THE AGS WITH TWO COLD SNAKES

K. Hock*[1], H. Huang[1], V. Schoefer[1]
[1]Brookhaven National Laboratory, Upton, NY, USA

Abstract

To preserve polarization in the Alternating Gradient Synchrotron (AGS), two partial snakes are used to avoid both imperfection resonances and vertical intrinsic resonances. One of these partial snakes is superconducting and the other is normal conducting, the so-called cold and warm partial snakes. Simulations show that adding an additional cold partial snake improves polarization transmission for both polarized protons and polarized helions. In this configuration, the spin-tune gap for protons is large enough to accommodate both Q_x and Q_y. For polarized helions, the spin tune gap is large enough for both Q_x and Q_y to be well separated but the additional cold-snake provides lossless transmission across the very strong $G\gamma = 60 - \nu_y$. This paper serves as an investigation into extraction of polarized helions above 15 GeV/u which is needed to support all snake precession axes of polarized helions in the Hadron Storage Ring.

INTRODUCTION

The Electron Ion Collider (EIC) calls for collisions of highly polarized and high intensity proton and helion beams on polarized electron beams [1]. The target polarization at injection is 75% to support a store average polarization of 70%, with an injected intensity of protons and helions of 3.2×10^{11} and 1.3×10^{11} ions per bunch (ipb), respectively. The beams are polarized at the source and polarization transmission is optimized through acceleration at the Hadron Injector Complex (HIC) and Hadron Storage Ring (HSR) to minimize polarization loss. The HIC consists of the Alternating Gradient Synchrotron (AGS) and the AGS Booster synchrotron. Polarized protons are produced at the Optically Pumped Polarized Ion Source (OPPIS) with a polarization of 80-85% and an intensity up to 8×10^{11} ipb. During normal operations, the proton bunch is shaped via scraping to reach the desired intensity and emittances for optimal polarization transmission. Polarized protons have been operated at the Booster and AGS for RHIC operations with polarization in AGS at extraction energy at 65% and 3.2×10^{11} ipb [2]. Nominal energy ranges correspond to $G\gamma = 2.18$ to 4.5 in the Booster, and $G\gamma = 4.5$ to 45.5 in the AGS. In the Booster, there are two imperfection resonances that do not result in polarization loss. The AGS has two partial snakes, one superconducting and one normal conducting, the so-called cold and warm snakes. These snakes are located a third of the ring apart. The transfer between accelerators at the half integer is due to n_o being nearest vertical when [3]

$$|G\gamma| = 3n + 1.5 \tag{1}$$

where n is an integer. The rotation from the cold and warm partial snakes corresponds to χ_c=10% and χ_w=6% of a 180° rotation, where χ_c and χ_w correspond to the rotation from the cold and warm snakes. In the AGS, the ν_y is set to be inside the spin-tune gap generated by the two partial snakes. Due to the relatively low strength of the partial snakes, both ν_x and ν_y cannot fit in the gap resulting in many horizontal resonances being crossed. These horizontal resonances have been compensated for by a weak tune jump [3], and most recently direct correction of the resonance driving terms generated by the snakes using skew quadrupoles [4]. The weak tune jump leads to modest emittance growth and cannot provide further improvements on polarization transmission. The skew quadrupole system relaxed the stringent timing requirements of the tune jump system and is still being commissioned. Polarized helions have yet to be commissioned, with the upgrade to the Electron Beam Ion Source to provide them scheduled for the 2026 summer shutdown. The source is expected to provide polarization up to 85% with an intensity of 2.5×10^{11} ipb. The intended energy range in Booster corresponds to $|G\gamma| = 4.19$ to 7.5 or 10.5, and $|G\gamma| = 7.5$ or 10.5 to 49.5 in AGS. In the Booster there are three or six imperfection resonances, and zero or two intrinsic resonances, dependent on the extraction energy. In the AGS, the snakes rotate the spin of helions more than protons due to the higher G, producing a large spin-tune gap that can accommodate both ν_x and ν_y. The rotation of helions with the nominal proton snake strengths corresponds to χ_c=15% and $\chi_w = 9\%$. Extraction of helions at $|G\gamma| = 49.5$ corresponds to $B\rho = 55.2$ Tm, however the design AGS to HSR transfer energy is approximately 80 Tm. This lower energy transfer avoids crossing the $|G\gamma| = 60 - \nu_y$ resonance in the AGS. The highest supported transfer energy for helions that has spin matched from AGS to HSR, consistent with Eq. 1, corresponds to $|G\gamma| = 70.5$ ($B\rho = 78.8$ Tm). To satisfy $\nu_s = 1/2$ in the HSR there will be six full snakes (180° rotation), with the nominal configuration of these snakes alternating precession axis of ±45°. An alternate configuration is alternating 0° and 90° [5]. However, 90° has a large orbit excursion in the snake aperture and a large matching requirement with the accelerator. The snake aperture has a radius of 4 cm, and the entrance and exit have a reduced vertical aperture to 2.4 cm to accommodate the actively cooled beam screens. At the intended injection energy of $|G\gamma| = 49.5$ and β_y=30 m and $\epsilon_y = 1.5$ μm, there is insufficient aperture as seen in Fig. 1. The minimum supported injection energy for this configuration is 15 GeV. The orbit matching requirement for the accelerator with the snake (y_{match}), the associated maximum orbit excursion in the snake (y_{mas}), and the clearance through the snake are summarized in Table 1.

* khock@bnl.gov

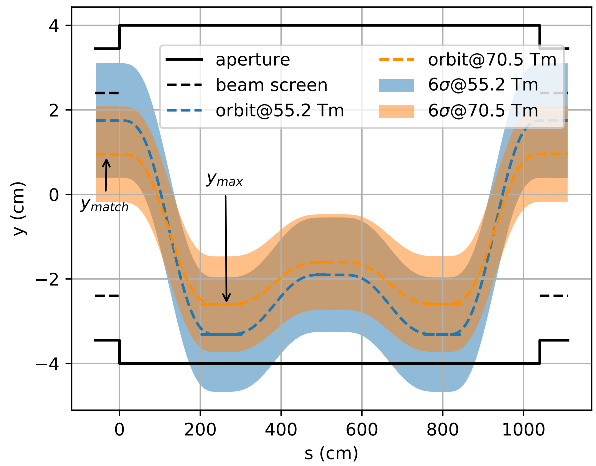

Figure 1: A comparison of the orbit taken by helions and their 6σ envelope in a snake configured with a 90° precession axis at 11 GeV (blue) and 15 GeV (orange), with β_y = 30 m and ϵ_y = 1.5 μm.

Table 1: Summary of the y_{match}, y_{max}, and the clearance inside the snake aperture at 11 and 15 GeV.

Energy	y_{match} **[cm]**	y_{max} **[cm]**	**Clearance** $[\sigma_y]$
11 GeV	0.95	–2.60	3.3
15 GeV	1.75	–3.32	7.5

SPIN DYNAMICS WITH TWO PARTIAL SNAKES

As the rotations of the cold and warm snake deviate further from each other, the projection of n_o on the vertical axis deviates further from 1. The maximum supported rotation angle for protons by the AGS cold snake corresponds to 20%, however, it cannot be operated at this strength due to the large difference with the warm snake. The ν_s and cos α_3 for protons in the nominal snake configuration of χ_c=10% and χ_w=6% is shown in Figs. 2 and 3, with a comparison of two equal strength cold snakes at 10%, 14% and 20%. As observed in Fig. 2, a substantial spin tune gap can be achieved if the warm snake is replaced with a second cold snake. As observed in Fig. 3, when the strength of each snake is equal, their projection on the vertical axis goes to 1.

Similarly for helions, the ν_s in the nominal snake configuration is χ_c =15% and χ_w=9% with a comparison of equal strength cold snakes of χ_c =15%, 21% and 31% are shown in Figs. 4. The cos α_3 is similar to that of protons and shown in Fig. 3, and not shown for helions. With an additional cold snake, the already large spin-tune gap is enhanced as seen in Fig. 4, allowing for more space to accommodate ν_x and ν_y.

POLARIZATION TRANSMISSION TO $|G\gamma|$ = 70.5

The benefit for protons is gaining access to an operational mode that supports both tunes being inside the spin-tune gap and avoiding horizontal resonances. There is no motivation

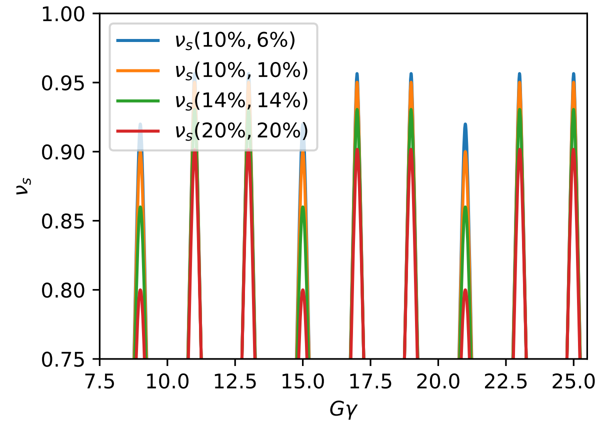

Figure 2: A comparison of ν_s of protons between the current configuration (10%,6%), and equal strength snakes at 10%, 14%, and 20%.

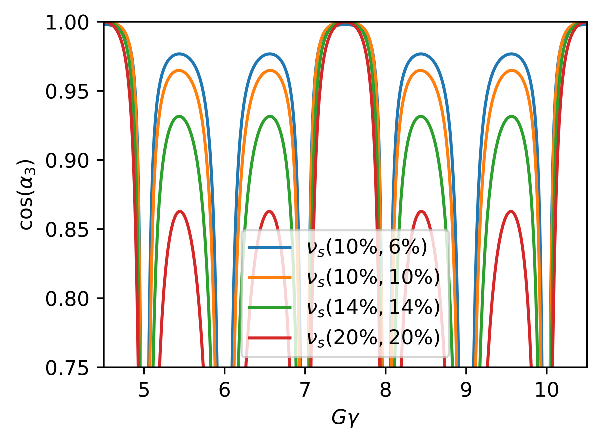

Figure 3: A comparison of the vertical projection of n_o for protons between the current configuration (10%,6%), and equal strength snakes at 10%, 14%, and 20%.

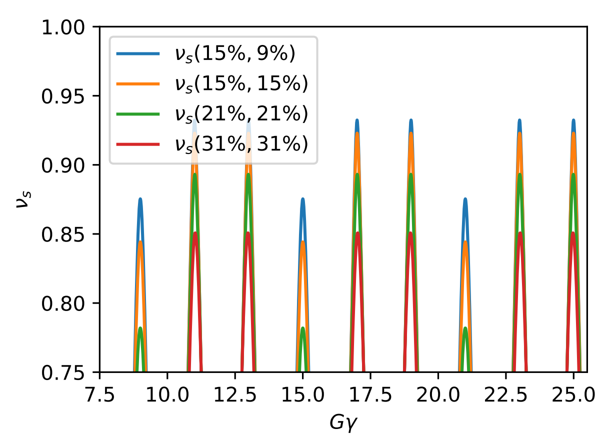

Figure 4: A comparison of ν_s of helions between the current configuration (10%,6%), and equal strength snakes at 10%, 14%, and 20%.

for raising the proton extraction energy. For helions, the additional cold snake allows the possibility of increasing the AGS to HSR transfer energy. Existing simulations of crossing the $|G\gamma| = 60 - \nu_y$ resonance show approximately 5% polarization loss with χ_c, χ_w=15%,9% [6]. Simulations of 1,000 particles crossing the $|G\gamma| = 60 - \nu_y$ resonance with two cold χ_c=31% snakes, with $\epsilon_x = \epsilon_y = 2.5\mu m$ and $\sigma_p = 0.1\%$, is shown in Fig. 5. Here the polarization loss is approximately 0.2%.

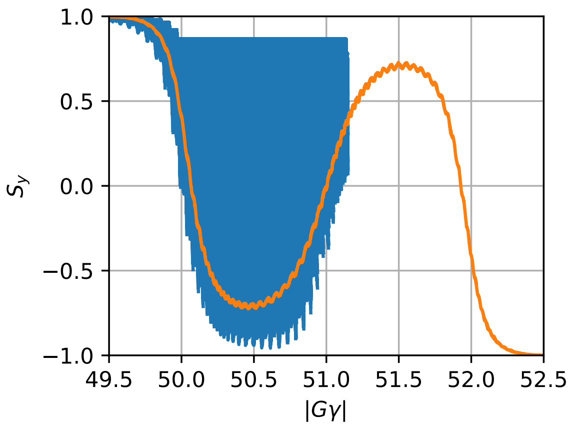

Figure 5: Polarized helions crossing the very strong $|G\gamma| = 60 - \nu_y$ resonance with two 31% snakes, all particles (blue) and their average (orange), with P_{loss}=0.2%.

The next strong intrinsic resonance after the $|G\gamma| = 60 - \nu_y$ resonance is the $|G\gamma| = 60 + \nu_y$ resonance. Fig. 6 shows simulation results of 1,000 particles crossing the $|G\gamma| = 60 + \nu_y$ resonance with two cold χ_c=31% and $\epsilon_x = \epsilon_y = 2.5\mu m$ and $\sigma_p = 0.1\%$. Here the polarization loss is 2.2%.

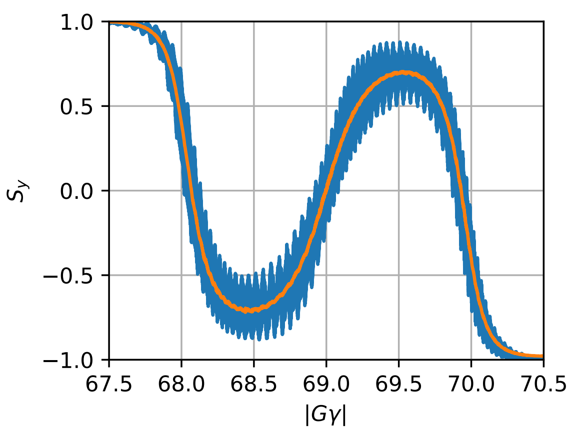

Figure 6: Polarized helions crossing the very strong $|G\gamma| = 60 + \nu_y$ resonance with two 31% snakes, all particles (blue) and their average (orange), with P_{loss}=2.4%.

Extracting from the AGS to the HSR at 15 GeV would result in 2% polarization loss, but would expand the number of supported snake configurations in the HSR, such as a HSR snake with a 90° precession axis which has a large orbit match to the rest of the ring [7]. Fourier analysis of

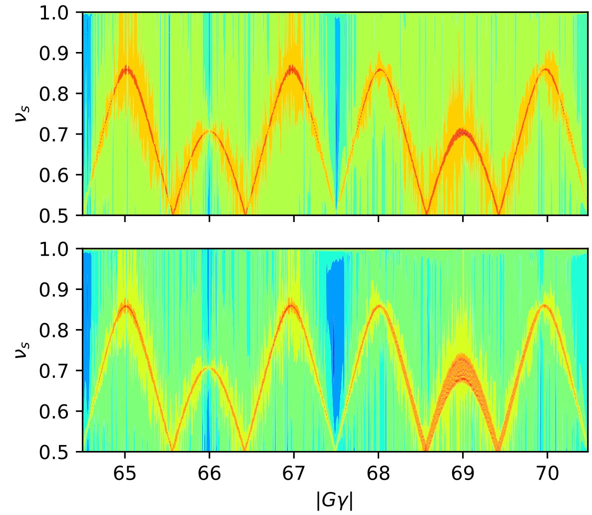

Figure 7: A heatmap of Fourier spectra from $|G\gamma| = 64.5$ to 70.5 for a $\varepsilon_y = 0\ \sigma$ particle (top) and a $\varepsilon_y = 6\ \sigma$ (bottom).

the spin motion is shown in Fig. 7 which shows a particle with initial coordinates corresponding to a 6 sigma ellipse (Fig. 7, bottom) has significant broadening of ν_s near the $|G\gamma| = 60 + \nu_y$ resonance compared to a zero amplitude particle (Fig. 7, top).

SUMMARY

Replacing the warm snake with a second cold snake will allow the full strength of the cold snake to be used with polarized beams in the AGS and maintain a spin-match for the Booster and the HSR. For polarized protons, a second cold snake will allow for an expanded spin-tune gap that can accommodate both ν_x and ν_y. For polarized helions, simulations show polarization loss of 2.4% beyond $|G\gamma| = 49.5$, allowing transport up to $|G\gamma| = 70.5$ and supporting 15 GeV extraction if the polarization loss is acceptable. Further studies will investigate the polarization loss at the $|G\gamma| = 60 + \nu_y$ to determine if the polarization loss can be minimized.

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