Machine learning and model calibration at the RHIC injector compound

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Summary

• Simulation studies with magnet misalignment at the AGS Booster

• Current to magnet strength calibration using orbit response at the AGS Booster

• AGS Booster injection optimization with Bayesian optimization
Motivation

Relativistic Heavy Ion Collider (RHIC): world’s only high-energy polarized proton beam and largest operating accelerator in the US

→ unique opportunities to study from where nuclei obtain their spin

Electron Ion Collider (EIC): new successor to RHIC; will collide polarized proton and electron beams

Increase in instrument complexity for EIC will require new tools to optimize accelerator performance and maximize the utility of polarized beam experiments
**Motivation**

The **Alternating Gradient Synchrotron (AGS)** and its **Booster** serve as part of the **injector compound** for RHIC and future EIC.

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<table>
<thead>
<tr>
<th>Typical Top Energies [Total, GeV/N]</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td><strong>Au</strong></td>
</tr>
<tr>
<td>Linac (H⁻)</td>
</tr>
<tr>
<td>Booster</td>
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<tr>
<td>AGS</td>
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<tr>
<td>RHIC</td>
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**Heavy Ions**  |  **Protons**
---|---
E-beam Ion Source (EBIS) | OPPIS (polarized)
Tandem Van de Graaf | High-intensity H⁻ (unpolarized)

Bright ion beams in AGS / Booster are required for optimal luminosity and highest polarization in RHIC and EIC.
Polarization at RHIC

<table>
<thead>
<tr>
<th></th>
<th>Max Energy [GeV]</th>
<th>Pol. At Max Energy [%]</th>
<th>Polarimeter</th>
</tr>
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<tbody>
<tr>
<td>Source+Linac</td>
<td>1.1</td>
<td>82-84</td>
<td></td>
</tr>
<tr>
<td>Booster</td>
<td>2.5</td>
<td>~80-84</td>
<td></td>
</tr>
<tr>
<td>AGS</td>
<td>23.8</td>
<td>67-70</td>
<td>p-Carbon</td>
</tr>
<tr>
<td>RHIC</td>
<td>255</td>
<td>55-60</td>
<td>Jet, full store avg*</td>
</tr>
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Loss in polarization along the chain

Polarimetry available at:
- Source
- End of Linac (200 MeV)
- AGS extraction
- RHIC injection energy
- RHIC flattop

No Booster polarimeter

Relative Ramp Polarization Loss (Run 17, full run avg)

<p>| | |</p>
<table>
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<tbody>
<tr>
<td>AGS</td>
<td>17 %</td>
</tr>
<tr>
<td>RHIC</td>
<td>8 %</td>
</tr>
</tbody>
</table>
Alternating Gradient Synchrotron (AGS) Booster

- Pre-accelerate particles entering the AGS ring
- Accepts heavy ions from EBIS or protons from 200 MeV Linac
- Serves as heavy ion source for NASA Space Radiation Laboratory (NSRL)
- 6 super-periods (A to F), 72 main magnets
Simulation studies with magnet misalignment at the ASG Booster
Booster magnet misalignment

- Magnet location in real machine from 2015 survey data
- Misalignment data for quadrupoles and dipoles
- There has been trouble with making physics simulation with misalignment agree with real orbit data
Misalignment simulation

- Simulation studies were done using Bmad Booster model to see how magnet misalignments affect the bare orbit (orbit with all correctors off).
- Survey misalignments from 2015 were used as the baseline values in the model.
- Three scenarios were studied: only misalign dipoles, only misalign quadrupoles, and misalign both.
- Using survey data as mean, normal distributions of misalignment values with 5% standard deviation were simulated.
Misalignment simulation results

- Quadrupole misalignment has much bigger impact on bare orbit than dipoles, especially in the vertical plane.
- 5% standard deviation can result in deviations as large as 2 mm.
- Further studies needed to compare simulation to real bare orbit.
Current to magnet strength calibration using orbit response at the AGS Booster
Magnet current to strength mapping

- **Magnet transfer function**: mapping between the power supply (PS) current and the resulting strength of a magnet.

- Example: 5\(^{th}\) order polynomial for Booster quadrupoles.

- Transfer functions are measured before the magnets were installed in the ring, and there is no existing way to verify them after installation.
CAD script to get real orbit responses

- Script development with Collider Accelerator Department (CAD) Controls Group

- FunctionEditor: send trapezoid-like time-dependent function to corrector power supplies

- Script sets three corrector settings: positive, zero, negative; and save corresponding orbits

- All magnet settings (including dipoles and quadrupoles etc.) are saved for model comparison
Orbit response data

- 2 difference orbits between 3 corrector settings: positive – zero, negative – zero
- Magnet settings saved during data collection are loaded into Bmad to generate simulated difference orbits
- Good agreements are reached, despite some faulty BPMs (i.e., PUEHC8)
- Small discrepancies (within 1 mm) beyond error bars could be results of inaccurate magnet transfer functions
Quadrupole transfer function calibration

- Discrepancies of difference orbits can be due to inaccurate quadrupole transfer function in the model (PS current $\rightarrow$ k1 value)

- Adjustments in k1 values of the quadrupoles are shown to affect difference orbit

- MSE between measurement and model decreases from 0.069 to 0.038
Summary of model calibration

• Simulation studies were done to show how magnet misalignments affect the bare orbit.

• Difficult to match model to reality, need new survey data.

• ORM script shows rough difference orbit agreement between measurements and Bmad simulation.

• Small deviations in difference orbit can come from inaccurate quadrupole transfer functions.

• Further investigation is underway to find best quadrupole adjustments to make model agree with measurements.
AGS Booster injection optimization with Bayesian Optimization
Booster injection

- Booster injection/early acceleration process sets maximum beam brightness for rest of acceleration through RHIC
- Linac pulse of 300 us, H- beam $\sim 6\times10^{11}$ protons, strip through a carbon foil
- Intentional horizontal and vertical scraping reduce emittance (and intensity) to RHIC requirements
- Goal: minimize beam loss at scraper / maximize beam intensity after scraping
- Controls: Linac to Booster (LtB) transfer line optics
- Method: Bayesian Optimization
ML package: Xopt

• Flexible **framework** for optimization of arbitrary problems using python

• **Independent** of problem type (simulation or experiment)

• **Independent** of optimization algorithm & easy to incorporate custom algorithms

• Easy to use text interface

https://github.com/ChristopherMayes/Xopt
Xopt structure

Note: this process can also be done asynchronously
LtB controls and measurement

- 13 quadrupoles and 16 correctors between Linac and Booster

- Common practice to improve Booster injection efficiency: tune last few correctors at the end of the LtB line

- Criteria to check injection efficiency: Booster early and late intensity
LtB corrector scan

- All 16 correctors were scanned on Jan 25, 6:55pm – 8:20pm, on PPM user 4 until Booster late intensity dropped by 50%
NN model for LtB scan

- Inputs: 15 correctors (lhn-d009 is excluded due to insensitivity)
- Outputs: 2 intensities (Bstr_Early, Bstr_Late)
- Got rid of points where input intensity dropped to zero
- Normalized inputs, standardized outputs
NN model for LtB scan

- 15 correctors → 2 intensities
- 2 hidden layers: ReLU + Tanh
- Training data 75% (893 points), testing data 25% (297 points), $R^2$ score = 0.85
Test Xopt on LtB scan NN model

- Controls: Power supply currents of three correctors (two horizontal, one vertical) at the end of the LtB line
- Booster late beam intensity (after scraping, before extraction to the AGS)
- BO algorithm developed using Xopt, using 242 LtB scan data points as training data
- Algorithm converged within 50 samples
Test Xopt on real machine

• Controls: Power supply currents of correctors and quadrupoles at the end of the LtB

• Goal: maximize Booster late beam intensity (after scraping, before extraction to the AGS)

• Objective function: send PS current to selected magnets, wait 5 seconds (each Booster cycle/injection pulse lasts ~ 4 seconds), read and return Booster intensity measurement

• BO algorithm developed using Xopt, with added features such as interpolated optimization and trust region BO (tuRBO)

https://christophermayes.github.io/Xopt/examples/single_objective_bayes_opt/turbo_tutorial/
Case 1: 2 correctors

- Feb 26, PPM user 4, 7pm – 9pm
- Controls: Power supply currents of two correctors (one horizontal, one vertical) at the end of the LtB line
- Algorithm converged within 100 samples (15-20 minutes)

Operator: Petra Adams
Case 2: 4 correctors

- Feb 27, PPM user 4, 7pm – 9pm
- Controls: Power supply currents of four correctors (two horizontal, two vertical) at the end of the LtB line
- Algorithm converged within 120 samples (20-25 minutes)
Case 3: 2 correctors + 2 quadrupoles

- Mar 4, PPM user 3, 7pm – 9pm
- Controls: Power supply currents of two correctors and two quadrupoles at the end of the LtB line
- Beam size decrease in both planes in the BtA line in correspondence with intensity increase

Operator: Petra Adams
Case 4: horizontal only

- Mar 13, PPM user 4, 9:30am – 10am
- Controls: Currents of two horizontal correctors and two horizontal quads
- Maximize Booster late intensity / input intensity (to reduce noise)
- Initial beam was sabotaged by changing magnets in the middle of LtB line
- Degeneracy problem: objective value converges but input values don’t
Case 5: vertical only

- Mar 14, PPM user 4, 12:30pm – 1pm
- Controls: Power supply currents of two vertical correctors and two vertical quads
- Maximize Booster late intensity / input intensity (to reduce noise)
- Initial beam was sabotaged by changing magnets in the middle of LtB line
- Degeneracy problem persists
Summary of ML test

• Bayesian optimization algorithm has been demonstrated to work well to improve and maintain Booster injection efficiency in both planes under different system settings (PPM users).

• If controls include upstream and downstream LtB magnets, changes made in the middle can be compensated to bring Booster beam intensity back up.

• Decrease in beam size in the BtA is observed in both planes in correspondence with intensity increase, which signals decrease in emittance.

• Degeneracy problem encountered during experiment may need further investigation.
Thanks

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