Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

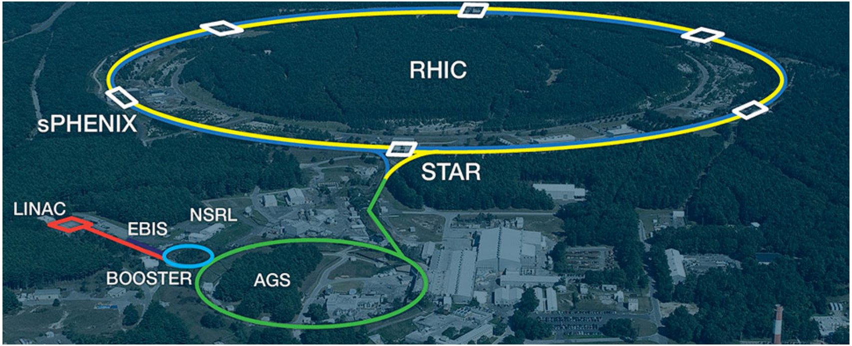
pp Luminosity Maximization for sPHENIX

Kiel Hock for team

C-AD MAC-20 Meeting
December 19, 2023

Table of Contents

Overview of the RHIC accelerator complex



- Polarized H- are produced at the Optically Pumped Polarized Ion Source (OPPIS) which accelerated to 200 MeV by the LINAC and strip injected into the Booster.
- These beams are then accelerated through Booster, AGS, and to the desired collision energy in RHIC.
- Beams in RHIC collide at the two detectors located at IP6 (STAR) and IP8 (sPHENIX).

Introduction

Run24 is expected to be up to 26 cryo weeks starting early March, 2024.
The 26 weeks include:

- 1 week for cooldown+warmup.
- 19 weeks of 100 GeV polarized protons.
  - 3 weeks of setup+ramp up.
  - 16 weeks of physics.
- 6 weeks carryover from Run23 for 100 GeV Au.

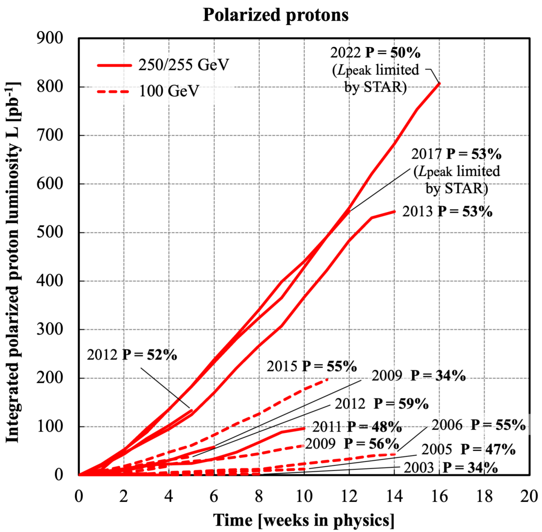
sPHENIX is a new detector at RHIC (as of Run23) located in IR8.

- Their luminosity region of interest is within ±10 cm.
- To optimize collisions so a high percentage of collisions are within this vertex, they plan to run with a crossing angle.

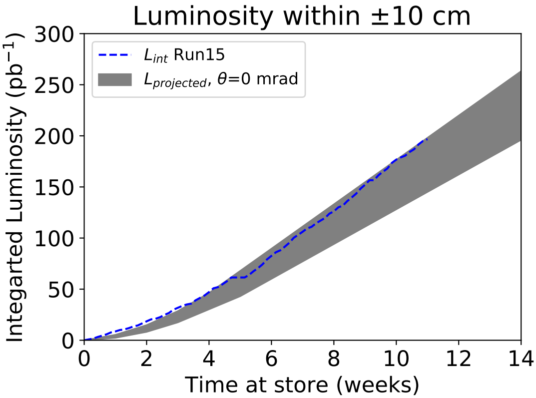
Given Run23 performance, Run15 performance is the presently expected maximum performance.

Polarized protons at 100 GeV

- Run15 is the highest luminosity run at 100 GeV and almost highest polarization run.
- Given performance from Run23, Run24 $p\uparrow$ performance expected to be equivalent to Run15.
- We will use Run15 as our benchmark.



An Overview of Run15 Performance

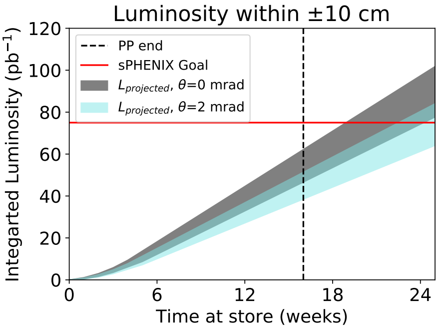


- Run15 had a peak intensity of 2.38×10^{11} ions/bunch at ev-lumi.
- The average intensity/store at the end of run was 2.27×10^{11} ions/bunch.
- The average polarization for the run was 55.2%.
- Run15 suffered from degraded polarization in the AGS due to jump quad timing shifts.
  - This has not been present since changing the timing scheme for jumps.
  - The new skew quad system a higher tolerance for timing errors (see V. Schoefer's talk).
- Polarization lifetime at store affected by beam-beam and tune placement between 7/10 snake resonance and 2/3 betatron resonance.

sPHENIX Luminosity Goals

sPHENIX requires a luminosity of 45 pb^{-1} for Run24, assuming 60% availability, would be 75 pb^{-1} of delivered luminosity.

- The desired luminous region is within a vertex cut of ± 10 cm, with minimal collisions outside of cut.
- Given Run15 performance, it would take 22 weeks to reach the luminosity goal with $\theta = 2$ mrad and 19 weeks at $\theta = 0$ mrad.
- Luminosity needs to be increased by 37% to reach these goals within 16 weeks.



Luminosity Reduction from Crossing Angles

A simplified form of the luminosity which includes crossing angles and the hourglass (HG) effect is[1]:

$$\mathcal{L} = \left(\frac{N_1 N_2 f k_b}{8\pi\sigma_x^*\sigma_y^*}\right)\frac{2\cos\frac{\theta}{2}}{\sqrt{\pi}\sigma_s}\int_{-\infty}^{+\infty}\frac{e^{-s^2 A}}{1+(\frac{s}{\beta^*})^2}ds \tag{1}$$

where

$$A = \frac{\sin^2\frac{\theta}{2}}{\sigma_x^{*2}(1+(\frac{s}{\beta^*})^2)} + \frac{\cos^2\frac{\theta}{2}}{\sigma_s^2} \tag{2}$$

where N_1 and N_2 are the per bunch intensities, k_b is the total number of bunches per ring, θ, σ_x, σ_y, σ_s, β^*. Typical bunch parameters of: $N_1 = N_2 = 2.1 \times 10^{11}$ protons/bunch, k_b=111, $f = 78.3\ \mathrm{kHz}$, $\sigma_s = 68.2\ \mathrm{cm}$, $\varepsilon_x = \varepsilon_y = 2\ \mu\mathrm{m}$ and β^*=0.85 cm.
However, the HG effect is largely suppressed with $\theta >$0.5 mrad.

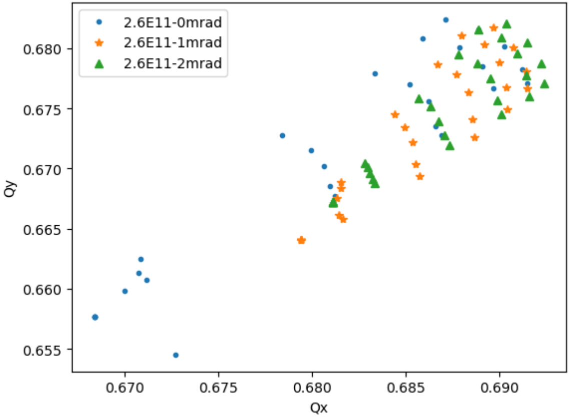
The luminosity can be increased primarily by reducing the β^* or increasing $N_{1,2}$ which raises the questions:

1. How much can the β^* be reduced?
2. How much can the intensity be increased?

---

[1] W. Herr and B. Muratori ”Concept of Luminosity” 2006.

Beam-beam tune footprint reduced with crossing angles

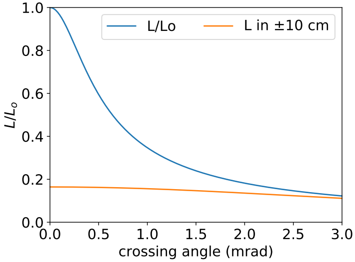


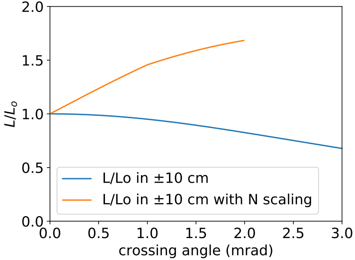
Although RHIC typically operates with protons at the beam-beam limit, operating with a crossing angle reduces the beam-beam footprint.

- Run15 used the electron lenses for beam-beam compensation, extending the intensity limit.
- Run24 will not require the electron lenses since sPHENIX intends to run with a crossing angle.
- The intensity limit with $\theta = 0$ mrad corresponds to 2.1×10^{11}.
- The crossing angle extends the intensity limit to 3×10^{11} with $\theta = 2\,\mathrm{mrad}$.

sPHENIX Luminosity

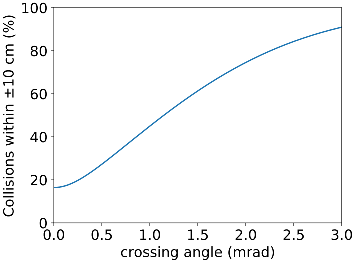
- Top: Luminosity reduction with crossing angle and within ±10 cm
- Bottom: Luminosity reduction with crossing angle normalized to L_o within ±10 cm and luminosity increase that maintains beam-beam tune spread
- Because of the L in ±10 cm, benefits from changing the crossing angle are not as substantial.
- collapsing the crossing angle mid-store would provide a 21% increase in instantaneous luminosity within ±10 cm.

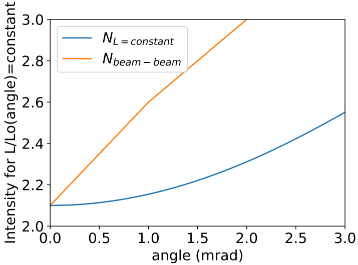




sPHENIX Luminosity II

- Percent of collisions within ±10 cm are 67% at 2 mrad, and 18% at 0 mrad.
- Intensity scaling that maintains beam-beam tune spread to achieve $\mathrm{L}(\theta) = \mathrm{L_o}|_{-10\ \mathrm{cm}}^{+10\ \mathrm{cm}}$, and the beam beam-beam intensity limit.
- At 2 mrad, 2.31×10^{11} is required to match the luminosity of 0 mrad and 2.1×10^{11}. 2.4×10^{11} is approximately the maximum achieved intensity in Run15.





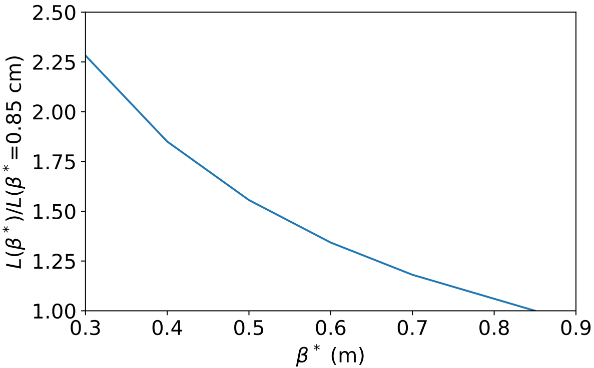
- Introduction
  - Polarized protons at 100 GeV
  - sPHENIX Luminosity Goals
  - Luminosity Reduction from Crossing Angles
- Reducing the $\beta*$
  - Aperture Limitations
  - Dynamic Aperture
- Increasing the maximum intensity of the injectors
  - More Intense LINAC Pulse
  - Two LINAC Pulses
- Summary

Reducing the β^*

The Run15 lattice had constraints on the phase advance from IP8 (PHENIX detector location) to IP10 (electron lenses location) inorder for the electron lenses to correctly compensate for the collision at IP8.

This same optics manipulation can be used to squeeze the β^* at IP8.

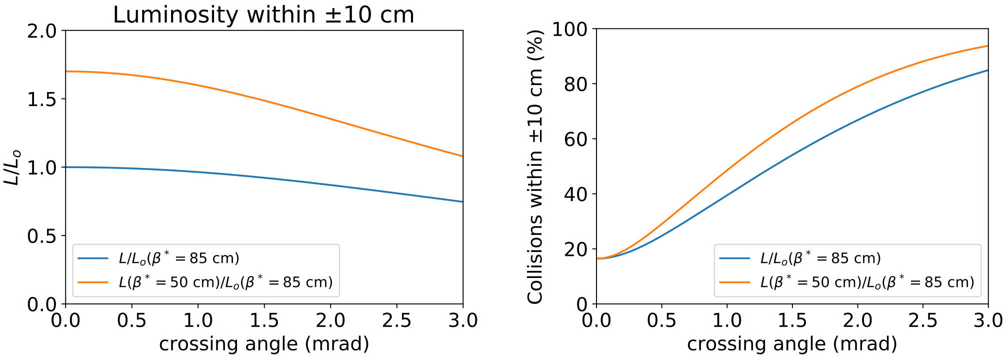
Looking at the luminosity scaling within $\pm 10\ \mathrm{cm}$ as a function of β^*



Reducing the β^* II

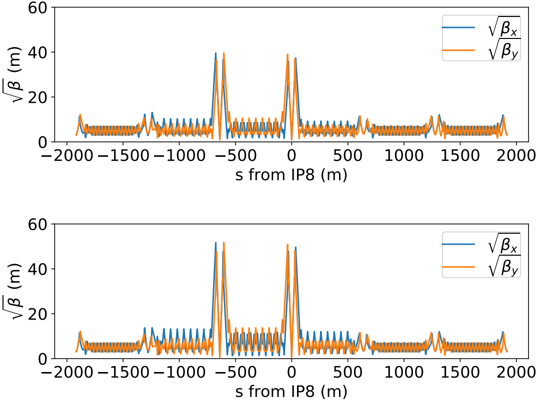
Comparing a 50 cm β^* to 85 cm with θ =2 mrad.

- the luminosity within ±10 cm increases by 51%, slightly lower than the linear scaling of head-on collisions, 0.85/0.5 →70%,
- The collisions within ±10 cm increases to 86% from 75%.



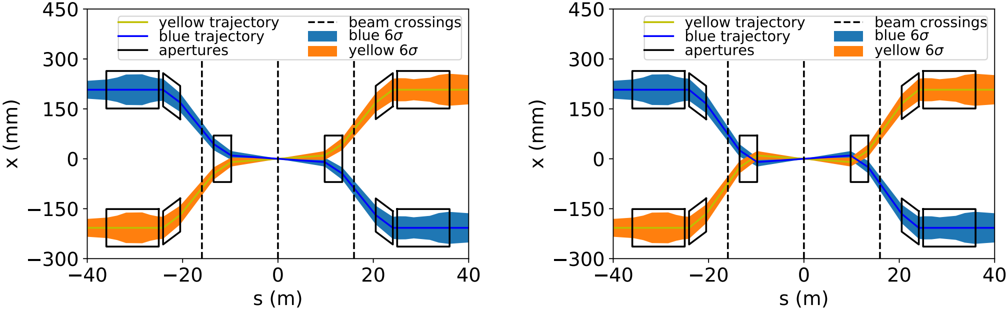
$\beta^* = 50$ cm Optics

- Optics for β^*=85 cm on top, and $\beta^* = 50$ cm on bottom.
- A beta wave is used to distribute the load of the squeeze among several arcs, as this was similar to the setup used in Run15 for eLens.



Aperture Limitations with Reduced β^*

Concern of scraping on the DX magnets with a +2 mrad crossing angle (left) is warranted. Operating with a -2 mrad crossing angle (right) provides sufficient clearance through the DX magnet aperture.



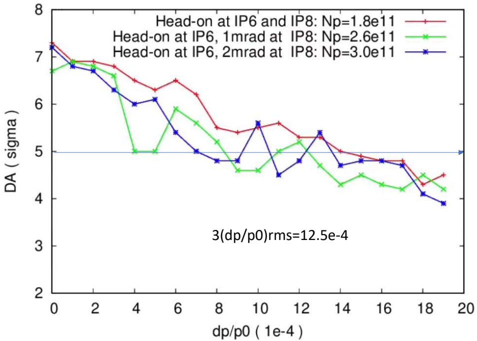
Operating with a -2 mrad crossing angle will require the polarity of the D0 shunt supply to be reversed.

Dynamic Aperture

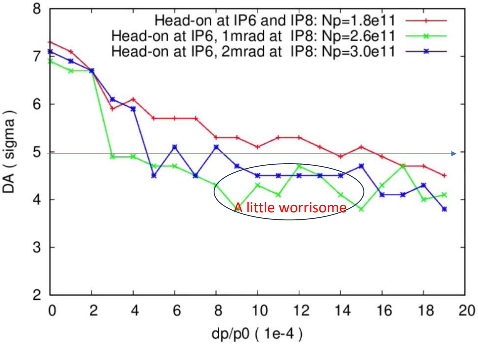
Overview of DA simulations:

- Left: DA of Run15 PP lattice with β^*=85 cm
- Right: DA of Run24 PP lattice with β^*=85 cm

From experience, 5σ is sufficient.
The Run24 lattices are still under development.



3(dp/p0)rms=12.5e-4



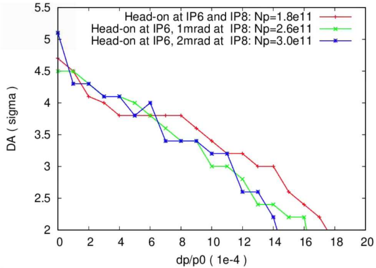
A little worrisome

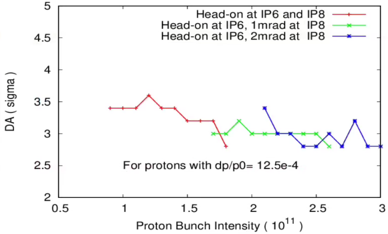
Dynamic aperture at 50 cm

The 50 cm lattice at the intended operating tunes have insufficient DA. Moving forward we will:

1. Perform tune scan to see if DA can be improved with working point.
2. Develop lattice with 0.5 cm$< \beta^* <$85 cm to both improve luminosity but also have a sufficient DA.

Determination of when the squeeze can occur has to be determined but estimates will use 3 hours, based off previous experience.





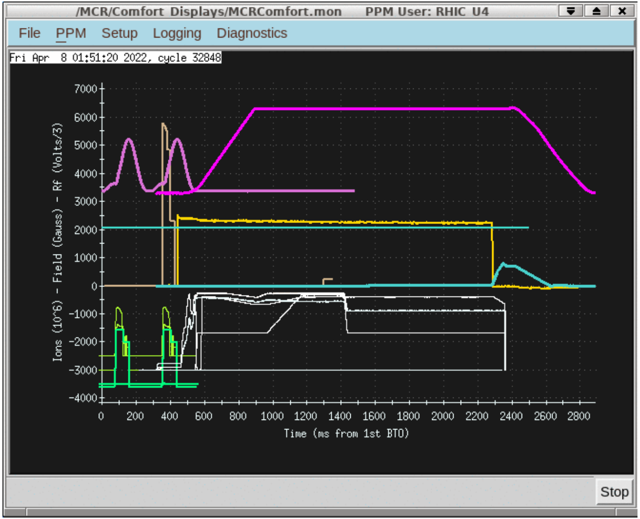
Introduction
- Polarized protons at 100 GeV
- sPHENIX Luminosity Goals
- Luminosity Reduction from Crossing Angles

Reducing the $\beta*$
- Aperture Limitations
- Dynamic Aperture

Increasing the maximum intensity of the injectors
- **More Intense LINAC Pulse**
- **Two LINAC Pulses**

Summary

Overview of standard PP Injector Setup



- Beam is strip-injected into the Booster from LINAC with a typical pulse length of 300 $\mu\mathrm{s}$.
    - With $f_{rev} = 841.2\,\mathrm{MHz}$ at Booster injection, particles will pass through the foil hundreds of times during the injection process.
- This is captured on RF harmonic h=1, and injected into the AGS at $G\gamma = 4.5$
- There is a long porch at AGS flattop to allow for polarization measurements and ensure a stable field for extraction into RHIC.
- This repeats every $\sim$4.2 s

Increasing the maximum intensity of the injectors

Using the efficiency from the highest intensity physics stores from Run15, the AGS will need a minimum of 3.4×10^{11} at extraction to reach 3.0×10^{11} at store. This likely underestimates the necessary AGS intensity.

1. OPPIS can supply two pulses but timing is constrained at 1 Hz, resulting in a longer supercycle.
   - The longitudinal emittance in this configuration is doubled and will require different optimization of parameters.
2. The split+merge scheme in the booster with a longer pulse from OPPIS.
   - The limit of the pulse width is 400 us where the nominal length is 300 us.
   - Splitting the more intense bunch into two bunches and remerging at top energy will help reduce the peak current of the bunch to mitigate space charge and improve tune jumps efficiency.

- The longer pulse means more time on the injection foil, leading to larger emittances.
- The required intensity should be attainable with a pulse length of 350 to 400 us.

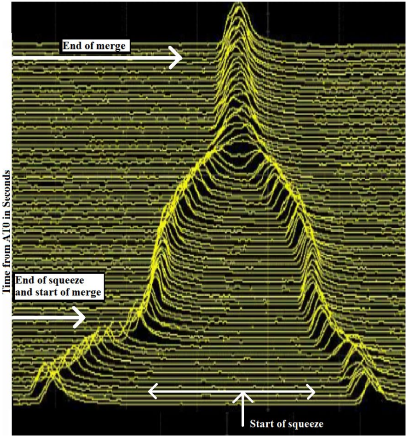
The Split+Merge and 2-bunch Merge

On right, image of polarized protons merging at AGS flattop [a]

Both the split+merge and two-bunch merge will utilize a merge in AGS:

- The split+merge will take a high intensity bunch and split it in Booster.
- The two-bunch merge will have two LINAC pulses accelerated on two separate Booster cycles and merge then merge in AGS at flattop.

Both setups also benefit from reduced space charge from reduced peak charge.



---

[a] K. Zeno, "The 2022 Polarized Proton Run in the Injectors", 2022.

LINAC and Booster Intensity Control

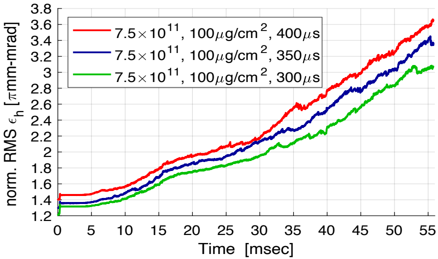
Typically the OPPIS is operated with a nominal pulse length of 300 μs and a Rb-cell temp of 82 $^\circ$C

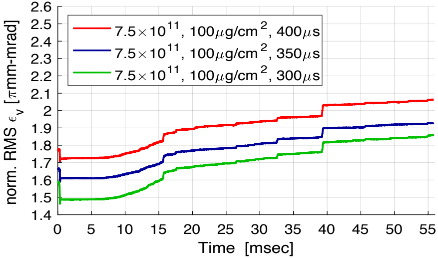
- The intensity can be controlled by adjusting the pulse length (up to a maximum of 400 μs) or by adjusting the Rb-cell temp.
- Adjustment of the Rb-cell temp are inversely correlated with the source polarization.
- A recent upgrade that shortened the transport from OPPIS to the RFQ improved intensity 15%.

Intensity control in the Booster primarily uses transverse scraping to control the intensity.

- This is the main intensity control used for RHIC.
- Higher intensity corresponds to increased transverse emittances and degraded polarization transmission.
- A new optimal for OPPIS can be found to improve the intensity through scraping while mitigating emittance growth is desirable.

Extending the LINAC Pulse

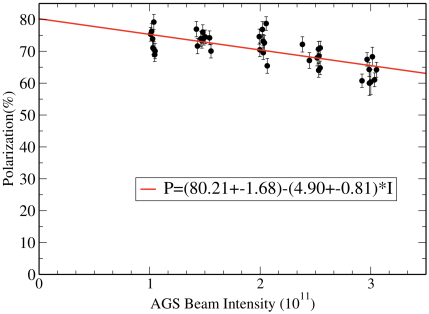


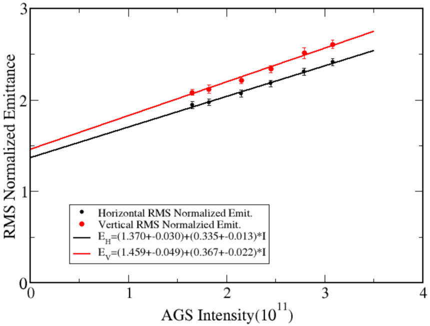


- The LINAC supplies H^- which is strip-injected as it enters the booster.
- A nominal 300 $\mu\mathrm{s}$ pulse is 260 turns in the Booster.
- The circulating protons pass through the stripping foil many times as the ribbon of H^- continue to be injected.
- Each pass through the foil causes emittance growth.
- On left, a bunch with equal intensity pass through the injection foil for 300, 350, and 400 $\mu\mathrm{s}$.
- These simulations include space-charge effects and effects from the foil, and a nominal foil thickness of 100 $\mu\mathrm{g}/\mathrm{cm}^2$.

Estimation of polarization with more intense LINAC pulse

An assessment of Polarization and emittance scaling vs. intensity [2]





3.4×10^{11} at AGS extraction would correspond to:

- 61-64% polarization and $\varepsilon_{\mathrm{x,RMS,Norm.}}, \varepsilon_{\mathrm{y,RMS,Norm.}}$=2.51, 2.76 μm.
- Note current existing measurements end at $3 \times 10^{1}1$ AGS intensity.

3.0×10^{11} at store would correspond to 50-54% polarization.

---

[2] V. Schoefer "Mitigation of Space Charge Effects in RHIC and its Injectors" 2023

Estimation of polarization with two OPPIS pulses

If RHIC could accept the entire bunch with twice the longitudinal emittance (very likely impossible),

- Two bunches at 1.7×10^{11} would correspond to:
    - 68-72% polarization in AGS,
    - $\varepsilon_{\mathrm{x,RMS,Norm.}}, \varepsilon_{\mathrm{y,RMS,Norm.}}$=1.94, 2.08 μm.

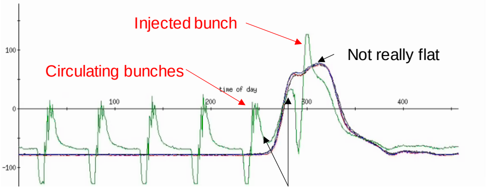
Polarization in RHIC with 3×10^{11} would correspond to 56-59% at store.

Outside of longitudinal acceptance, the amount of scraping for each parameter needs to be determined. Longitudinal scraping down to 2σ

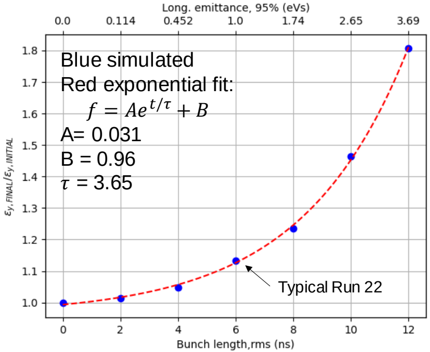
- Two bunches at 2.7×10^{11} would correspond to:
    - 63-67% polarization in AGS,
    - $\varepsilon_{\mathrm{x,RMS,Norm.}}, \varepsilon_{\mathrm{y,RMS,Norm.}}$=2.27, 2.45 μm.

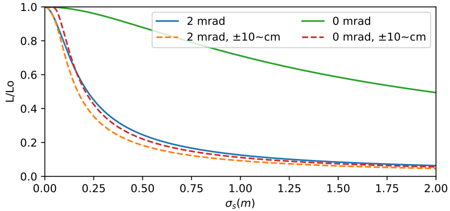
Polarization in RHIC with 3×10^{11} would correspond to 52-55% at store.

Longitudinal Acceptance of RHIC



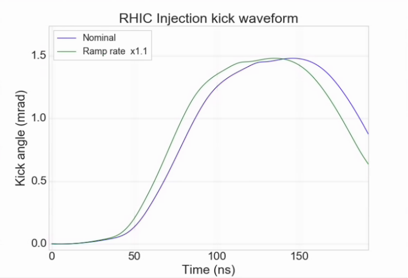
- The non-uniformity of the RHIC injection kicker (top left) results in a bunch length dependant kick, leading to transverse emittance growth (top right).
- Doubling the longitudinal emittance would make the transverse emittance growth 7% larger.
- Doubling the longitudinal emittance would also result in 30% reduction in the luminosity within ±10 cm, that is from 0.7 m to 1.0 m.

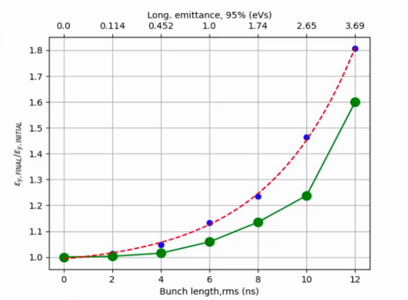




A Possible Injection Kicker Upgrade

- It may be possible to tune the injection kicker power supply for a faster rise time, allowing for less disturbance of the circulating and/or incoming beam.
- An example kick (lower right) with a 10% faster rise time has the observed benefit as seen on the upper right.
- This would to ∼10% improvement on emittance degradation from the injection kicker with a 2 eVs bunch.



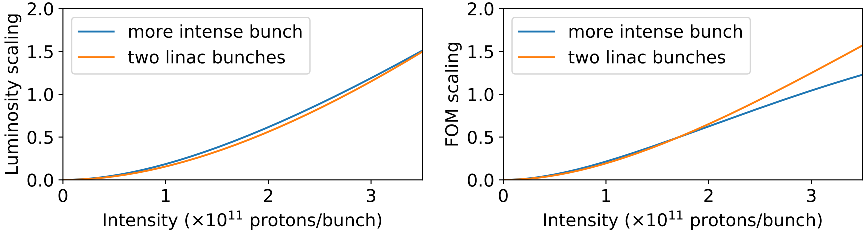


Brookhaven National Laboratory

Comparison of Injector Setups

For $\varepsilon_{x,y}$, values in () and bold correspond to more realistic emittances.

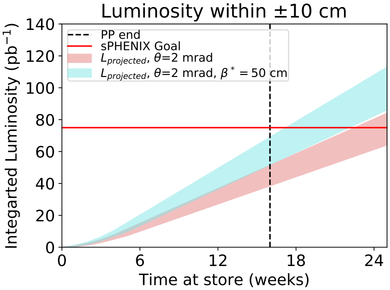
	Nominal	Two LINAC Pulses	More Intense LINAC Pulse
Intensity $\times 10^{11}$	2.1	3.0	3.0
$\varepsilon_{x,y}$ (μm)	2.11, 2.27	1.96, 2.08 (1.96, 2.39)	2.51, 2.71 (2.51, 2.79)
ε_s (eVs)	1.0	2	1.2
Polarization	57%	59%	51%
Geometric Scaling	1.00	0.71	0.92
Luminosity Scaling	1.00	1.53 (**1.43**)	1.64 (**1.53**)
FOM Scaling	1.00	1.68 (**1.57**)	1.41 (**1.31**)

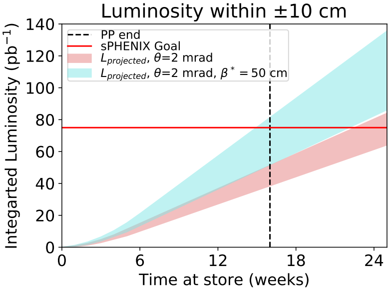


Integrated Luminosity Outlook with reduced β^* and higher intensity

Squeezing the β^* from 85 to 50 cm 3 hours into the store, in combination with exceeding 2.25×10^{11} protons/bunch, sPHENIX will reach their luminosity goals in the expected time at store. Intensity beyond 2.25×10^{11} assumes three additional weeks after the nominal 4-week ramp up time.

Parameter	Run15	Run24-A	Run24-B	Run24-C	Run24-D	Run24-E
β^* (cm)	85	85	85	50	60	50
θ	0	2	2	2	2	2
$N_{1,2}$ (10^{11})	2.25	2.25	2.5	2.25	2.5	2.5
$L_{max}/week$ pb^{-1}	25	3.8	4.7	5.1	5.7	7.1
Weeks to 75 pb^{-1}	-	22	19	17	16	15





Ongoing Studies and Discussions

Simulations, studies and developments:

1. Lattice design with reduced β^*
2. Beam-beam effects
3. Dynamic aperture
4. Longitudinal acceptance of RHIC
5. Space charge simulations at Booster injection
6. Bunch merge optimizations
7. AGS skew quads for horizontal resonance crossings.
   - See "Polarization increase in AGS with skew quads - update" by V. Schoefer.
8. ML/AI applications for emittance reduction and polarization maximization
   - See "ML for beam polarization increase (FOA)" by Georg Hoffstaetter.

Regular meetings are held to discuss the status of simulations

- Meetings every 2 weeks to discuss injector improvements and simulations.
- Meetings every 2 weeks to discuss RHIC lattice development and simulations.
- 2-3 meetings per week on ML/AI initiatives.

Summary

- sPHENIX requires high luminosity within a small vertex of ±10 cm and intends to run with a crossing angle to maximize collisions within their desired region, while minimizing collisions outside.
  - This is to maximize the number of collisions within their ±10 cm vertex while remaining under their TPC limit.
- Luminosity needs to be increased 37% to reach their luminosity goals within the 16 week run.
- Multiple avenues exist for improving the performance of RHIC over Run15.
  - Reducing the β^* to 50 cm 3 hours into the store would increase luminosity 35%
  - Increasing the intensity to 3×10^{11} with two merged LINAC pulses would increase the luminosity by up to 57% in the longitudinally unscraped scenario.
  - Although 3×10^{11} is the goal, it is possible a lower intensity is settled at, say $2.5{\times}10^{11}$.
- A combination of the two options above will give a significant improvement to sPEHNIX's luminosity.

MAC Recommendation from MAC-19

On ”He-3 Polarization Preservation in Injectors”

Charge Questions:
A) Yes.
B) No.
C) Yes.
Recommendation: Consider testing the beam dynamics of this scheme with unpolarized He-3 beams

Outcome: The EBIS upgrade and commissioning suffered from degraded vacuum and unpolarized helions would further spoil the vacuum.

Plan: Use unpolarized helions now that the EBIS vacuum issue has been resolved, or polarized protons with the helion settings this year.

MAC Recommendation from MAC-19

On ”Operations with sPHENIX”

Charge Questions:
A) Yes.
B) See recommendation.
C) Yes.
Recommendation: Clarify the consequences of a quench protection diode failure

Response: From Run16, a failed diode corresponded to 19.5 days of downtime. This involved a warm up of the sector, diode replacement, cool down and electrical tests. This was a diode in an arc where the diode is readily accessible. For more complicated cryostats and diode configurations, the diode replacement in situ could take up to two days longer. For the most complicated systems, the magnets need to be removed for the diode to be replaced, downtime of $\sim$40 days.

Thank you

Thank you and questions.

Contributors:
Grigor Atoian, Joanne Beebe-Wang, Angelika Drees, Wolfram Fischer, Xiaofeng Gu, Haixin Huang, Chuyu Liu, Yun Luo, Michiko Minty, Deepak Raparia, Guillaume Robert-Demolaize, Vincent Schoefer, Keith Zeno

Contributors on diode repair details:
Don Bruno, Angelika Drees, Greg Heppner, Jon Sandberg, Scott Seberg, Joseph Tuozzolo