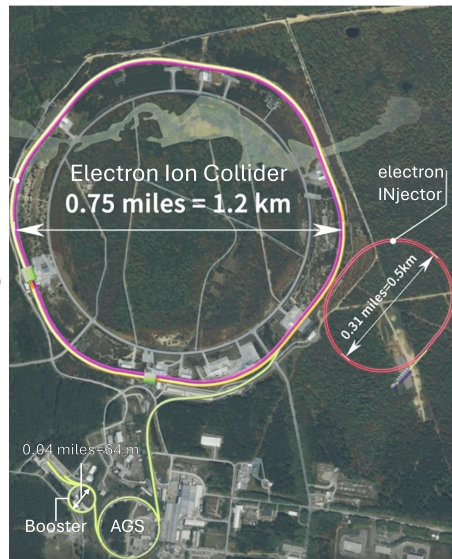
History of the Booster

Its design had three main objectives

1. Increase unpolarized proton intensity delivered to AGS by a factor of four (to 6×10^{13}).
2. Increase polarized proton intensity by a factor of x20 (to $\times 10^{12}$).
3. Accelerate heavy ions up to Au for AGS and eventually RHIC.

The Booster is a 201.78 m synchrotron (or 40 μ jiffies for $\beta = 1$), 1/4 the size of the AGS, that accelerates and delivers beam to the AGS and NSRL.

- Operations began in 1991 with beam delivery to the AGS.
- The NSRL line was commissioned in 2002 and became operational in 2003.
- Prior to the installation of the Booster, the heaviest ion supported by the AGS vacuum was Si.
- The Booster has since accelerated and delivered ion beams from protons to uranium.



Ground breaking



Booster as a high intensity injector for AGS

Booster had a planned operating intensity for protons of 1.5×10^{13} protons per pulse with a repetition rate of 7.5 Hz and 4 cycles delivered to the AGS at 1.5 GeV.

- This was exceeded and the ultimate performance was achieved with 2.3×10^{13} protons per pulse with a repetition rate of $6\frac{2}{3}$ Hz and 4-6 cycles delivered to the AGS at 1.9 GeV.
- Moving from $h=3$ to dual harmonics of $h=2$ and 4 to reduce the peak current alleviated space charge forces in Booster.
- Increasing the extraction energy from 1.5 to 1.9 GeV alleviated space charge in AGS.
- This maximum performance marked a 50% increase over the design intensity.
- High intensity operation ceased in ~ 2000 .
- In this configuration, it supported the AGS fixed target experiments.

Stripping in LTB

Polarized protons are strip injected into the Booster with a stripping foil at the exit of the C5 dipole.

- The pulse from LINAC is $\sim 300 \mu\text{s}$, and at 200 MeV injection, the front of the pulse circulates $\sim 250\times$ by the time the end of the pulse arrives at the foil.
- Optimizing the foil thickness for efficient stripping yet minimal energy loss and emittance growth is essential.
- The foil geometry was adjusted to minimize the beams exposure to the foil.
- Optimization of the beta functions and orbits at the foil were a large effort and the result of many studies.
- Emittance growth improved from $2\times$ growth to $\sim 1.4\times$



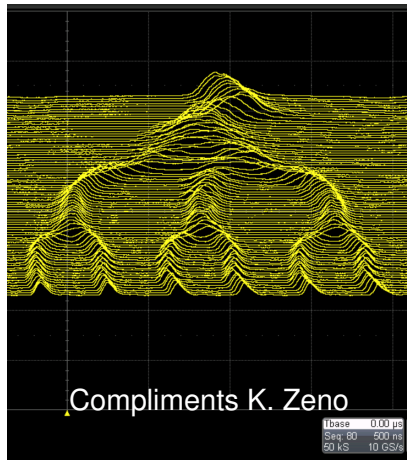
Bunch Merging in Booster

Pre 2012, heavy ion beam from Tandem was captured and accelerated in Booster with $h=6$ ¹. Bunch merging in AGS from 24→4.

Enter **EBIS**

- In 2012, EBIS became primary source of heavy ions for RHIC.
- EBIS provided $\sim 25\%$ of the intensity Tandem provided, per pulse.
- In 2012, a 4:1 merge in Booster, and a 4:1 merge in AGS, competitive per bunch intensity with Tandem.
- In 2016, a 4:1 merge in Booster, and a 6:1 merge in AGS.

A return to Tandem for runs 18+. Bunch merging in Booster has become a standard and single bunch transfers from Booster to AGS continued.



¹C. Gardner Run22 RHIC Retreat.

Stripping in BTA

Strippers early on were made of graphite.

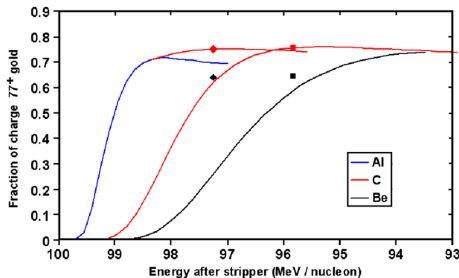
- Introduced large energy spread into Au ions as a combination of energy straggling and non-uniformities in the foil.
- This triggered development of new foils, including: Be, Mica, Ti, fused Silica..

Mica

- Minimal energy straggling
- Good Au^{77+} yield

Al+C

- The King of foils from 2007 on.
- Glassy carbon with heavy duty Al foil gave the fast rise in stripping from the Al but the maximum yield of the C.
- Other combinations tested and used, such as Ni+Al.



P. Thieberger PRAB 2008.

The Al+C Foil's Downfall

During high intensity heavy ion operation, damage to the BTA stripping foils has been observed.

- With high intensity heavy ion beams, the Al reaches its melting point and the foil degrades.
- This has been observed with Tandem intensities, and expected from EBIS after the extended EBIS solenoid.
- Heating calculation using nominal operation parameters for high intensity tandem beam, 8 transfers per supercycle, separated by 267 ms, a total of 16×10^9 ions transferred every 5.4 s supercycle.
- To limit damage to the foil, the total beam allowed through BTA per unit time is limited.

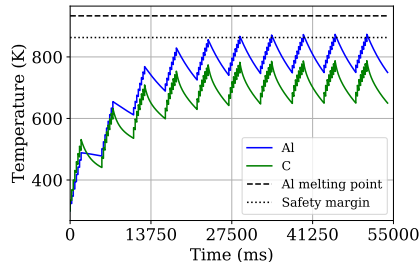
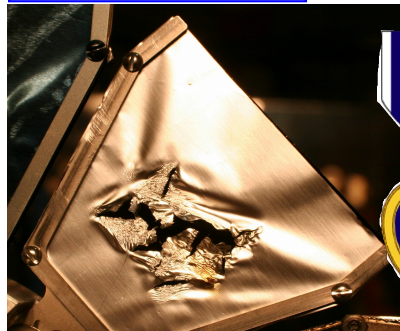


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High Energy BTA Upgrade

Summary

Polarized protons

Polarized protons in Booster are relatively uneventful.

- Injected at $G\gamma \sim 2.2$ and extracted at $G\gamma = 4.5$ to satisfy $G\gamma = 3n + 1.5$.
- zero intrinsic resonances, two imperfection resonances ($G\gamma = 3, 4$)
- The $G\gamma = 3$ resonance is corrected by correcting the $h=3$ orbit harmonic component (top right),
- the $G\gamma = 4$ resonance is enhanced to induce a spin flip (bottom right).
- Polarization loss estimated to be 0-2%.
- Polarization measured in AGS.

It could get more exciting if we bump the energy higher ex. $G\gamma = 0 + \nu_y$ resonance crossing which was used for the AC dipole commissioning.

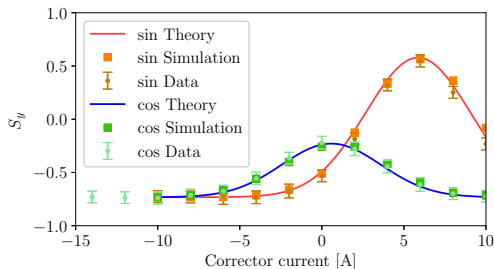
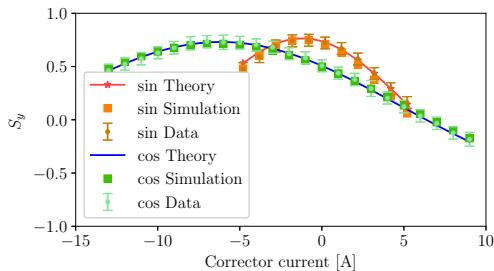


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The BTA Stripping Foil

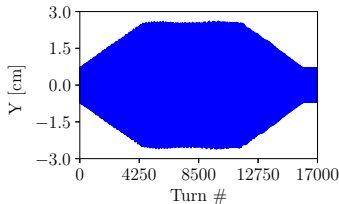
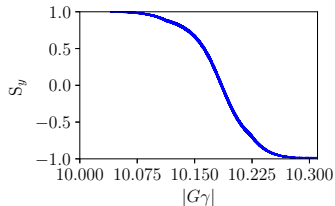
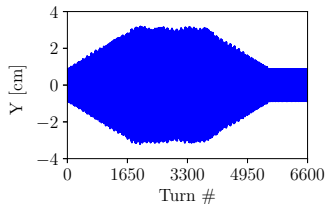
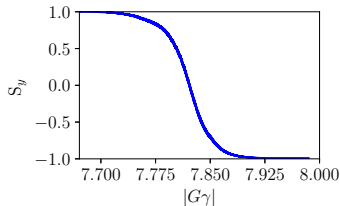
High Energy BTA Upgrade

Summary

Polarized helium-3 in the Booster

Polarized helium-3 will be produced at EBIS and accelerated to 2 MeV/u.

- Injecting at $|G_\gamma| = 4.19$ with $\nu_y < 4.09$, to avoid the $|G_\gamma| = 0 + \nu_y$.
- There are three imperfection resonances up to $|G_\gamma| = 7.5$.
- There are six imperfection resonances and two intrinsic resonances up to $|G_\gamma| = 10.5$.



- Full spin-flip achieved with $B_{m1} = 16.5 \text{ G} \cdot \text{m}$ ($|G_\gamma| = 12 - \nu_y$) and $B_{m1} = 20.5 \text{ G} \cdot \text{m}$ ($|G_\gamma| = 6 + \nu_y$), with $\delta_m = 0.01$.
- Simulations show sufficient corrector strength to flip/correct each imperfection resonance (although with minimal margin).

Booster Polarimeter Upgrade

There is no independent polarization measurement in the Booster.

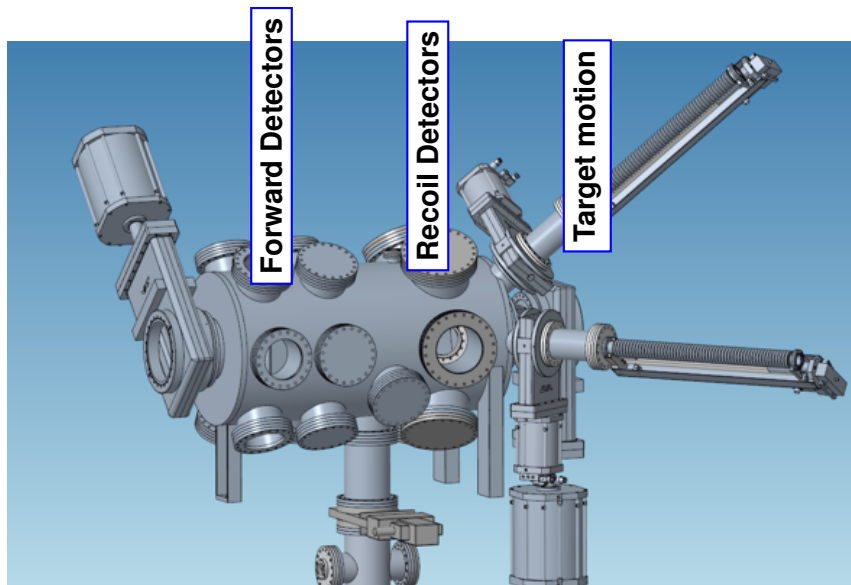
- Currently, polarization studies can only take place if the AGS is available.
- Collectively, Booster and AGS lack an absolute polarimeter.

The design investigated uses scattering of p and ^3He on a carbon target, outside of the CNI region.

- The recoil detectors to provide both energy and angle of recoil carbons for correlation with elastic events (detectors must be in vacuum).
- The targets will be mounted in an air lock isolated from the main polarimeter body.
- A long insertion of ~ 40 cm will get the target near the beam, followed by fast insertions during measurements.
- The forward detectors to be used in the new h-jet for the EIC.

As a bonus, the current design will work for other polarized beams, such as d, ^6Li , and ^7Li .

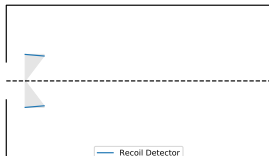
Polarimeter Chamber



Polarimeter Stages

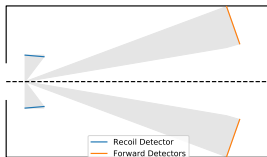
Stage 1

- Installation of at least one motor control for target insertion
- Installation of two Si recoil detectors for measurement of relative polarization



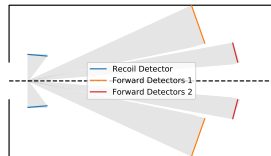
Stage 2

- Installation of six recoil detectors and six forward detectors.
- Determination of P_x and P_y with veto of collisions for polarized helium-3 measurements.



Stage 3

- Installation of additional forward detectors for improved forward region coverage.
- Forward-most detectors insertable to avoid interference with slow extracted beams.

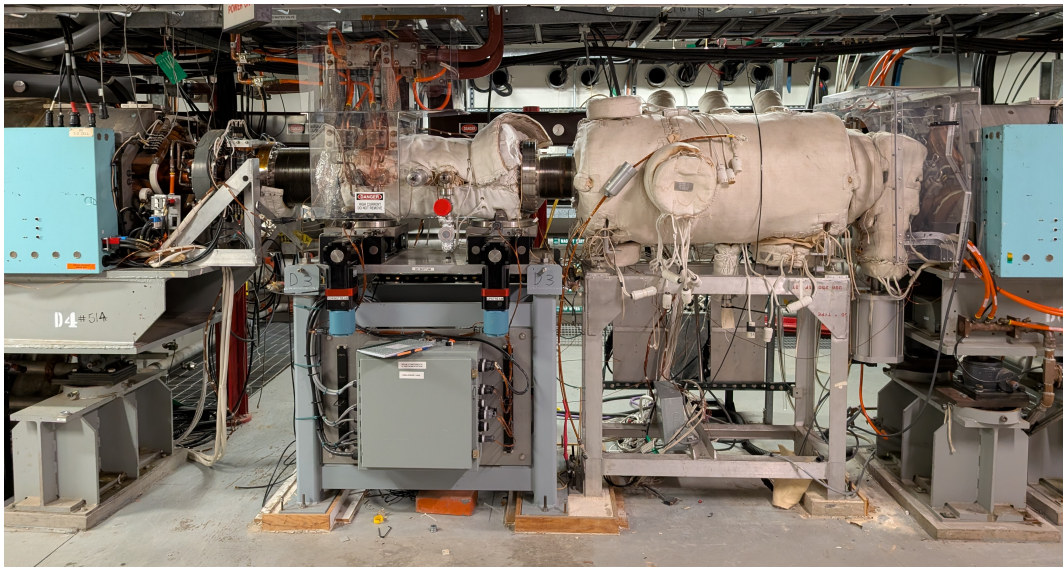


Where will the polarimeter go?



One of the more available spaces in Booster

Enter the D3 section and the IPM



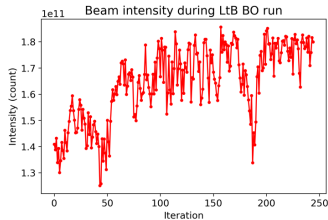
AI/ML efforts for Booster

From Lucy Lin

AI/ML is improving Booster beam quality, model fidelity, and injection/extraction control through optimization, uncertainty quantification, and Digital Twin development.

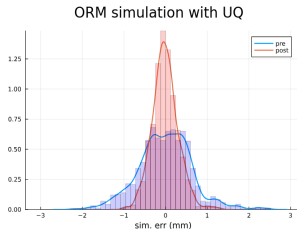
LtB Bayesian Optimization

- Bayesian Optimization (BO) adjusts LtB optics to maximize Booster beam intensity
- Result:** Reduced beam size and improved injection efficiency.



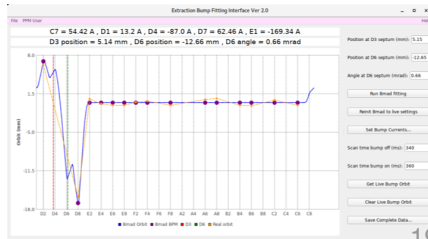
Uncertainty Quantification

- Bayesian Uncertainty Quantification (UQ) analyzes orbit response discrepancies to improve Booster model fidelity.
- Result:** Improved simulation-measurement agreement.



Extraction Bump Digital Twin

- Digital Twin models the extraction bump to enable predictive, model-based tuning.
- Result:** Supports more stable slow extraction configuration studies.



Booster Turn by turn BPM: AI/ML benefits

From Lucy Lin

Current Diagnostics Bottleneck

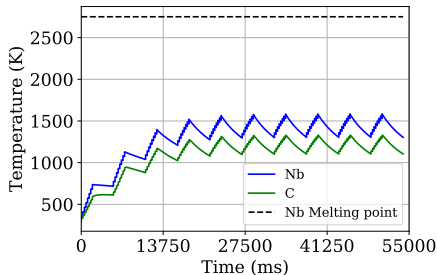
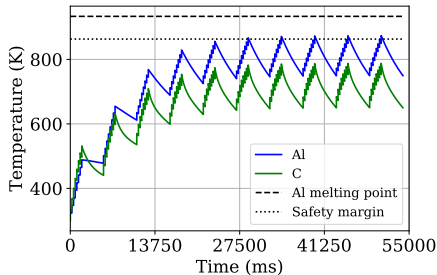
- Only one TBT BPM pair currently available in the Booster
- Weak signal for low intensity EBIS beam
- Low signal peak due to space charge tune spread at high intensity
- Limited visibility of:
 - Betatron oscillations
 - Chromaticity evolution
 - Beta-beating
 - Injection/extraction mismatch
 - Fast transient beam dynamics
- Insufficient observables for advanced model calibration and AI-driven optimization

AI/ML Opportunities Enabled by TBT Upgrade

1. Physics-informed Digital Twin Calibration
 - i. Extract turn-by-turn optics observables throughout the Booster cycle
 - ii. Continuously calibrate and validate lattice models against measurements
 - iii. Enable faster uncertainty quantification to identify model deficiencies
 - iv. Improve tune/chromaticity control (OpticsControl upgrade)
2. Richer Observables for Online Optimization
 - i. Additional objectives and constraints for optimization
 - ii. Better reward signals for Reinforcement Learning
 - iii. Faster convergence toward optimal settings

An Upgrade to the BTA Stripping Foil

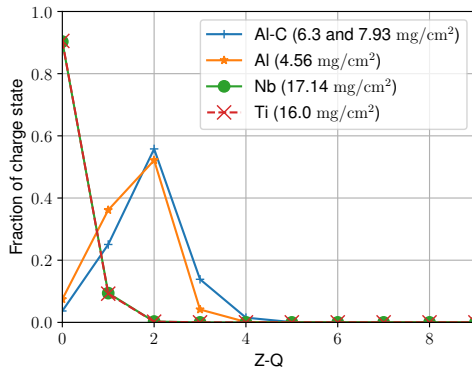
- As mentioned previously, the Al in the Al+C foils is prone to damage.
- Al+C foil with our nominal operations with high intensity tandem beam, 8 transfers per supercycle, separated by 267 ms, a total of 16×10^9 ions transferred every 5.4 s supercycle.
- Intensity limitations put in place for Al temperatures to not exceed "Safety Margin"
- It would be best to not have to worry about foil damage.
- Changing the 6.4 mg/cm^2 Al foil to a 4.8 mg/cm^2 Ti or 4.285 mg/cm^2 Nb foil would give improved margins.
- Nb foil heating shown on right: more than 1000 K margin with equivalent beam conditions.



Stripping of 239 MeV/u Ag

Our existing stripping foils are optimized for a transfer energy of 100 MeV/u.

- Ag beam has an expected transfer energy of 239.4 MeV/u.
- Stripping efficiency of 239 MeV/u Ag on a Al, Al+C, Nb, and Ti foil shown on right.
- Our best foils would give less than 60% stripping efficiency.
- Changing to a single Nb or Ti foil, a stripping efficiency of 90% can be achieved.
- Intensity demands for Ag may not be high.

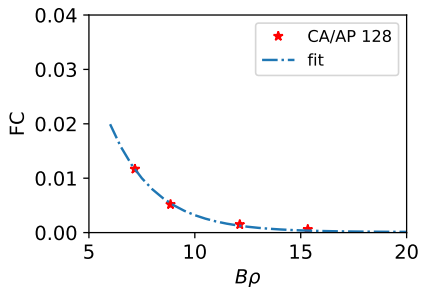
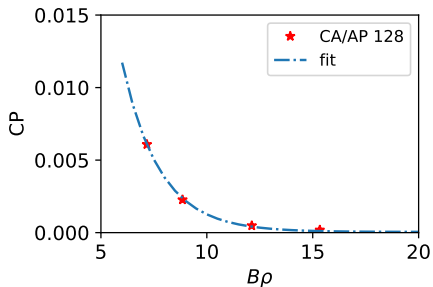


High Energy BTA Upgrade

The cold snakes in the AGS impart large optical defects into the lattice, reducing the admittance at injection.

- From the transport matrix, the total coupling (CP) and focusing (FC) are calculated from transport matrix elements.
- These optical distortions reduce exponentially with $B\rho$.

	$G\gamma$	$B\rho$ (Tm)	$1/\gamma^3$	$FC_{snake, scaling}$
Protons	4.5	7.21	0.0632	1
	6.5	10.9	0.0210	0.1867
	7.5	12.7	0.0137	0.0859
Helium-3	7.5	6.97	0.1736	1
	10.5	10.8	0.0628	0.1772



High Energy BTA Upgrade

BTA is operated at a maximum $B\rho$ of 9.5 Tm.

- The goal is to hit 10.8 Tm to support polarized Helium-3.
- The improved admittance at 10.8 Tm from reduced optical defects from the snakes will allow both tunes to be inside the spin-tune gap at injection.
- The A5 kicker has a design $B\rho = 8.5$ Tm (below 1.9 GeV protons and nominal Au injection).
- A bump in AGS is used to compensate for the weak A5 kick.
- The line is being evaluated with a target of 12.7 Tm to support proton transfer at $G\gamma = 7.5$ and provide some margin over the necessary helium-3 transfer at $|G\gamma| = 10.5$ at 10.8 Tm.

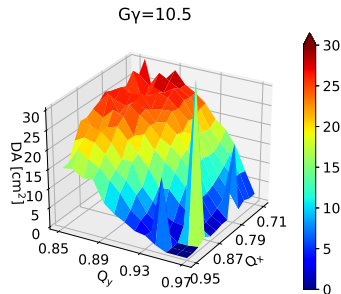
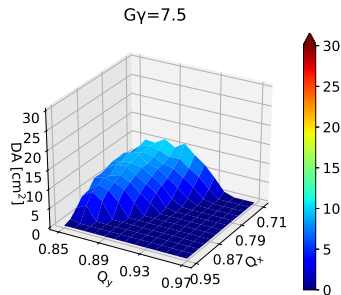


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The Future of Booster

There is broad interest in improvements to the Booster ahead of the EIC to improve: polarization transport, emittance preservation, modeling, and ML/AI applications to the previous three.

P+ ϵ transport

- Haixin Huang
- Vincent Schoefer
- Kiel Hock
- **Keith Zeno**
- Jonathan Lee
- Alexei Fedotov
- Yichao Jing
- Brendan Lepore

Polarimetry

- Frank Rathmann
- Vera Shmakova
- Evgeny Shulga
- Oleg Eyser
- George Mahler
- Richard Porqueddu
- Frank Mizzi
- Josh Adams

ML/AI

- Zhengqiao Zhang
- Prashanth Shanmuganathan
- Nebin George (FU)
- Paolo Lenisa (FU)
- Rahul Shankar (FU)
- Prajwal Mohan Murthy (MIT)
- Kevin Brown
- Georg Hoffstaetter
- Lucy Lin
- Eiad Hamwi
- Yuan Gao
- Jun Ma
- Levente Hajdu
- Trevor Olsen
- many outside of BNL.

Many of these advancements (i.e. development of new Si detectors for precise polarimetry, or applications of ML/AI) are applicable directly to the EIC and serve as a test bench for such developments.

Summary

The Booster is the workhorse of the HIC, supplying various beams to AGS and NSRL to meet programmatic needs.

- For the EIC, it will pre-accelerate polarized light ions and heavy ions for the AGS.
- Polarized helium-3 is an exciting new polarized ion for the HIC.
- A polarimeter in Booster will fill a gap in absolute polarimetry at the HIC, a means to test new technologies for the EIC, and provide cost savings for future polarized beam setups.
- New stripping foils for the BTA line have been proposed for improved stripping of high energy ions, and to improve the margin on heating for high intensity heavy ions.
- ML/AI efforts are advancing and serve as an application that can be applied elsewhere in the EIC accelerator chain.
- A high energy upgrade to BTA is being evaluated for polarized protons and helium-3 to improve the optical defects from the cold snakes.

Booster Staff 1998

