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LUMINOSITY MAXIMIZATION IN A SMALL VERTEX REGION AT RHIC

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ABSTRACT

For the 2024 100 GeV polarized proton run at the Relativistic Heavy Ion Collider (RHIC), the new sPHENIX detector will require a maximum amount of collisions within ±10 cm of its Interaction Point (IP) and preferably with minimal collisions outside of this range. To maximize the collisions within this vertex, a large crossing angle of up to 2 mrad will be used, operating the Large Piwinski Angle (LPA) scheme. To compensate for the reduction in luminosity from the large Piwinski angle, a β^*=60 cm lattice has been designed and supported with dynamic aperture simulations. To further compensate for the luminosity reduction, injector studies are being performed to support up to a 45% increase in the injected intensity relative to the previous 100 GeV run in 2015.

INTRODUCTION

sPHENIX is a new detector at RHIC which was commissioned during Run23 with 100 GeV/u Au beam, and is now using 100 GeV polarized proton beams. sPHENIX requires a sampled luminosity of 45 pb^{-1} for Run24 which corresponds to 75 pb^{-1} of delivered luminosity, assuming 60% availability. Their desired luminous region is within a vertex cut of ±10 cm, with minimal collisions outside of this cut region. To provide the luminosity inside this vertex, a large crossing angle of θ =2 mrad will be used. Given the performance during Run15, it would take 22 weeks to deliver the desired luminosity within this vertex with a $\theta = 2$ mrad and 19 weeks at $\theta = 0$ mrad. Luminosity needs to be increased by 37% to reach these goals within 16 weeks.

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

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

where

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

where N_1 and N_2 are the colliding per bunch intensities from each ring, k_b is the total number of bunches per ring, θ is the full crossing angle, σ_x and σ_y are the transverse RMS beam-sizes, σ_s is the longitudinal RMS beam-size, and β^* is the minimum β at the location of the IP. Typical bunch parameters are $N_1 = N_2 = 2.1\times10^{11}$ protons/bunch, k_b=111, $f = 78.3$ kHz, $\sigma_s = 0.682$ m, $\varepsilon_x = \varepsilon_y = 2$ µm and β^*=0.85 cm. The Piwinski angle is defined as,

$$\theta_{PA} = \frac{\theta\sigma_s}{2\sigma_x}. \quad (3)$$

With the above parameters θ_{PA}=6.43. Here, the HG effect is largely suppressed with θ >0.5 mrad. The luminosity can be increased primarily by reducing the β^* or increasing N_1 and N_2. As seen in Fig. 1, although the total luminosity at $\theta = 2$ mrad is reduced to 18%, the luminosity delivered within ±10 cm is 75%. For polarized collisions in Run24, the

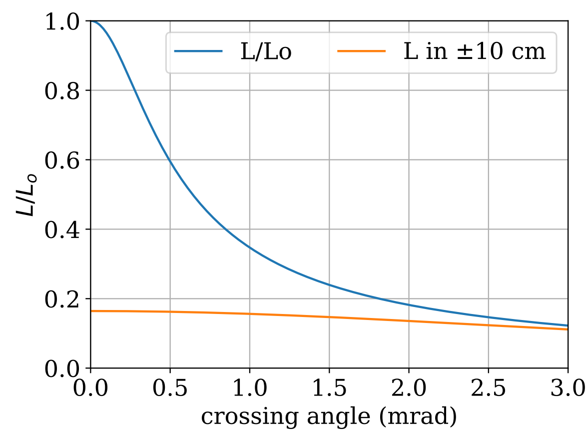

Figure 1: Luminosity scaling across the full luminosity region and luminosity scaling within ±10 cm as a function of crossing angle.

accelerator performance is measured by the Figure-of-Merit, FOM, defined as

$$FOM = \mathcal{L}P^2, \quad (4)$$

where P is the average polarization of both rings.

Due to the large crossing angle, there is a smaller overlap of the beams in collisions leading to a reduced beam-beam parameter [2], as seen in Fig. 2. This reduction in the beam-beam parameter allows operation at higher intensity to compensate for the reduction in luminosity from the crossing angle. This allows operation with two colliding IPs without the electron lens for partial compensation of beam-beam effects [3].

REDUCING THE β^*

The nominal β^* for 100 GeV polarized protons is $\beta^* = 0.85$ m. To improve the luminosity, a $\beta^* = 0.60$ m lattice was developed. The intent is to squeeze into this lattice at three hours into the store. To maximize the clearance through the DX magnets, IP8 will be operated with a negative crossing angle, as seen in Fig. 3 [4].

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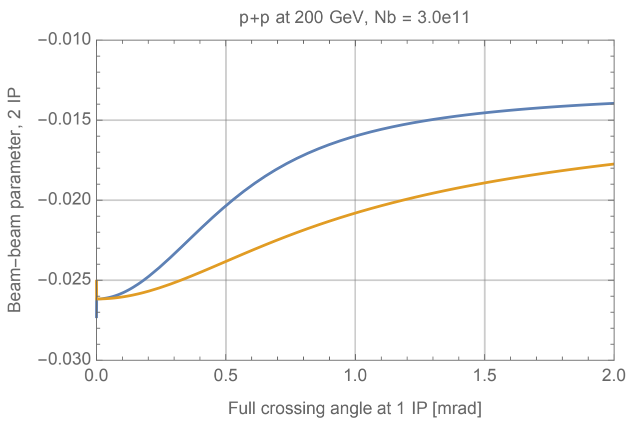

Figure 2: Beam-beam parameter at $3{\times}10^{11}$ with one IP θ=0 mrad and the second IP θ =0 to 2 mrad.

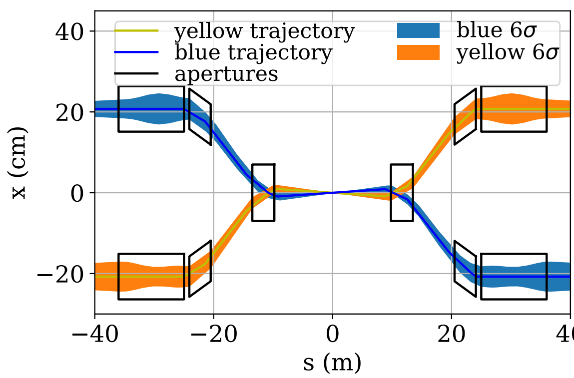

Figure 3: Comparison of 6σ beam envelopes with θ=+2 mrad (top) and θ =-2 mrad (bottom).

Dynamic Aperture

To quantify the quality of the lattice, dynamic aperture simulations were performed at a range of tunes. The results of these simulations are shown in Fig. 4 which indicates a larger dynamic aperture for the θ = 2 mrad (bottom) compared to the 0 mrad crossing case (top). From previous experience at RHIC, 5σ is suitable for off-momenutm particles.

INCREASING THE DELIVERED INTENSITY

In the Booster and AGS, the main intensity control during normal operations is through transverse scraping of the beam. To reach 3×10^{11} protons per bunch at store in RHIC, a minimum of 3.4×10^{11} is required in AGS at extraction, a 50% increase over nominal AGS intensity. This means an increase in the intensity using the conventional method of reduced scraping results in an increase in transverse emittances [5]. This is not a realistic approach for achieving a 50% increase in intensity. To increase the delivered intensity to RHIC, two different configurations of the injectors are to be investigated. Configuration 1, which uses a single bunch

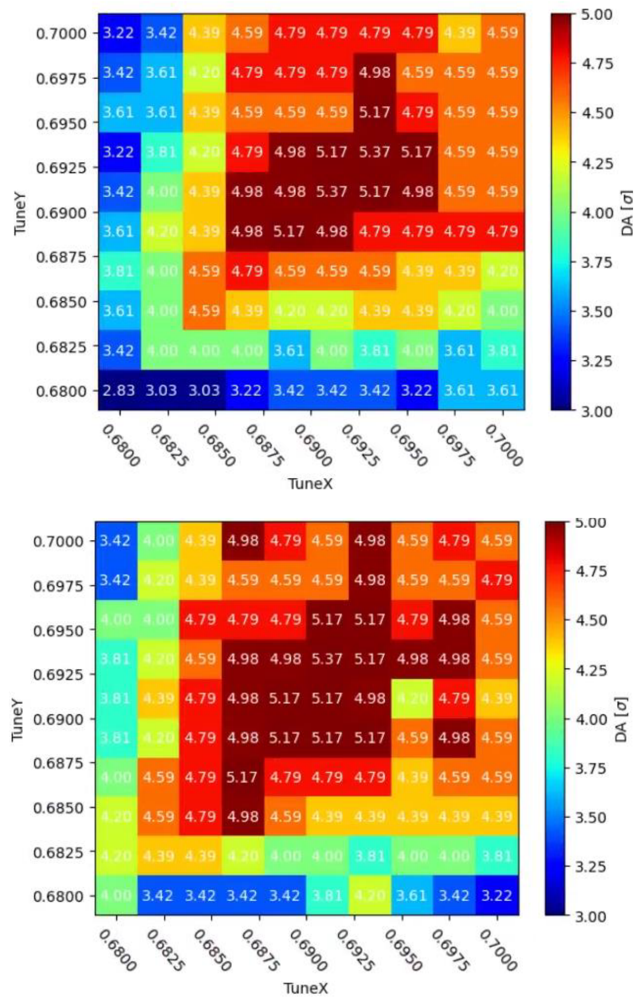

Figure 4: Dynamic aperture simulations with β^* =60 cm, including beam-beam effects, at θ = 0 mrad (top) and θ = 2 mrad (bottom).

from the LINAC delivered into the Booster, where it is split into two bunches to reduce space-charge emittance growth, and then the two bunches are merged together in the AGS at extraction energy [6]. Configuration 2, which uses two bunches from the LINAC and Booster which are merged into one in the AGS at extraction energy. Configuration 1 aims to further improve the efficiency of the Booster and AGS cycles, so that the increase in emittance from the corresponding increase in intensity is less severe. Configuration 2 will allow for much smaller transverse emittances at the expense of increased longitudinal emittance, since each bunch can be scraped more than normal.

Following the expected polarization performance given beam intensity and emittances, for configuration 1, the polarization in RHIC 52-55% at store for a bunch with 3×10^{11} protons/bunch, and emittances of $\varepsilon_{x,RMS,Norm.}, \varepsilon_{y,RMS,Norm.}$=2.51, 2.76 μm. For configuration 2, two bunches at $1.7{\times}10^{11}$ merged would correspond to $3.0{\times}10^{11}$ in RHIC at store with 59-62% polarization,

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and emittances of $\varepsilon_{\text{x,RMS,Norm.}}, \varepsilon_{\text{y,RMS,Norm.}}$=1.94, 2.08 μ$m$. One caveat of these setups is the increased bunch length from inefficiencies of the bunch merging. For configuration 1, the longitudinal emittance at the end of the merge is 20% larger than the nominal configuration. For configuration 2, this longitudinal emittance is doubled. From Eq. (1), the luminosity reduction for configuration 1 is approximately 9%, and for configuration 2 the luminosity reduction is approximately 28%. The effects this has in the luminosity scaling is seen in Fig. 5 where despite the better transverse emittance, the reduction in luminosity from the longer bunch length reduces the luminosity scaling relative to configuration 1. However, due the flexibility of having two bunches, configuration 2 provides the best route for achieving these record high bunch intensities. Likewise, the reduced transverse emittance will provide improved FOM performance.

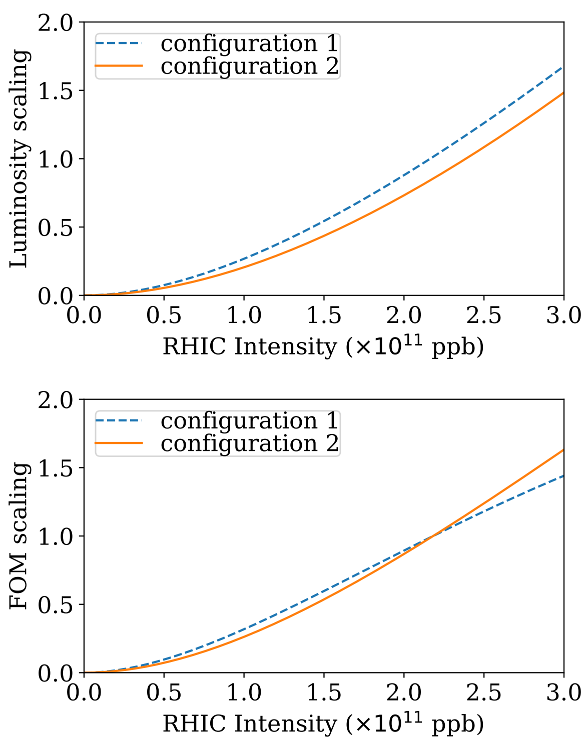

Figure 5: Comparison of configuration 1 with configuration 2 for luminosity scaling (top) and FOM scaling (bottom).

INTEGRATED LUMINOSITY OUTLOOK

Squeezing the β^* from 85 to 60 cm at 3 hours into a nominal 8 hour store, the increase in delivered luminosity would be 26%. This in combination with reaching 2.5×10^{11}protons/bunch, sPHENIX will reach their luminosity goals in the expected time at store. Intensity beyond $2.25{\times}10^{11}$ assumes three additional weeks after the nominal 4-week ramp up time. These changes in parameters are summarized in Tab. 1 and the change in integrated luminosity outlook shown in Fig. 6.

Table 1: Table summarizing parameters from Run15 and including possible scenarios for Run24, specifically Run24-A coincides with no change over Run15 performance and with the inclusion of θ = 2 mrad, and Run24-B coinciding with an increase in intensity and a reduction of the β^* 3 hours into store.

Parameter	Run15	Run24-A	Run24-B
β^* (cm)	85	85	85→60
θ	0	2	2
$N_{1,2}$ (10^{11})	2.25	2.25	2.5
L_{max}/week pb^{-1}	25	3.8	5.7
Weeks to 75 pb^{-1}	-	22	16

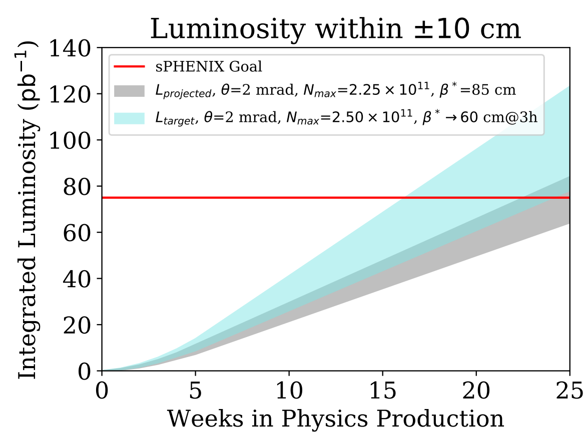

Figure 6: Integrated luminosity projections given Run15 performance (grey), the target luminosity range given a β^* squeeze to 60 cm three hours into a store, and an increase of intensity to $2.5{\times}10^{11}$ (cyan), and the sPHENIX luminosity goal (red). The cyan area is semi-transparent to allow the grey area to be visible, noting the overlap region.

SUMMARY

Performance improvements for RHIC have been identified for 100 GeV protons during Run24 while operating under the Large Piwinksi Angle regime. The improvements have been supported with numerical simulations and show that they are reasonably achievable. Increasing the per bunch intensity beyond $2.25{\times}10^{11}$ will correspond to the highest achieved proton intensity at RHIC. These improvements are to support the high luminosity goals of sPHENIX within their narrow ± 10 cm vertex region. With Run24 currently underway, the extent of these improvements have not yet been realized.

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