SPIN DYNAMICS SIMULATIONS AND HORIZONTAL INTRINSICS RESONANCE STUDIES IN THE AGS USING THE ZGOUBI CODE* †

Y. Dutheil, L. Ahrens, H. Huang, F. Méot, V. Ranjbar, T. Roser, V. Schoefer, N. Tsoupas
BNL, Upton, Long Island, New York

Abstract

A critical point for the polarized proton program of RHIC[1] is the polarization transmission during the AGS[2] acceleration cycle. Recent developments in the Zgoubi model of the AGS[1] allow multi-particle tracking with realistic beam and machine conditions on a large scale computing system. This gives the opportunity to simulate the influence of many beam and machine conditions on the polarization transmission and leads to a better understanding of the depolarization processes, for instance the horizontal intrinsic resonances, that cannot be accurately explored by the conventional simulation approaches or by the experiments with beam. This paper introduces the developments realized on the Zgoubi code to run these simulations and shows some of the latest results.

INTRODUCTION

To preserve the polarization two partial helical magnets, or Siberian snakes, were installed in the AGS [2]. These magnets allow most of the polarization to be preserved during the acceleration but feature a complex twisted dipole field with strong linear and non-linear components. Maximum polarization transmission also requires a particular tune path during the acceleration ramp, the vertical tune needs to be kept very close to the integer.

While partial Siberian snakes configurations can avoid depolarization caused by the imperfection and vertical intrinsic resonances, it can also induce depolarization through horizontal intrinsic resonances. The stable spin direction is never perfectly vertical with partial snakes and therefore the non-zero horizontal component of the spin can resonate with the horizontal betatron tune [2]. The installation of two fast quadrupoles, in two straight sections of the AGS, helps to reduce the depolarization across the horizontal intrinsic resonances by increasing their crossing rate [3].

Experimental polarization results, in particular since the commissioning of the tune jumps [3], drove a strong interest for realistic, multiparticle and long term spin tracking in the AGS. The specific features of the AGS for polarized protons operation makes the simulation of beam and spin dynamics very hard when using conventional theoretical or computational models. We will see that the Zgoubi code[4], based on stepwise ray-tracing methods, is perfectly adapted to realistically simulate beam and spin dynamics in the AGS.

SIMULATIONS VALIDATION

Extensive development of the AGS Zgoubi on-line model provides a realistic model of the polarized proton machine [5]. Measured currents of the power supplies along the acceleration cycle are used by the Zgoubi on-line model to generate corresponding optics. The complex, direct current driven, Siberian snakes use 3-D OPERA field maps to exploit the specificity of the stepwise ray-tracing code Zgoubi and achieve the high accuracy required for long term spin tracking.

This paper focuses on the later part of the AGS cycle. This simplifies tracking by avoiding the gamma-transition region, but still allows to study the high energy part of the ramp. While the AGS accelerates polarized protons from $\gamma = 2.5$ to $\gamma = 23.4$, this study is limited to the range between $\gamma = 10.9$ to $\gamma = 23.4$.

Simulations Conditions

An accurate model of the optics is critical since the polarization transmission can be very sensitive to tunes and tune spreads, in particular with the tune jumps. Measurements are used to constrain the model and achieve realistic optical parameters. As shown in figure 1, the tunes and chromaticities are very close to the measured ones.

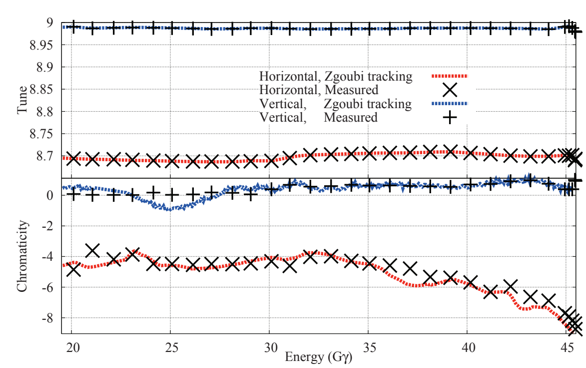

Figure 1: Comparison between measured and modeled tunes and chromaticities as a function of the energy.

No dipole error is added to the lattice, thus the modeled orbit coincides with the design orbit of the AGS.

Longitudinal dynamics is naturally handled by the Zgoubi code. The model uses a single RF cavity and the

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[1] Relativistic Heavy Ion Collider
[2] Alternating Gradient Synchrotron

synchrotron motion is determined by the characteristics of the lattice and the RF parameters. A realistic RF voltage of $\hat{V}_{\text{RF}} = 240\,\text{kV}$, a harmonic number of $h = 12$ and a variable synchronous phase computed from the measured acceleration rate are used.

The beam consists of 2000 particles. The initial coordinates are picked in a 6D Gaussian distribution, cut at 4σ. The transverse emittances, typical for polarized proton operations, are $\epsilon_x^{N,95\%} = 13.5\,\pi$·mm·mrad in normalized 95% in the horizontal plane and $\epsilon_y^{N,95\%} = 14\,\pi$·mm·mrad in the vertical one. An emittance of $\epsilon_l^{rms} = 4.97\,.10^{-2}$eV·s is used to generate the longitudinal distribution. The initial spin vector is aligned with the stable spin direction on the closed orbit $\vec{n}_0$, resulting in a fully polarized beam.

Beam Dynamics for Long Term Tracking

Since the real acceleration rate is used, around 100000 turns need to be tracked from $G\gamma = 19.5$ to $G\gamma = 45.5$. Thus the evolution of the emittances needs to be verified before the polarization results are discussed. The emittance is estimated by computing the variance of the distribution after having subtracted the chromatic orbit from each particle coordinate. Figure 2 shows small variations of the transverse emittance that could be attributed to variations in bunch shape. The energy spread is rather constant until $G\gamma = 43$ when the acceleration rate and the synchronous phase are reduced, as expected from the equations of longitudinal dynamics.

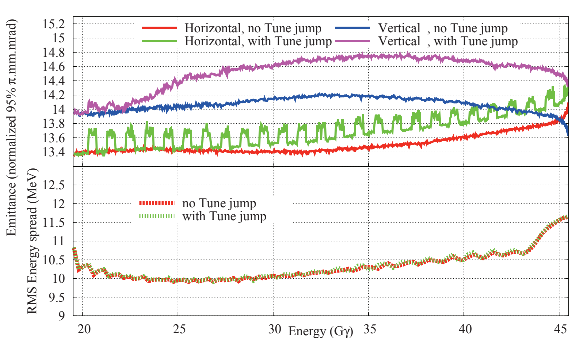

Figure 2: Comparison of the transverse emittances and energy spread with or without tune jumps, as a function of the energy.

As seen in Figure 2 the beam emittances can be considered as conserved along the tracking, validating the beam dynamics. The simulations can now be used to investigate the effect of different beam and machine parameters on the polarization.

TUNE JUMP EFFICIENCY AND MOMENTUM SPREAD

Figure 3 shows the evolution of the polarization as a function of the energy. The polarization is estimated by averaging the projection of the spin vectors on the stable spin direction $\vec{n}_0$. This averaging induces artificial polarization spikes when $G\gamma$ crosses an integer, due to the flip of $\vec{n}_0$ and the momentum spread of the particles. We can see that the polarization losses are not localized but spread along the simulation. Each crossing of a horizontal intrinsic resonance induces a small depolarization of the beam and the resonant condition is satisfied two times per unit of $G\gamma$, when :

$$Q_s \pm Q_x = I \tag{1}$$

With Q_x the horizontal tune, I an integer and Q_s the spin tune, Q_s can be approximated to the energy in $G\gamma$.

The tune jumps are meant to accelerate the crossing of the resonant condition and reduce the depolarizations. But in presence of momentum spread the resonant condition (Eq. 1) is widened by the chromaticity and the energy spread. Therefore particles at large momentum excursions might cross the resonant condition before or after the tune jump and we expect to see a reduction in the tune jumps efficiency. The simulations show a relative reduction of polarization of 5% due to the momentum spread when the tune jumps are used.

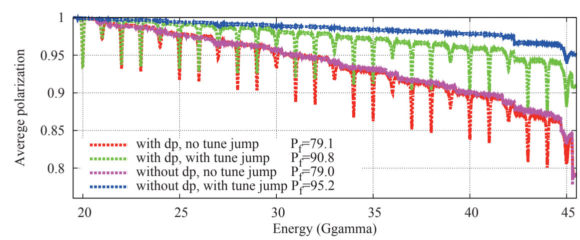

Figure 3: Effect of the tune jumps and the momentum spread on the evolution of the polarization, as a function of the energy.

Without tune jumps (red and pink curves in figure 3) no depolarization mechanism depends on the momentum distribution, thus no loss of polarization is expected from the energy spread.

POLARIZATION LOSSES AT THE END OF THE RAMP

In the AGS, the acceleration rate on the roll-over to the flat-top is slowly reduced to zero at the extraction field. In addition the depolarization across a spin resonance is related to it's crossing rate. Therefore larger depolarization due to the horizontal intrinsic resonances were expected in this region but the relative importance wasn't quantified.

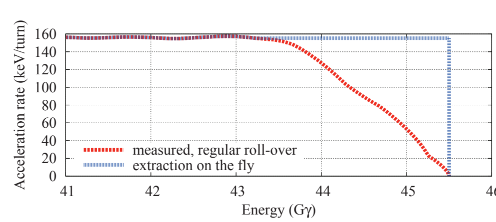

Figure 4: Acceleration rate at the end of the ramp as a function of the energy.

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Figure 3 shows that the depolarization across the last horizontal intrinsic resonance, without tune jump, can reduce the polarization by as much as 5%. It was proposed to use the Zgoubi code to simulate the expected polarization gain in the case of the extraction-on-the-fly. In this scenario the acceleration rate would not decrease and the beam would be extracted at the full acceleration, allowing the last spin resonances to be crossed much faster.

Figure 4 shows the acceleration rate decreasing slowly after $G\gamma = 44$. A ramp with constant acceleration rate until extraction energy was generated to simulate the evolution of the polarization with the extraction-on-the-fly.

Figure 5 shows that without the tune jumps the relative increase would be 6.8%. Despite the high crossing rate provided by the tune jumps a relative gain of 2.4% can be seen in the case with tune jumps.

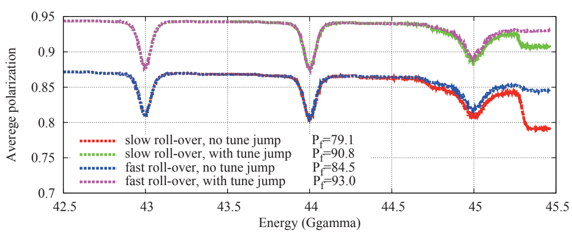

Figure 5:Effect of the fast roll over on the final polarization.

Expectation of higher polarization drove a strong interest for the extraction-on-the-fly scenario but a simpler solution was found. A new magnet function for the AGS dipoles was created to provide a quick transition between the ramp and the flat-top. This new function allows the AGS to ramp at the full acceleration rate up to the extraction energy. Thus the last horizontal intrinsic resonance is also crossed at the maximum acceleration rate. Experimental comparisons are then possible between the simulation involving extraction-on-the-fly and the AGS using the faster roll-over.

Experimental Results and Simulations

Polarization measurements were taken with both magnet functions and with or without tune jumps. Table 1 summarizes the measurements taken at an intensity of $1.2\,.10^{11}$ particles and using a vertical fixed target polarization measurement. The simulations show a good agreement when the tune jumps are not active with a polarization gain of 6.8%.

With the tune jumps active the effect of the faster roll-over is expected to be smaller since the crossing rate of the horizontal intrinsic resonances is dominated by the tune jumps. Nevertheless the simulations show a relative gain of 2.4%. Figure 5 shows that the polarization gain occurs across the last horizontal intrinsic resonance, at $G\gamma = 45.3$, where the acceleration rate is very small.

The discrepancy between the simulated and measured gains is not explained but the probable cause are :

Table 1: Summary of the Polarization Measurements with Both Magnet Functions and Simulation Results

machine state	**measured polarization**	**measured gain**	**simulated gain**
tune jumps OFF			
slow roll over	62.8 ± 1.1		
fast roll over	67.3 ± 1.1	+7.2%	+6.8%
tune jumps ON			
slow roll over	70.1 ± 1.1		
fast roll over	70.5 ± 1.1	+0.6%	+2.4%

- The faster roll-over imposes a fast modification of the 9^{th} vertical harmonic orbit across $G\gamma = 45$ to avoid the depolarization due to the imperfection resonance. This is harder with the two closest tune jumps at $G\gamma = 44.7$ and $G\gamma = 45.3$, separated by 5ms.
- The uncertainty on the measurements leads to an uncertainty in the measured gain of 3.3%. Therefore the measured gain can be considered in agreement with the simulations if the uncertainty of the measurement is propagated to the gain.

Polarization measurements do not show measurable gain from the faster roll-over with the tune jumps and more measurements are required to reduce the uncertainties. Nevertheless a clear gain has been measured without tune jumps, giving strong confidence in the Zgoubi model for this application.

The faster roll-over is used for operation since March 2013.

CONCLUSION

The agreement between simulations and experimental results gives a strong confidence in the spin dynamics simulation using the AGS Zgoubi model with long term trackings.

Numerous study of beam and spin dynamics remain to be done. Different machine conditions are being simulated to improve the polarization transmission during the AGS cycle.

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