POLARIZATION PROFILE AND SPIN DYNAMICS SIMULATIONS IN THE AGS USING THE ZGOUBI CODE*

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Abstract

Polarization transmission during the AGS acceleration cycle is critical for the RHIC polarized proton program.Thus drives a strong interest on the exploration of the polarization losses in the AGS. Intrinsic spin resonances are the main source of depolarization in the AGS. This results in the formation of a polarization profile since the strength of such depolarizing resonance depends on the Courant-Snyder invariant of each particle. The Zgoubi code and the AGS Zgoubi on-line model now allow exploration of the formation of the polarization profile during the acceleration cycle using multi-particle trackings with realistic beam and machine conditions. This paper introduces the specifics of these simulations and compares some of the latest simulated and experimental results.

INTRODUCTION

Acceleration of polarized protons in a synchrotron requires particular schemes to conserve the polarization. Two main types of depolarization resonances can reduce the overall polarization of the beam. The imperfection resonances are driven by vertical closed orbit distortions and occur when $Q_s = I$ with Q_s the spin tune and I an integer [1]. The intrinsic resonances are driven by the vertical betatron motion and occur when $Q_s = I \pm Q_y$ with Q_y the vertical tune.

The AGS uses two partial Siberian snakes to overcome the spin resonances [2], usually called *warm* and *cold* snakes. While in a regular synchrotron $Q_s = G\gamma$ (G is the anomalous gyromagnetic g-factor of the proton), the complex helical dipole fields of the Siberian snakes open forbidden bands in the spin tune around the integer values of $G\gamma$, the spin tune gap. The imperfection resonances are avoided since the integer values of Q_s are now forbidden. The vertical intrinsic resonances are overcome by keeping the vertical tune in the spin tune gap, typically around $Q_y = 8.98$.

Despite the use of Siberian snakes polarization losses are observed in the AGS and while the polarization profile at injection is negligible, measurements show significant profiles of polarization in both vertical and horizontal planes after the acceleration. We will present the main candidates that can explain the observed profiles then some simulation methods and results will be compared to measured polarization profiles.

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Sources of Polarization Profile

The strength of an intrinsic spin resonance depends on the *Courant-Snyder* invariant, hence the depolarization experienced by a particle across such a spin resonance also depends on the single particle emittance. The crossing of such resonance can result in the particles at larger amplitude being depolarized while the center of the beam remains polarized.

The injection in the AGS occurs at $G\gamma = 4.5$ and the vertical tune needs to be placed in the spin gap before the first vertical intrinsic resonance, around $G\gamma = 5$. Figure 1 shows the vertical tune crossing the spin tune around $G\gamma = 5$. Due to the strong optical distortions caused by the Siberian snakes it is not possible to push vertical tune high enough at low energy. We expect that the crossing of vertical intrinsic resonances in this region depolarizes part of the beam and induces a polarization profile in the vertical plane.

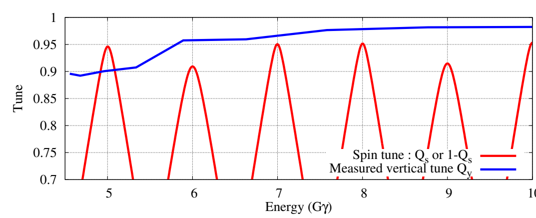

Figure 1: Fractional part of the vertical tune and spin tune at low energy.

While the partial Siberian snakes configuration avoid depolarizations caused by the imperfection and vertical intrinsic resonances, it can also induce depolarization through horizontal intrinsic resonances when $Q_s = I \pm Q_x$ with Q_x the horizontal tune. 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. The strength of these resonances depends on the horizontal emittance and horizontal component of polarization. The crossing of these resonances builds up an horizontal polarization profile.

Other sources of depolarization can contribute to the polarization profile. For instance linear betatron coupling or high order partial snake resonances [3] can increase the polarization profile but will not be discussed here.

SIMULATIONS

Extensive development of the AGS Zgoubi on-line model provides a realistic model of the polarized proton machine [4][5][6]. Measured currents of the power supplies along the acceleration cycle are used by the Zgoubi on-line model to generate corresponding optics of the AGS. The Siberian snakes were represented by 3-D OPERA field maps to exploit the precision of the stepwise ray-tracing code Zgoubi and achieve the high accuracy required for long term spin tracking.

Simulations Conditions

Due to the lack of a reliable field map to simulate the warm snake, a cold snake map has been scaled down to achieve the same snake angle as the warm snake and is used as the warm snake in this model. This provides a realistic spin dynamics and a better behavior of the beam dynamics at low energy. This is the solution adopted while a new field map of the warm snake is being developed.

Measurements are used to constrain the model and achieve realistic machine parameters. Modeled tunes have been modified around $G\gamma = 10$ and $G\gamma = 35$ to avoid resonant lines during the tracking but the modeled and measured tunes are very close elsewhere (Fig. 2). The measured chromaticity has been smoothed before being used to tweak the model in order to avoid fast variations of the chromaticity during the tracking.

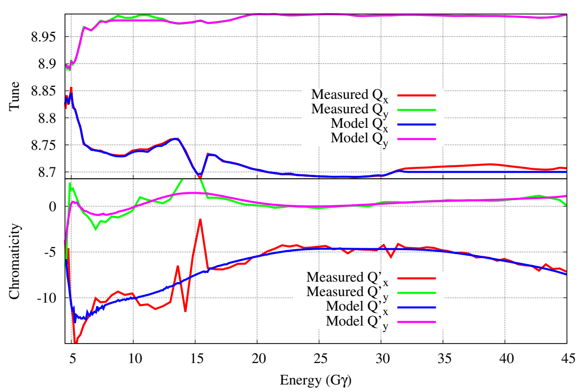

Figure 2: Comparison of tune and chromaticity used in the model and measured in the machine.

The simulations also include the tune jumps, used in the AGS to reduce the polarization losses across the horizontal intrinsic resonances [7].

No dipole error is added to the lattice, hence 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 synchrotron motion is determined by the characteristics of the lattice and the RF parameters. A harmonic number of $h = 8$ and a realistic RF voltage are used, synchronous phase is computed from measured acceleration rate. This results in a tracking of 150 000 turns to go from the injection energy $G\gamma = 4.5$ to the AGS flat-top at $G\gamma = 45.5$.

The beam is formed by 5000 particles picked in a 6D Gaussian distribution, cut at 3σ. The transverse emittances were chosen at $\epsilon_x^{N,95\%} = 10\,\pi{\cdot}\text{mm}{\cdot}\text{mrad}$ and $\epsilon_y^{N,95\%} = 10\,\pi{\cdot}\text{mm}{\cdot}\text{mrad}$, values slightly lower than the measured values at extraction but still realistic. A longitudinal emittance of $\epsilon_l^{95\%} = 0.8\,\text{eV}{\cdot}\text{s}$ is used, leading to a realistic bunch length of $l^{95\%} = 28\,\text{ns}$ at extraction. The spin of the particles is randomly chosen with the condition $\vec{S} \cdot \vec{n}_0 = 0.82$ with $\vec{S}$ the spin vector of the particle and $\vec{n}_0$ the stable spin direction, such that the initial polarization is realistic with $82\,\%$ without profile. These simulations require huge amount of computation power and are carried on the supercomputer of the NERSC but the tracking of a single particle on a single CPU for the full acceleration cycle takes one to two hours.

Beam Dynamics

In order to simulate the full AGS cycle the main challenge was to introduce the gamma transition optics and RF gymnastics. The gamma transition quadrupoles were naturally handled by the Zgoubi On-line model, the same way as the other magnets [4][5][6]. Figure 3 shows the behavior of the momentum spread across the transition region during a tracking of 1000 particles, with realistic momentum spread. Despite the perfectly timed jump of the synchronous phase, the transition induces a quadrupole oscillation of the beam but likely due to the non-linear momentum compaction factor of the lattice it is unavoidable.

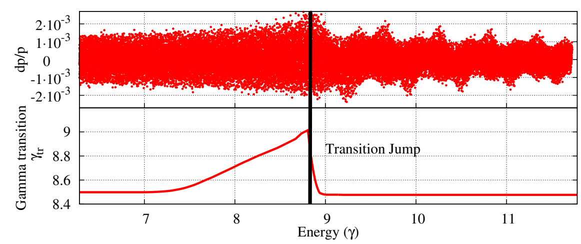

Figure 3: Momentum distribution of the particles and gamma transition of the lattice as a function of the energy around the gamma transition region.

The transverse emittance is estimated by using the variance of the particles coordinates after removing the effect of the chromatic orbit. Figure 4 shows important variations of the estimated emittance when particles are lost during the tracking. Some particles are lost during the transition around $G\gamma = 15$ but also at lower energy ($G\gamma = 6$) when the vertical tune is brought very close to the integer. Beam dynamics behavior is clearly smoother than using the warm snake map but losses during the tracking remains, likely due to the crossing of resonant lines.

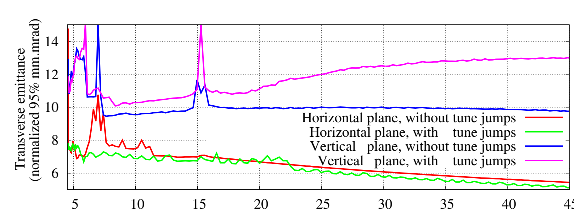

Figure 4: Evolution of the estimated emittances with or without tune jumps.

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POLARIZATION PROFILE

The polarization measurement in the AGS uses a thin carbon foil target plunged into the circulating beam. One of the operation modes moves the target across the beam during the measurement and determine the polarization of the beam as a function of the target position. Measured intensity and polarization as a function of the target position are fitted to a Gaussian function to extract σ_P and σ_I respectively the standard deviations of the polarization and beam intensity. Then the polarization profile is defined by P_{max} the maximum polarization at the center of the profile and $R = \sigma_I^2/\sigma_P^2$ to characterize the steepness of the profile.

Simulations and Measurements

The particles coordinates at the end of the tracking are transported to the location of the polarimeter and binned, along with the polarization. The top plot on figure 5 shows the binned beam profile in grey and the average polarization in each beam in blue. The polarization is fitted to a Gaussian and the number of particles in each beam is used as weight for the fit. The process is very similar to the measurements analysis and lead to a similar figures.

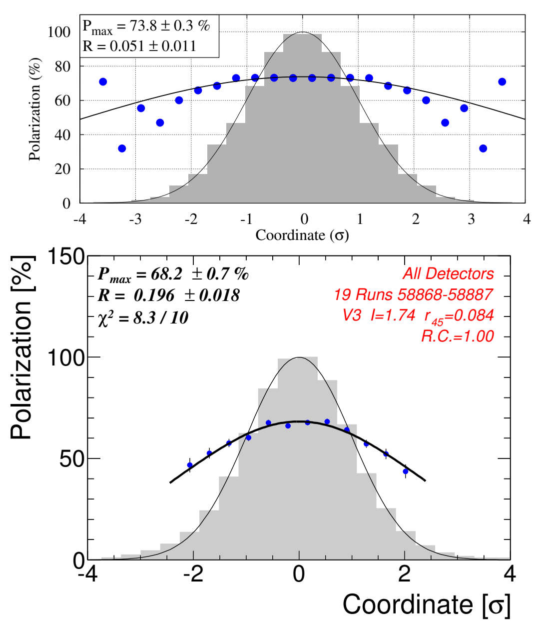

Figure 5: Polarization profile in the horizontal plane without tune jumps along with the beam profile for the simulation (top plot) and for a measurement (bottom plot).

Table 1 summarizes the simulation results and compares them to measured data. The simulated profiles are not as big as the measured ones but it is expected since the emittance used in the simulations is smaller than the usual emittance in the AGS. The simulated horizontal profile is greatly reduced when the tune jumps are used, which is expected and consistent with the measured data.

CONCLUSION

The Zgoubi on-line model provides variable and realistic optics of the polarized proton AGS for tracking. In addition, recent developments allow tracking with realistic longitudinal dynamics around the injection and transition regions.

The model of the AGS currently uses a replacement for the warm snake field map while a new warm snake map is being developed. While this model does not allow us to draw definite answers for now, it still provides good indications about depolarization sources. Polarization profiles and maximum polarization are not comparable to the measured values but the evolution of the profiles when the tune jumps are used is consistent with the measurements. More work is needed to refine the model in view of improved comparison with measured beam and polarization data.

The Zgoubi model of the AGS is a unique and extremely accurate tool to simulate the polarized proton acceleration in the AGS. Ongoing work based on the Zgoubi code aims to develop new and original schemes to reduce polarization losses at low energy using, for instance, the tune jumps.

Table 1: Polarization Profiles Simulated (Sim.) and Measured (Meas.), With or Without Tune Jumps (TJ)

	Horizontal	Vertical
No TJ Meas.	$P_{max} = 68.2 \pm 0.7\,\%$ $\mathrm{R} = 0.196 \pm 0.018$	$P_{max} = 66.5 \pm 0.9\,\%$ $\mathrm{R} = 0.190 \pm 0.022$
No TJ Sim.	$P_{max} = 73.8 \pm 0.3\,\%$ $\mathrm{R} = 0.051 \pm 0.011$	$P_{max} = 72.2 \pm 0.2\,\%$ $\mathrm{R} = 0.015 \pm 0.006$
TJ Meas.	$P_{max} = 73.8 \pm 0.6\,\%$ $\mathrm{R} = 0.109 \pm 0.012$	$P_{max} = 71.6 \pm 0.7\,\%$ $\mathrm{R} = 0.080 \pm 0.014$
TJ Sim.	$P_{max} = 76.3 \pm 0.1\,\%$ $\mathrm{R} = 0.012 \pm 0.004$	$P_{max} = 77.3 \pm 0.2\,\%$ $\mathrm{R} = 0.035 \pm 0.006$

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