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NUMERICAL SIMULATIONS OF RHIC FY17 SPIN FLIPPER EXPERIMENTS

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Abstract

Spin flipper experiments during RHIC Run 17 have demonstrated the 97% effectiveness of polarization sign reversal during stores. Zgoubi numerical simulations were setup to reproduce the experimental conditions. A very good agreement between the experimental measurements and simulation results was achieved at 23.8 GeV, thus the simulations are being used to help optimize the various Spin Flipper parameters. The ultimate goal for these simulations is to serve as guidance towards a perfect flip ($P_f/P_i \approx -1$) at high energies to allow a routine Spin Flipper use during physics runs.

INTRODUCTION

Spin physics programs in the Relativistic Heavy Ion Collider (RHIC) and in the future electron ion collider eRHIC require measurement of bunch polarization with great accuracy which requires reducing systematic errors. One means to achieve that consists of frequent reversal of bunch polarization during detector data taking. This can be done without harming beam polarization by using a spin flipper [1–3], a device which reverses the polarization sign of all bunches without changing other beam parameters or machine settings.

Spin Flipper

RHIC spin flipper magnet assembly is located in one of the straight sections of the Blue ring. It consists of four horizontal dipoles ("spin rotator") and five vertical AC dipoles (Fig. 1) [4].

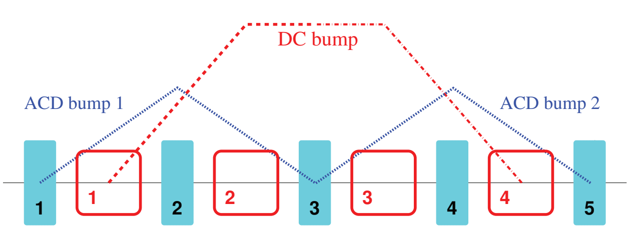

Figure 1: Spin Flipper layout.

The four y-rotator dipoles (vertical field) are DC, with field integral $B_{dc}L$. They yield spin rotation angles $+\psi_0/-\psi_0/-\psi_0/+\psi_0$ respectively, with

$$\psi_0 = (1 + G\gamma)\frac{B_{dc}L}{B\rho}. \tag{1}$$

Orbit-wise this defines a closed local horizontal bump and, spin-wise, it leaves the spin tune $\nu_s \approx 1/2$ unchanged.

The horizontal magnetic field in the AC dipoles has the form $B_{osc}(t) = \hat{B}_{osc}\cos(2\pi f_{osc}(t)t + \varphi_0)$ with φ_0 a reference phase and $f_{osc}(t) = \nu_{osc}(t)f_{rev}$ the time-varying oscillation frequency where f_{rev} is the revolution frequency. ACD1-3 and ACD3-5 triplets both ensure the same $+\phi_{osc}(t)/-2\phi_{osc}(t)/+\phi_{osc}(t)$ spin x-rotation sequence, with

$$\phi_{osc}(t) = (1 + G\gamma)\frac{B_{osc}(t)L}{B\rho}. \tag{2}$$

Orbit-wise, each triplet ensures a locally closed vertical orbit bump (Fig. 1). The phases of the first (ACD1-3) and second (ACD3-5) vertical bumps are correlated, namely,

$$\varphi_{0,ACD1-3} - \varphi_{0,ACD3-5} = \pi + \psi_0. \tag{3}$$

This configuration of the AC dipole assembly induces a spin resonance at $\nu_{osc} = \nu_s$, with the phase relationship (Eq. 3) canceling the image resonance at $1 - \nu_s$. This allows for the spin tune to remain $\frac{1}{2}$ during the spin flip [1]).

Spin Flip Efficiency

Froissart-Stora formula describes the spin flip efficiency for the single resonance crossing,

$$P_f = P_i\left(2\exp^{-\frac{\pi}{2}\frac{|\epsilon|^2}{\alpha}} - 1\right), \tag{4}$$

where P_i and P_f is the initial and final polarization.

The strength of the spin resonance excitation is

$$|\epsilon| = \frac{\phi_{osc}}{\pi}\sin\psi_0\sin\frac{\psi_0}{2}. \tag{5}$$

The crossing speed (rate of sweep of ν_{osc} through $\nu_s \approx \frac{1}{2}$) is

$$\alpha = \frac{\Delta\nu_{osc}}{d\theta}, \quad d\theta = 2\pi N \tag{6}$$

with $\Delta\nu_{osc}$ the AC dipole frequency span and N the number of turns of the sweep.

The sweep time $\tau_X = N/f_{rev}$ is the time period during which the AC dipole frequency is changing.

Spin Tune Oscillations and Multiple Resonance Crossings

The synchrotron motion induces the spin tune ν_s oscillations [4, 5],

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$$\delta\nu_s = \frac{1+G\gamma}{\pi}\Delta D'\frac{\Delta p}{p}, \tag{7}$$

where $\Delta D'$ is a difference of the dispersion function derivatives at the two snakes. Since the AC dipole frequency is linearly swept across ν_s this effect is liable to induce multiple crossing of the resonance and thus cause polarization loss during the spin flip.

EXPERIMENTAL AND SIMULATION SETUP

Spin Flipper During RHIC Run 17

The Spin Flipper experiments were conducted over several dedicated periods during Run 17 [2]. Nominal RHIC lattice, beam conditions and RF settings (dual harmonic 9MHz+197MHz) were used. The strength of the spin resonance $|\epsilon|$ was set to 0.0002397 at 23.8 GeV and 0.0005682 at 255 GeV. The AC dipole frequency span was tuned to $\Delta\nu_{osc}$=0.005. Sweep time was varied between 0.5 s and 3.0 s with RHIC synchrotron frequency between 5-6 Hz. Transition quads were used to vary $\Delta D'$ with only a marginal effect on RHIC optics. $\Delta D'$ was scanned down from the nominal 63 mrad to 3 mrad at 23.8 GeV to 0.12 mrad at 255 GeV.

Simulations

Multiple particle (960 particles per bunch) tracking was done using Zgoubi [6] with RHIC FY17 magnet lattice both at 23.8 GeV and 255 GeV energy [4]. Dual 9MHz and 197MHz RF systems, typical RHIC beam emittances, betatron tune and chromaticities were implemented. Figure 2 is an example of Spin Flip simulation.

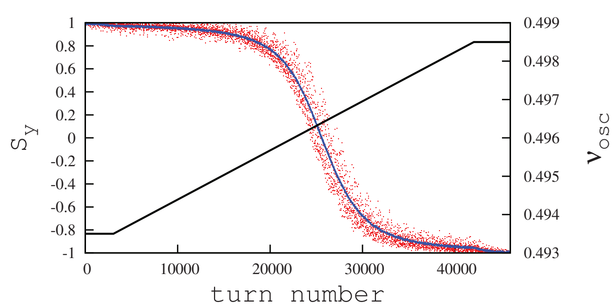

Figure 2: Spin Flip at 255 GeV: Red - vertical spin component of 10 different particles. Blue - an averaged vertical spin component of 960 particles. Black - AC dipole frequency.

EXPERIMENTAL AND SIMULATION RESULTS

An excellent agreement (within 10%) between the experimental data and simulations was achieved for injection energy (23.8 GeV). The results as shown in Fig. 3 confirm that the Spin Flip efficiency is dependent on $\Delta D'$.

Figure 4 shows that the Spin Flip is not just governed by the Froissart-Stora formula. Its efficiency deteriorates for larger values of Sweep Time for the non-zero values of $\Delta D'$.

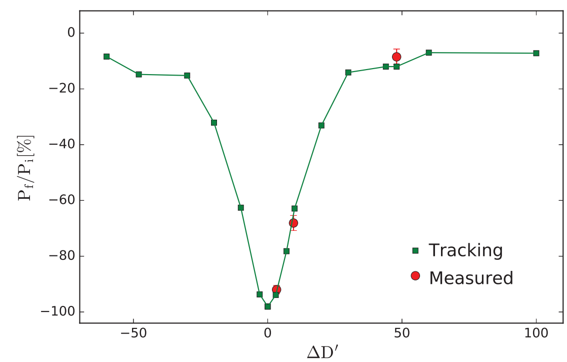

Figure 3: $\Delta D'$ Scan at 23.8 GeV: $\tau_X = 3$s.

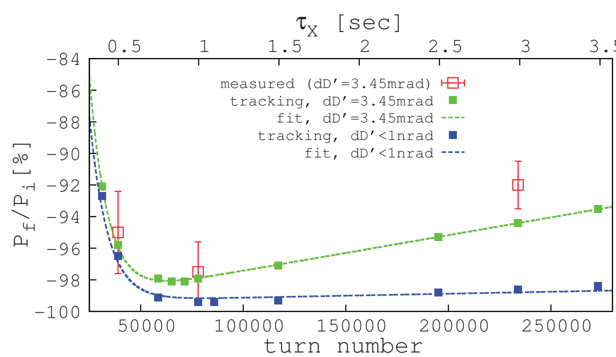

Figure 4: Sweep Time Scan at 23.8 GeV: For $\Delta D'$ = 3.45 mrad the best $|P_f/P_i| \approx$ 98% is achieved for $\tau_X \approx$ 1s.

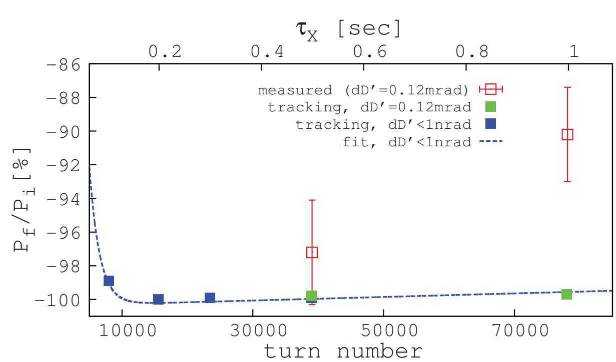

Figure 5: Sweep Time Scan at 255 GeV: The experimental data for $\Delta D' = (0.12 \pm 0.1)$mrad shows a strong dependence on the sweep time, which deviates from the Froissart-Stora formula and the simulations predictions.

The 255 GeV simulations do not agree with measurements as well as shown in Fig. 5. These simulations at 23.8 GeV and at 255 GeV describe the well balanced Spin Flipper and

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RHIC lattice with no errors. Nevertheless, the conclusion can be made that the optimal Sweep Time is around 0.2 s (approx. one synchrotron oscillation) for this Spin Flipper setup at 255 GeV. Multiple attempts were made to explain the experimental data in Fig. 5 by introducing errors into the RHIC lattice and Spin Flipper or by changing the values of $\Delta D'$ and the momentum spread [3].

ADDITIONAL RESULTS

Mirror Resonance

The additional experimental results [2], namely the Static Spin Tune Scan, reveal a secondary resonance to be present where the mirror resonance would be at 255 GeV.
The mirror resonance can be introduced in simulations if errors are added to the Spin Flipper, such as changing the field of one of the AC dipoles, putting an incorrect phase shift between two vertical bumps, or changing the two AC frequencies at a different rate. The single particle tracking covering the mirror resonance is shown in Fig. 6.

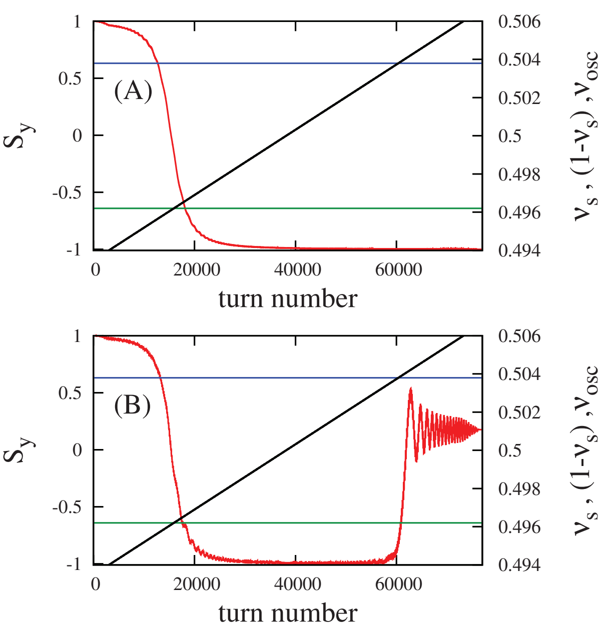

Figure 6: (A) - The spin flips only at $\nu_{osc} = \nu_s$ when the Spin Flipper is balanced; (B) - The spin flips at $\nu_{osc} = \nu_s$ and at $\nu_{osc} = (1 - \nu_s)$ when the error is introduced into the Spin Flipper.

Partial Resonance Sweep

The importance of having a wide enough oscillator range covering the whole resonance is demonstrated in Fig. 7. Here "Distance to Spin Tune" is defined as spin tune minus the lower limit of the oscillator range. If the resonance is not covered, the Spin Flip efficiency is poor.

CONCLUSION

The agreement between the experimental data and the simulations is very encouraging in the sense that it confirms

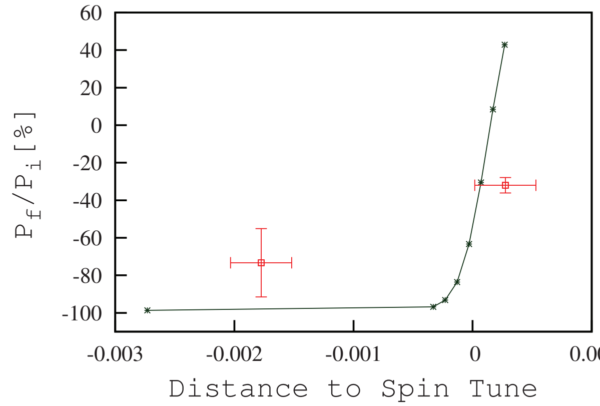

Figure 7: Partial resonance sweep. The oscillator range is 0.005, $\Delta D'$ = 3mrad, τ_X = 3 s at 255 GeV. Red - measured data; Black - simulations.

the understanding of Spin Flipper operation.

The optimal values of Sweep Time, the AC dipole frequency range and $\Delta D'$ can be obtained from the simulation results.

The current plan is to perform more simulations for different RF settings, when 28 MHz and 197 MHz systems are used. This corresponds to the conditions that are used during RHIC physics stores.

ACKNOWLEDGMENTS

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