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Brookhaven National Lab, Upton, NY 11973

H. Spinka, D. Underwood
Argonne National Lab, Argonne, IL 60493

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Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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H. Huang†, L. Ahrens, M. Bai, K.A. Brown, C. Gardner, J.W. Glenn, F. Lin, A.U. Luccio,
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Brookhaven National Lab, Upton, NY 11973, USA
H. Spinka, D. Underwood, Argonne National Lab, Argonne, IL 60493, USA

Abstract

Dual partial snake scheme has been used for the Brookhaven AGS (Alternating Gradient Synchrotron) polarized proton operation for several years. It has provided polarized proton beams with 1.5×10^{11} intensity and 65% polarization for RHIC spin program. There is still residual polarization loss. Several schemes such as putting horizontal tune into the spin tune gap, and injection-on-the-fly were tested in the AGS to mitigate the loss. This paper presents the experiment results and analysis.

INTRODUCTION

During acceleration, a depolarizing resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. In the presence of the vertical dipole guide field in an accelerator, the spin precesses $G\gamma$ times per orbit revolution, where $G = (g-2)/2 = 1.7928$ is the gyromagnetic anomaly of the proton, and γ is the Lorentz factor. The number of precessions per revolution is called the spin tune ν_s and is equal to $G\gamma$ for circular accelerators.

There are two main types of depolarizing resonances: imperfection resonances, which are driven by magnet misalignments; intrinsic resonances, driven by the vertical betatron motion through quadrupoles. The resonance condition for an imperfection resonance is $\nu_s = n$, where ν_s is the number of precessions per revolution or the spin tune, n is an integer. The resonance condition for an intrinsic resonance is $\nu_s = nP \pm \nu_y$, where n is an integer, $P = 12$ is the super-periodicity of the unperturbed AGS, and ν_y is the vertical betatron tune.

For nearly a decade, the AGS has been used as injector for the polarized proton program in the Relativistic Heavy Ion Collider (RHIC). Over the years, the depolarizing resonances have been overcome with different devices including a solenoidal partial snake[1], an ac dipole[2] and a helical partial snake[3]. Most recently, the dual partial snake scheme has been proposed [4] and tested[5]. It has provided higher polarization and higher intensity for RHIC spin program. Nevertheless, there are still polarization losses. Some of them are related to the introduction of the stronger partial snakes. The challenge remains to reach even higher polarization with higher intensity.

The dual snake scheme has several advantages. It not only can match the spin direction better at injection and extraction, but also can increase the effective partial snake strength with properly chosen snake locations [4]. When the two partial snakes are separated by one third of the ring, a periodicity of three units is introduced into the spin tune dependence on $G\gamma$. Since both the super-periodicity of the AGS (12) and the vertical betatron tune (9) are divisible by three, the spin tune gap will be the same at all strong intrinsic resonances, namely for $G\gamma = 3n$. Currently, AGS has two partial snakes. A 1.53T normal magnet partial snake (a.k.a. warm partial snake)[3] has been installed in 2004 and a 3T superconducting magnet partial snake (a.k.a cold partial snake)[5] has been installed in 2005. The cold snake is capable of being a 20% partial snake at top energy. As spin matching at extraction and injection is much better with two properly arranged partial snakes, we run the two snakes together. Since the horizontal resonance (see below) strength is proportional to the partial snake strength, the cold partial snake was powered only to 2.11T. Since both partial snakes were run at constant fields, the spin rotation angles drop rapidly as energy goes up. Fig. 1 shows the snake strengths for the two partial Siberian snakes of 2.11T (10% partial snake at flattop) and 1.53T (5.9% partial snake at flattop), respectively. In this case the polarization loss due to injection and extraction mismatch is only about 3%.

The AGS injection and extraction energies are set to occur at $G\gamma = 4.5$ and 45.5, respectively. The extraction energy is chosen such that the spin transmission between AGS and RHIC is optimized [6]. At low energies, the helical magnets cause significant lattice distortion. Four compensation quads are added for each of the two helical snake magnets. The vertical tune is ramped into the gap at slightly higher energy after $G\gamma = 5$. To avoid the so-called partial snake resonances, the vertical betatron tune was pushed as high as 8.98 in general and even 8.99 for $36+\nu_y$. Polarization at AGS extraction has reached 65% for an intensity of 1.5×10^{11} per bunch with a 10% cold partial snake and a 5.9% warm partial snake.

RESIDUAL POLARIZATION LOSS

Horizontal Resonances

Besides the spin mismatch at injection and extraction, and the partial snake resonances associated with vertical betatron motion, there are additional causes for polarization loss. In the presence of a partial snake, the stable spin direction is not purely vertical. For the horizontal compo-

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† huanghai@bnl.gov

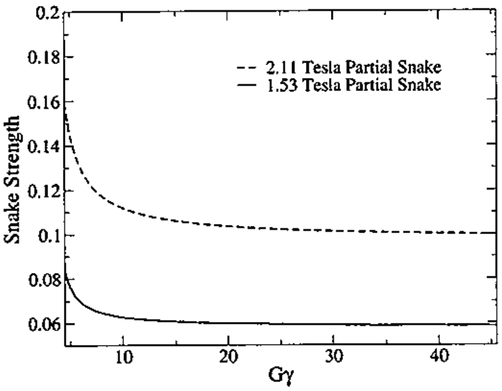

Figure 1: The partial snake strength as function of $G\gamma$. Note the snake strength drops quickly at lower energies but is almost a constant at higher energies.

nent of polarization, the vertical magnetic field can drive spin resonances. Therefore, the perturbing fields that rotate the spin away from the stable spin direction have vertical as well as horizontal components. Particles undergoing horizontal betatron oscillations encounter vertical field deviations at the horizontal oscillation frequency. As a result, resonances are driven by the horizontal betatron oscillations, and will occur whenever the spin tune satisfies $G\gamma = k \pm \nu_x$, where k is an integer [7]. The polarization loss due to horizontal spin resonances is proportional to the partial snake strength. The total snake strength is then a compromise between overcoming vertical intrinsic resonances and minimizing the effect of horizontal resonances. Hence, a combination of 10% cold partial snake and 5.9% warm partial snake was used in runs of 2006 and 2008.

To avoid these horizontal spin resonances, the horizontal betatron tune can also be put into the spin tune gap generated by the partial snakes. Since these resonances are generally weak, the horizontal tune does not need to be pushed as close to 9 as the vertical tune to avoid snake resonances. However, due to the tune spread, they still need some distance from the lower edge of the spin tune gap. With two unequal partial snakes and asymmetric locations in the ring, the spin tune gap varies. As the vertical tune is around 8.98, it is hard to push the horizontal tune above 8.96. Then the cold snake strength needs to be strong to provide large enough spin tune gap. A 14% cold snake combined with a 5.9% warm partial snake will provide spin tune gap that varies between 0.90 to 0.94. This is enough to put two betatron tunes within the spin tune gap.

A test was carried out by comparing the two lattices with high and low horizontal tunes in the later part of the energy ramp. The two lattices were carefully set up so that the only difference between them was the horizontal tune. Horizontal polarization profiles were measured for both cases. The polarization values were higher with the high tune case and the polarization profile was also flatter for the high tune case [8]. Both results are consistent with the polarization being better when the horizontal tune is in the spin tune gap. It should be noted that a stronger partial snake would in turn make the overall horizontal resonance strengths stronger. In addition, the stronger snake strength increased the optics distortion at injection and made it hard to reach the required intensity.

Injection Lattice Distortion

One more polarization damaging feature of our setup is associated with the broken super-periodicity due to the insertion of stronger partial snakes. Some of the originally very weak resonances may now be strong enough to cause polarization loss. The intrinsic resonance condition changes to $\nu_s = n \pm \nu_y$, although the ones with n as multiples of $P = 12$ are still strong. Generally this is not a problem, since the vertical tune is put into the spin tune gap generated by the partial snakes and the resonance conditions are avoided. However, due to the large orbit distortion for the lower energy part (below $G\gamma = 7.5$), the vertical tune can not be pushed into the spin tune gap. The slow ramp rate at the beginning of the ramp only makes the situation worse. Spin tracking shows [9] that the polarization loss before $G\gamma = 7.5$ is about 10% due to both vertical and horizontal resonances.

INJECTION-ON-THE-FLY

Since the depolarizing resonance effect is aggravated by the slow ramp rate in the early part of the energy ramp, the idea of injecting proton beam into the accelerating bucket to maintain a high acceleration rate in the early part is proposed. The tuning of injection is harder since the RF bucket is smaller and synchronization between the AGS Booster and AGS is critical. However, in the new injection scheme, we encountered the transverse emittance growth problem. Fig. 2 shows the emittances measured at the extraction of AGS by Ionization Profile Monitor (IPM) for various injection schemes.

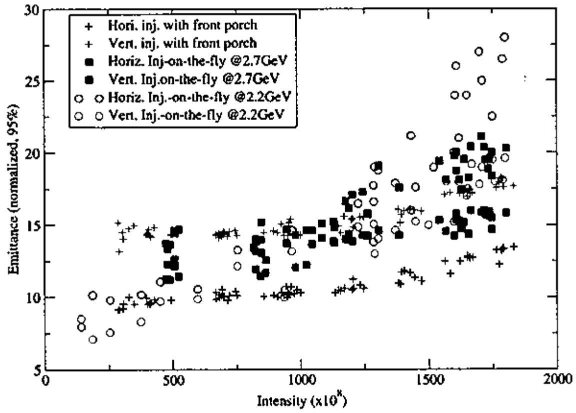

Figure 2: Emittances as function of beam intensity for various injection schemes.

The large lattice distortion causes injection mismatch which could be a source of emittance growth. Since the beam is relatively bright, the space charge related emittance growth is also a concern. These forces will also affect measured profile widths. Actually, the IPM overestimates the transverse emittance for bunched beams. Allowing the beam to debunch at flattop results a smaller beam size to be reported by the IPM. Nevertheless, when the beam was both accelerated then decelerated back to near injection energy without losses, the IPM reported equal beam sizes for each energy along the way. There was no indication of growth during acceleration.

The beam emittance as function of beam intensity was also measured with several multi-wire harps in the Booster to AGS transfer line. The results showed that emittances increased slightly with higher intensity, but not as dramatic as the AGS extraction measurements showed. All of these suggest that the emittance growth happened right near injection. To understand the emittance growth near injection, the injection-on-the-fly was adjusted to occur at a higher injection energy: the injection was raised from $\gamma = 2.51$ to 3.07. The emittance was then measured again as function of intensity. As seen in Fig. 2, the intensity dependence is weaker for the higher injection energy but not completely gone.

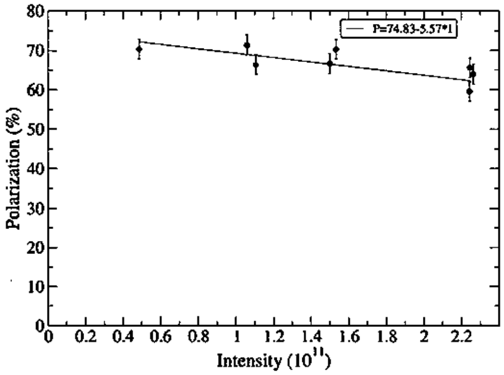

Figure 3: Polarization as function of intensity for injection with a dwell field, measured in 2006. The line is a linear fitting of the experimental data.

As shown in Figs. 3 and 4, the measured polarization dependence can be attributed to the emittance dependence with intensity. As the emittance grows faster with intensity in the case of injection-on-the-fly, the slope of the fitting is steeper. The polarization level with zero intensity was lower for run8, which is consistent with the lower polarization measured at AGS injection. The AGS injection polarization measurement was 4% lower in 2008 than in 2006. The emittance growth issue has to be solved before we can use the injection-on-the-fly. Simulation and analysis are underway to understand the emittance growth issue.

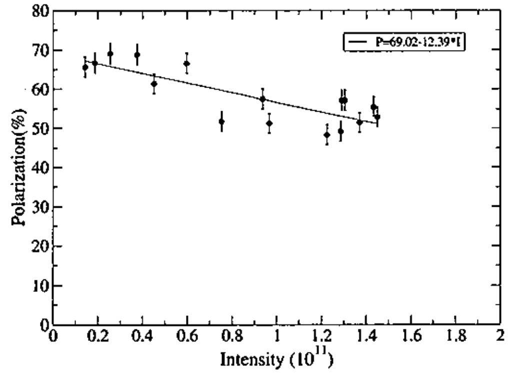

Figure 4: Polarization as function of intensity for injection-on-the-fly, measured in 2008. The line is a linear fitting of the experimental data.

CONCLUSION

As shown in the past few runs, higher intensity polarized proton beam has been achieved with stronger partial snakes. There remains polarization loss after introducing the strong partial snakes. The horizontal resonances associated with stronger partial snakes also caused sizable polarization loss. This kind of resonance is difficult to overcome. Putting the horizontal tune into the spin tune gap requires stronger partial snakes, which in turn increases the lattice distortion. In Run8 injection-on-the-fly was tested. This was an attempt to reduce the intensity dependence of the polarization, but the stronger emittance growth effect prevented it from being beneficial. Under investigation now is a scheme to jump all horizontal spin resonances in the AGS with fast quadrupoles. Such a scheme could increase the polarization out of the AGS by as much as 5%. In addition, the linac low energy beam transfer line will be upgraded to maintain the small emittances out of the source. The horizontal beta function at the Booster injection stripping foil will also be reduced to minimize the emittance growth there. All of these will result in smaller input emittances for the AGS, which will improve the polarization transmission in the AGS.

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