AGS POLARIZED PROTON OPERATION IN RUN 2009*

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Abstract

After installation of two partial snakes in the Brookhaven Alternating Gradient Synchrotron (AGS), a polarized proton beam with 1.5×10^{11} intensity and 65% polarization has been achieved. There are residual polarization losses due to horizontal resonances over the whole energy ramp and some polarization loss due to vertical intrinsic resonances. Many efforts have been put in to reduce the emittances coming into the AGS and to consequently reduce polarization loss. This paper presents the accelerator setup and preliminary results from run 2009 operations.

INTRODUCTION

The AGS has been running as RHIC polarized proton injector with two partial snakes [1] since 2006. The dual partial snake scheme has several advantages. With properly chosen snake locations, it not only can match the spin direction better at injection and extraction, but also can increase the effective partial snake strength. 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 $G\gamma$, where $G = (g-2)/2 = 1.7928$ is the gyromagnetic anomaly of the proton, and γ is the Lorentz factor. 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 $G\gamma = 3n$. A 1.53T normal magnet partial snake (a.k.a. warm partial snake) [2] was installed in 2004 and a 3T superconducting magnet partial snake (a.k.a cold partial snake) [3] was 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. 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 [4]. At low energies, the helical magnets cause significant lattice distortion. Four compensation quads are added for each of the two helical snake magnets. Before run 2009, the vertical tune was ramped into the gap at slightly higher energy after $G\gamma = 5$. To avoid the partial snake resonances, the vertical betatron tune was pushed as high as 8.98 in general and even 8.99 for 36+ν_y. The system has delivered 65% polarization with 1.5×10^{11}/bunch intensity with 82% as input polarization [5]. The focus in past a few years was to overcome the residual polarization losses.

RESIDUAL POLARIZATION LOSS

Imperfection and vertical intrinsic resonances have been taken care of by the dual partial snakes, except for a few vertical intrinsic resonances near injection as vertical tunes are outside the spin tune gap in the early part of the energy ramp. 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 component 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 $G\gamma = N \pm \nu_x$, where N is integer and ν_x is the horizontal tune [6].

A series of spin tracking studies were performed to evaluate the residual polarization loss. The remaining polarization losses seen in the spin tracking can be divided into three categories:

1. the loss due to horizontal intrinsic resonances along the ramp, which accounts for about 10% loss;
2. the loss associated with snake resonances near the strongest resonance 36+ν_y;
3. the polarization loss resulting from vertical intrinsic resonances near injection due to the slow ramp rate and large lattice distortions.

POLARIZATION LOSS NEAR INJECTION

The vertical intrinsic resonances near injection $G\gamma = N \pm \nu_y$ are typically quite weak and should not cause much polarization loss, since N is not a multiple of super-

* Work performed under contract No. DE-AC02-98CH10886 with the auspices of the DoE of United States, and support of RIKEN(Japan).
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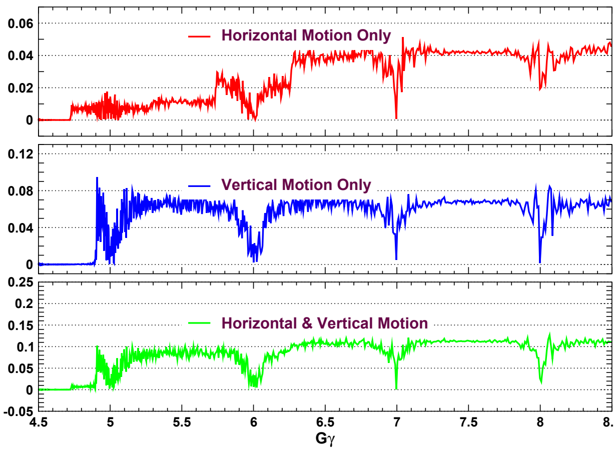

Figure 1: Simulation of the polarization loss on the early part of ramp. For an input of polarization of one, the polarization loss is defined as the reduction from one. As the bottom plot shows, there is about 10% polarization loss due to the resonances in the early part of the energy ramp.

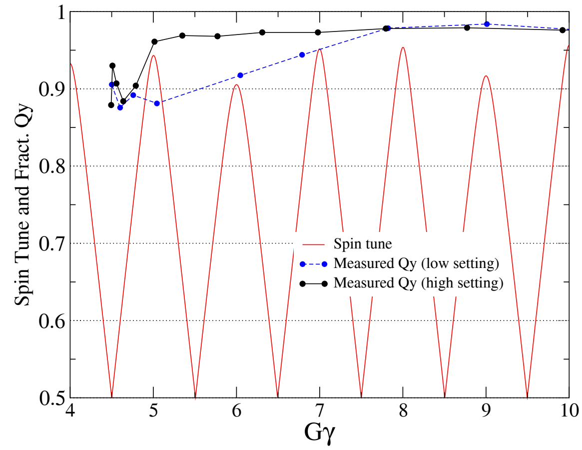

Figure 2: The solid curve is the spin tune. The dashed line and dots are the measured vertical tunes through the energy ramp from last year. The solid line and dots are the new vertical tunes along early part of the ramp for this run.

periodicity P. However, in the presence of two partial snakes, the super-periodicity P is actually one and the lattice is also greatly distorted. As the acceleration rate is very slow near injection, these resonances will cause some polarization loss. Figure 1 shows the polarization loss near injection due to both vertical and horizontal intrinsic resonances.

To speed up the acceleration, the idea of injecting protons into an accelerating bucket to maintain a higher acceleration rate in the early part of the energy ramp was tested. The tuning of injection is more difficult for this scheme since the RF bucket is smaller and synchronization between the AGS Booster and AGS is more critical. With this new injection scheme, we encountered transverse emittance growth. The large lattice distortions cause injection mismatch, which could be a source of emittance growth. In addition, since the beam is relatively bright, space charge related emittance growth could also be a concern. The emittance growth issue has to be resolved before we can use this injection method.

To avoid polarization loss from the vertical intrinsic resonances near injection, the vertical tune can be raised to fall inside the spin tune gap near injection (from 8.88 to $>$ 8.95) with the price of modestly increased beta functions near injection. These optics have been put in place as shown in Fig. 2.

HORIZONTAL RESONANCES

To avoid horizontal spin resonances, the horizontal betatron tune can also be put inside 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 nine as the vertical tune to avoid snake resonances. However, due to the tune spread, the horizontal tune still needs to be at some distance from the lower edge of the spin tune gap. With two unequal partial snakes and asymmetric locations in the ring, the size of the spin tune gap varies as a function of energy. As the vertical tune is around 8.98, it is difficult to push the horizontal tune above 8.96. A 14% cold partial snake combined with a 5.9% warm partial snake will provide a spin tune gap that varies between 0.90 to 0.94. This is enough to place the two betatron tunes within the spin tune gap.

A beam test was carried out by comparing the two lattices with high and low horizontal tunes in the later part of the energy ramp. The results are consistent with the polarization being better when the horizontal tune is in the spin tune gap. However, the stronger snake increased the optics distortions at injection and made it hard to reach the required beam intensity.

To overcome horizontal depolarizing resonances for the required high beam intensity, two quadrupoles, which can ramp horizontal tune by 0.04 in 100μs, are going to be installed in the AGS. So the resonances can be crossed effectively four times faster. These resonances can be divided into two categories: one with $N + \nu_x$; one with $N - \nu_x$. The tune has to be shifted up for the $N - \nu_x$ resonances and to be shifted down for the $N + \nu_x$ resonances. . For practical operation, we need to maintain the horizontal tune and radius constant throughout the ramp. Simulations, using a realistic AGS lattice and acceleration rate, have been carried out to find out how fast the lattice can be changed without incurring significant horizontal and vertical emittance growth [8]. The magnets and power supplies will be ready for a test during this run [9].

PARTIAL SNAKE RESONANCES

To maintain polarization in the AGS, we have to put the vertical tunes along the energy ramp into the spin tune gap generated by the two partial Siberian snakes. Moreover, due to the partial Siberian snake resonances [10], the available tune space is reduced even further. The partial snake resonances happen when the spin tune ν_{sp} satisfies following condition:

$$\nu_{sp} = k \pm l\nu_y, \quad (1)$$

where k and $l(>1)$ are integers. With $l = 1$, this is the intrinsic resonance discussed earlier. In the presence of the snakes, the higher order resonances constrain the available betatron tune space. The polarization was measured as a function of vertical betatron tune in the vicinity of several intrinsic resonances. Figure 3 shows the effect of the snake resonances near the intrinsic resonance $36 - \nu_y$ with 2.11T cold partial snake and 1.53T warm partial snake. The scan also reveals that 8.975 is a better operation point than 8.99. A series of polarization measurements with both tunes confirmed this.

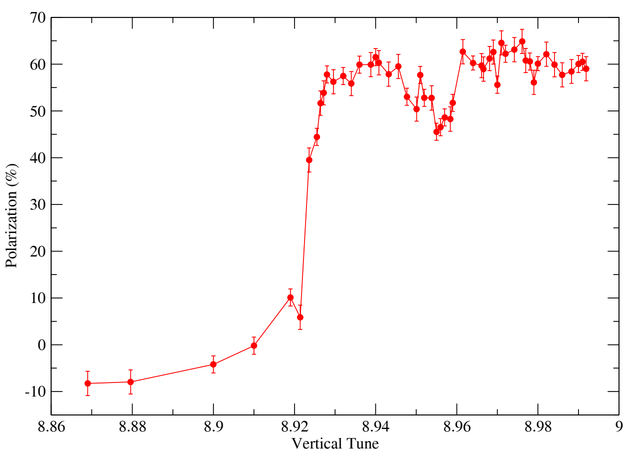

Figure 3: Polarization as function of vertical tune at the intrinsic resonance 36-ν_y. The locations of the partial snake resonances are predicted to be at 8.954, 8.972, 8.979 and 8.984. They are visible in the tune scan. The spin tune gap extends to 8.92. Outside of the spin tune gap, the polarization is quickly reduced to the partial spin flip of the intrinsic resonance $36 - \nu_y$ itself.

REDUCE EMITTANCE GROWTH

Since the intrinsic resonance strength is proportional to the square root of emittance, reducing beam emittance benefits polarization. The emittances measured in the AGS extraction are larger than the ones from linac. If we can find ways to reduce the emittance growth, it will affect polarization positively.

Several attempts have been made to reduce the emittance. Improved matching between the RFQ and the drift tube linac has greatly reduced the transverse beam emittance. The charge-exchange stripping foil at Booster injection is thinner and smaller. In addition, the beta function at the foil location has also been reduced to reduce the emittance growth due to multiple-scattering on the stripping foil. The emittances at Booster extraction are significantly reduced after all of these efforts.

CONCLUSIONS

High intensity polarized proton beam has been achieved in the AGS using strong partial snakes. In this run, a new lattice with the vertical tune in the spin tune gap near injection has been used. In addition, emittances have been reduced through various means before reaching the AGS, which will improve the polarization transmission in the AGS. The horizontal resonances associated with the stronger partial snakes also caused sizable polarization loss. A scheme to jump all horizontal spin resonances in the AGS with fast quadrupoles is now under investigation.

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