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Impact of Imperfection Spin Resonance Strength on Depolarization in RHIC

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Using a simple smooth step like function of emittance developed from direct spin-orbit tracking simulations, we characterize the polarization performance from previous RHIC runs.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

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[*] Speaker

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PoS(SPIN2023)090

1. INTRODUCTION

Subatomic particles possess an intrinsic property known as spin. Approximately twenty percent of a proton's spin is derived from that of its three constituent quarks, however, the main source of spin remains unknown (theoretical research suggests that it may originate from gluons or the relative moment of quarks and gluons)[1]. In order to investigate such mysteries, intense beams of polarized protons, whose spins are magnetically manipulated to point in a consistent direction, are accelerated in the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory. The resultant collisions are studied. Maintaining polarization throughout acceleration is extremely difficult. Resonance conditions, which arise from the alignment of the spin precession around its axis with coherent kicks from focusing magnets, represent a major source of depolarization. Imperfection resonances occur due to random misalignments of magnets in the machine, while intrinsic resonances appear as a result of the beam's natural betatron oscillation as it makes its way through the ring. In order to mitigate depolarization due to these resonances, snake magnets rotate the spin vector 180 degrees about a horizontal axis[2]. Without snakes, the net number of precessions per orbit, spin tune ν_s, is equal to $G\gamma$, where G is the anomalous magnetic moment coefficient and γ is the Lorentz factor. Thus, ν_s increases with energy and resonance conditions will be crossed. The resonance condition is given by:

$$K = \nu_s = n + \nu_z \tag{1}$$

where the spin precession ν_s is equal to the value of betatron tune ν_z plus some integer n (i.e., the condition in which the spin precession is in sync with the harmonics of the machine). With the addition of snakes, spin tune remains fixed at a value of $\frac{1}{2}$ while $G\gamma$ varies with energy. Therefore, the aforementioned resonance condition can be avoided.

However, depolarizing resonances are still possible with snakes. These are known as snake resonances. This condition occurs when:

$$\nu_z + lK = n \tag{2}$$

where the betatron tune plus the resonance condition K times some integer l is equal to an integer n. In a system containing only intrinsic resonances, certain even order snake resonances, where l is equal to an even integer, do not occur. This is because the coherent kicks of one side of the machine negate those of the other, preventing depolarization. With the additional presence of an imperfection resonance, however, even order snake resonances are bound to arise, since the magnetic misalignment in combination with the existing resonance condition thoroughly offsets the spin precession[3]. Undoubtedly, polarization loss occurs due to the presence of an imperfection resonance under conditions involving snake magnets, yet the accuracy of existing models in predicting the amount of depolarization remains subject to question. This study attempts to investigate the relationship between polarization transmission and imperfection resonance strength at the location of strong intrinsic resonances. A Mathematica notebook file was used to determine a value, b, representing polarization aperture. b is calculated by fitting the measured values for polarization before and after the acceleration ramp and values for the beam emittances (i.e., action) for each fill. A fill represents a single acceleration cycle from 25 GeV to 255 GeV. Additionally, imperfection spin resonance strengths have been estimated based on existing orbit data. Nine of these resonances are correlated with the calculated b values. The estimated imperfection spin resonances are sampled near the strongest three intrinsic spin resonances on the RHIC acceleration ramp; thus, they have the potential to interfere with one another and create conditions for depolarization. A negative correlation between polarization transmission and the estimated imperfection spin resonance strength would reflect the results of simulations and analytical studies.

2. Methods

Data from the 2012 [6], 2013 [7], and 2017 [5] polarized proton RHIC runs has been inputted into the smooth step-function, Eq. 1, which gives average polarization Pf / Pi as a function of emittance (ϵ).

$$\frac{P_f}{P_i}(\epsilon) = 1 - \frac{1}{1 + e^{-a(\epsilon - b)}}. \tag{3}$$

Due to the nature of this model and the fact that no data gives individual values of polarization as a function of emittance, average polarization transmission per run, b, (representing the step in the function) could not be determined using Eq. 3 alone. In order to find values for b, Eq. [**?**] was integrated over a Gaussian particle distribution to yield Eq. 5 [4].

$$\overline{P}_f = \int_0^\infty P_f(\epsilon)\rho(\epsilon)d\epsilon \tag{4}$$

$$= \frac{P_0\epsilon_0 e^{ab}\,{}_2F_1\left(1, \frac{2a\epsilon_0+R_{y,i}+1}{2a\epsilon_0}; \frac{4a\epsilon_0+R_{y,i}+1}{2a\epsilon_0}; -e^{ab}\right)}{(\epsilon_0 R_{x,i}+\epsilon_0)(2a\epsilon_0+R_{y,i}+1)} \tag{5}$$

Thereafter, the hypergeometric function given by Eq. 2 was set equal to zero by subtracting the final polarization (Pf) from the left side. Next, figures for polarization before and after the acceleration ramp, emittance, and R values representing the polarization profile were inputted into the function, which was evaluated using Mathematica. Finally, the Mathematica notebook was modified to calculate polarization transmission per fill, b, in both the Blue and Yellow rings for each run. The newly determined b values were then imported into a spreadsheet, alongside their associated fill number. A Python program was utilized to correlate the imperfection resonance strengths to their associated polarization aperture/fill number (note that each value of b was associated with nine imperfection resonance strengths, at 259, 260, 261, 380, 381, 382, 421, 422, and 423 $G\gamma$). The results were graphed on a set of scatter diagrams, with b as the x-axis and a single set of polarization transmission values as the y-axis. A correlation coefficient was assigned to each plot. The polarization aperture was subject to a large error bar, being that measurements of initial and final polarization, emittance, and imperfection strength were highly inaccurate. In order to calculate the degree of error, the assigned b values were inputted back into Eq. 2, which was set equal to zero. Never were the resulting numbers exactly zero, but they generally fell below 10^{-5}. Thus, the error for the b values was due solely to propagation of the polarization and emittance errors. The errors were typically about +/- 1.5 units of b.

3. Results

All b values fell between 2 and 25, with the Blue 2012 having overall the highest polarization aperture (avg. 14.41561619). By contrast, the Blue 2013 run, in which the FY12 lattice condition was applied, performed relatively poorly, averaging to a mere 7.57703394. Generally, b values averaged between 9 and 11. Results correlating polarization aperture to imperfection resonance strength were highly inconsistent. While a trend to negative correlation could be observed in the Blue 2013 Elens lattice run, the Yellow 2017 and Blue 2012 runs exhibited positive correlations at every value of $G\gamma$. Moreover, the Yellow 2017 run displayed exceedingly large values for imperfection resonance strength, usually exceeding .09. This in combination with the presence of elevated b values (averaging out to 11.85669776) is completely contradictory to existing models, which predict a negative correlation between imperfection resonance strength and polarization aperture. Similarly peculiar, the Blue 2013 (FY12 lat.) run, which had the lowest values for b, had the smallest imperfection resonance strengths (avg. .00343421378).

4. Discussion

The absence of a negative correlation between polarization aperture and imperfection resonance strength fails to support predictions made by current models and studies. Nonetheless, researchers are quite certain that a strong imperfection resonance at the site of major intrinsic resonances causes an overlap that should reduce the bunch polarization. The magnet conditions of one side of the RHIC machine no longer negate the effects of the other side, causing certain even order snake resonances arise. Theoretically, a net loss of polarization should occur.

Existing simulations predict that the largest imperfection resonances cause the most depolarization. This was not the case for the Yellow 2017 and Blue 2013 (FY12 lat.) runs, in which high polarization aperture correlated to high resonance strength and vice versa. Imperfection resonance strengths are found using Beam Position Monitors, which measure the distance that the beam travels off-axis at various points in the ring. A larger distance indicates that the beam is off-center in the quadrupoles. This leads to larger coherent kicks from quadrupole magnets which in turn lead to stronger resonances. Thus, if the BPMs are not calibrated properly, they may record the beam as being highly off-centered when in reality this is not the case. By falsely measuring the position off-set, the estimated imperfection resonance strength will be subject to significant error. In the case of Yellow run 17, the BPMs suggested large imperfection spin resonance strengths; in the case of Blue run 13, the opposite is true. Weak resonances were misrepresented as strong resonances, and strong ones misrepresented as weak.

5. Conclusion

Through this study, values for polarization aperture were fitted to the given model, Eq. 1, which represents final polarization over initial polarization as a function of emittance. The computed b values were then correlated to estimated imperfection spin resonance strengths. While simulations predicted a negative correlation between the two factors, the resulting plots often exhibited a positive relationship particularly in the case of the Yellow 2017 polarized proton run. This run was unique

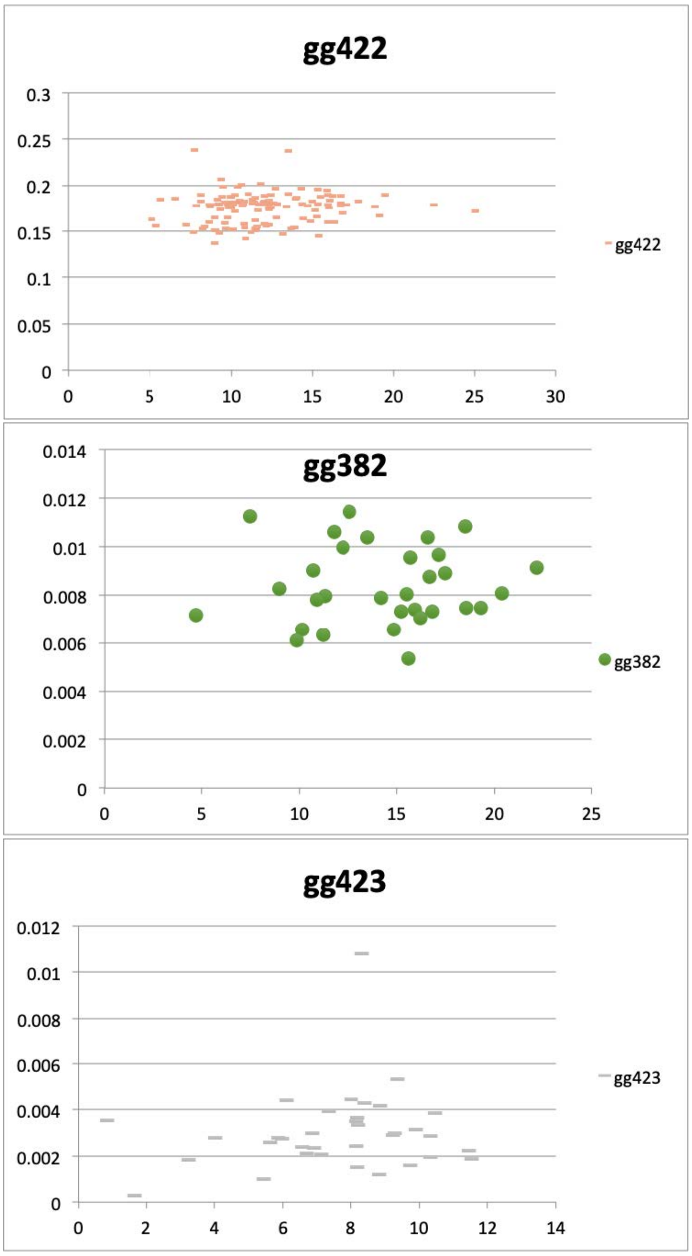

Figure 1: Polarization Aperture vs. Calculated Imperfection Resonance Strength (x-axis b, y-axis Imperfection strength). (top) Yellow Run 17, Gγ 422; Correlation +.084195436. (middle) Blue Run 12, Gγ 382; Correlation +.036649579. (bottom) BlueFY12 Run 2013, Gγ 423; Correlation +.1611153926

in that its imperfection resonance strengths greatly exceeded those of its counterparts. Hence, one would expect to observe especially low polarization aperture- yet this was far from the case. b values of Yellow run 2017 were among the highest, raising suspicions with regards to the accuracy of measurements made by the Beam Position Monitors. The Blue 2013 run also appeared to point to the BPMs as a source of error, being that low average polarization aperture corresponded to small imperfection resonance strength. Based on the analyses of polarization aperture and imperfection

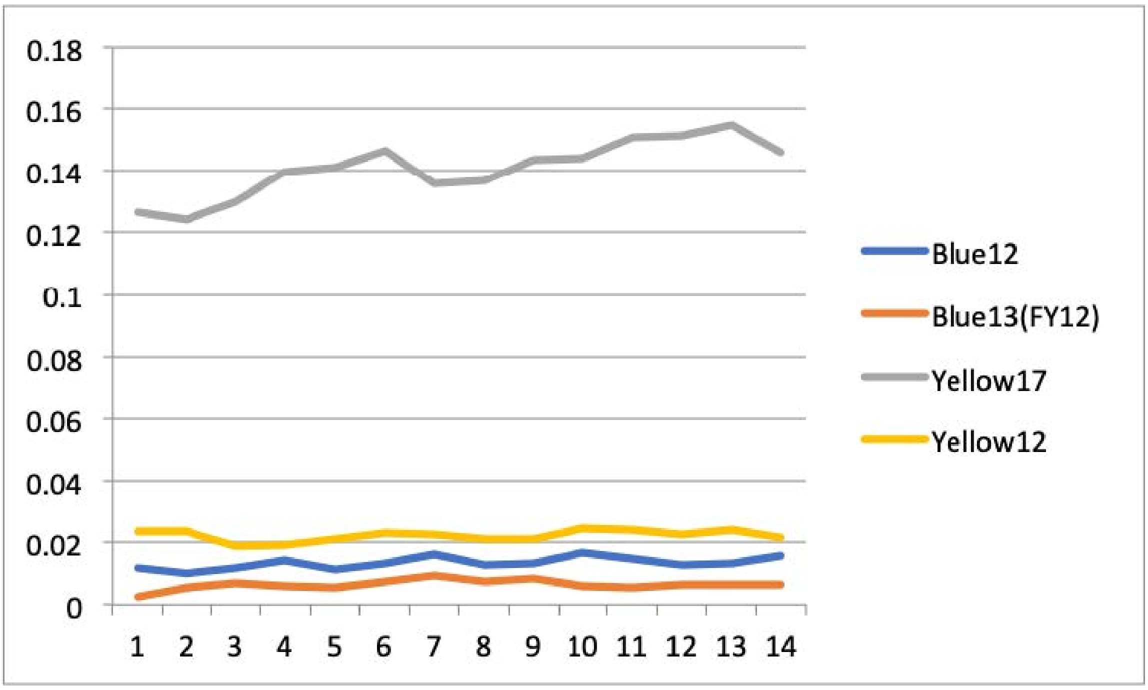

Figure 2: Imperfection Resonance Strength Comparison for Runs Blue 2012, Blue 2013 (FY12 lat), Yellow 2017, and Yellow 2012 The nature of these values suggests an error in the measurement of the resonance strength, being that Yellow 2017 is over 350% higher and Blue 2013 (Elens) 80% lower the other runs.

resonance strength, evidence suggests that Beam Position Monitors are likely miscalibrated. In order to further study the sources of depolarization within the Relativistic Heavy Ion Collider, it is imperative that internal machinery correctly measures the factors that contribute to polarization loss.

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