OPTIMIZATION OF THE AGS SUPER-CONDUCTING HELICAL PARTIAL SNAKE STRENGTH*

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Abstract

Two helical partial snakes, one super-conducting (a.k.a cold snake) and one normal conducting (a.k.a warm snake), have preserved the polarization of proton beam up to 65% in the Brookhaven Alternating Gradient Synchrotron (AGS) at the extraction energy from 85% at injection. In order to overcome spin resonances, stronger partial snakes would be required. However, the stronger the partial snake, the more the stable spin direction tilted producing a stronger horizontal intrinsic resonance. The balance between increasing the spin tune gap generated by the snakes and reducing the tilted stable spin direction has to be considered to maintain the polarization. Because the magnetic field of the warm snake has to be a constant, only the cold snake with a maximum 3T magnetic field can be varied to find out the optimum snake strength. This paper presents simulation results by spin tracking with different cold snake magnetic fields. Some experimental data are also analyzed.

INTRODUCTION

The interaction between spin and external electromagnetic fields make the behavior of the polarized proton beam complicated during the acceleration in the AGS. Numerous depolarizing spin resonances cause polarization loss when the number of spin precessions per turn ν_{sp} (spin tune) equals the frequency of the spin-perturbing magnetic field. Two main spin resonances are the imperfection resonance driven by the vertical closed orbit errors in quadrupoles, and the vertical intrinsic resonance driven by the vertical betatron motion in quadrupoles. The imperfection resonances happen at $\nu_{sp} = G\gamma = n$, where $G = (g-2)/2 \approx 1.7928$ is the proton anomalous gyromagnetic g-factor, $\gamma = \frac{E}{mc^2}$ is the Lorentz factor and n is an integer. The strong intrinsic resonances happen at $G\gamma = kP \pm \nu_y$, where n and k are integers, ν_y is the vertical betatron tune and P is the super-periodicity of the machine lattice [1], $P = 12$ for AGS. In the AGS, seven strong intrinsic resonances can cause partial spin flips resulting in depolarization.

All of these resonances can be overcome by introducing local spin rotators , called Siberian snakes [2], with a rotating axis in the horizontal plane. With a snake of strength χ in a perfect circular accelerator, the spin tune ν_{sp} becomes [1]

$$\nu_{sp} = \frac{1}{\pi}\arccos\left(\cos\frac{\chi\pi}{2}\cos G\gamma\pi\right), \qquad (1)$$

which depends on snake strength χ and beam energy γ. A full Siberian snake corresponds to $\chi = 1$ and a partial Siberian snake [2, 3, 4] is $\chi < 1$. When $G\gamma$ is close to an integer, the spin tune ν_{sp} is shifted away from the integer by $\pm\frac{\chi}{2}$. The partial snake can overcome the imperfection resonance successfully provided the resonance strength is much smaller than the spin tune gap generated by the snake. For medium energy synchrotron such as the AGS, a partial snake, more compact than a full snake, is more practical due to the lack of long straight sections and large orbit excursion associated with a full snake.

Two partial snakes have been commissioned in the AGS to preserve the polarization of proton beam. The weaker snake (warm snake) is a normal conducting helical dipole partial snake. The stronger snake (cold snake) is a super-conducting helical dipole snake. These two snakes are separated by $1/3$ of the ring to eliminate the spin mismatching at the injection and extraction energy. Hence, the spin tune is given by [5],

$$\nu_s = \frac{1}{\pi}\arccos\left(\cos\frac{\chi_c}{2}\cos\frac{\chi_w}{2}\cos[G\gamma\pi] - \sin\frac{\chi_c}{2}\sin\frac{\chi_w}{2}\cos[G\gamma\frac{\pi}{3}]\right), \qquad (2)$$

where χ_c, χ_w are the spin rotation angles caused by the cold and warm snake, respectively. The deviation of spin tune from an integer reaches its maximum every $G\gamma = 3n$, where n is an integer. Since the AGS has a super-periodicity of 12 and the vertical betatron tune is close to integer 9, this feature provides the maximum spin tune gap to place the vertical betatron tune inside at all the strong vertical intrinsic resonances. The spin tune gaps at all other integers are large enough to avoid all weak spin resonances.

DIFFERENT STRENGTH OF COLD SNAKE IN THE AGS

In practice, the two partial snakes run at constant fields, which results in the snake strength dropping when the beam energy ramps up. The partial snake percentage quoted in this paper is the strength at the top energy. At the top energy, the field of the warm snake runs at 1.53 Tesla and is a 5.9% partial snake; and the maximum 3 Tesla field of the cold snake can provide a variable strength with a maximum value of about 23% [6].

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Not only the spin tune but also the stable spin direction (defined as the invariant direction of spin vector after one revolution) are modified due to the partial snakes. The stronger the partial snakes, the more the non-vertical component of stable spin direction. A result is that an additional resonance, called the horizontal intrinsic resonances and contributes to polarization loss [7]. The horizontal intrinsic resonances happen at $\nu_{sp} = n \pm \nu_x$, where ν_x is the horizontal betatron tune. However, the stronger snake generates a wider spin tune gap, which is more convenient from the machine point of view to overcome the vertical intrinsic resonance by pushing the vertical betatron tunes high. The balance of reducing both horizontal and vertical intrinsic resonances has to be investigated with the different strength of partial snake in the AGS.

In 2006 AGS has commissioned three different strengths of cold snake, 1.5 Tesla (6%), 2.1 Tesla (10%), 2.5 Tesla (14%). Different strength of cold snake generates different width of spin tune gap as shown in Fig.1. Since the two partial snakes run at constant fields, the strengths of snakes drop when the beam energy ramps up. This results a wider spin tune gap in the beginning of acceleration. From the upper to the bottom plot in Fig.1, the strength of cold snake increases. The stronger the partial snake, the wider the spin tune gap. Meanwhile, one measured vertical betatron tunes along the whole beam acceleration is also plotted in the same graph.

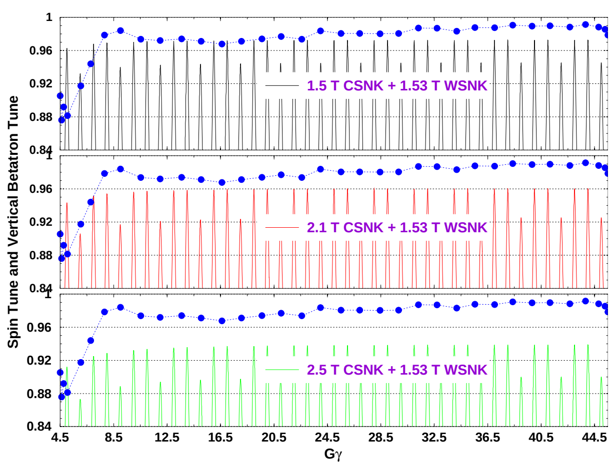

Figure 1: The spin tune (solid line) and the measured vertical betatron tune (dot line) in one acceleration cycle as function of $G\gamma$. The warm snake is fixed at 1.53 Tesla. The cold snake field is different. The upper plot is for 1.5 Tesla cold snake, the middle one for 2.1 Tesla cold snake, the bottom one for 2.5 Tesla cold snake.

Figure 1 clearly shows that the vertical betatron tunes have been pushed inside the spin tune gap after $G\gamma = 6$ for 2.1 Tesla and 2.5 Tesla cold snake, but after $G\gamma = 8$ for 1.5 Tesla cold snake due to the narrow spin tune gap. It is quite a challenge to push the vertical betatron tune close to an integer at low energies because of the large lattice distortion caused by the two partial snakes. For an isolated resonance, the polarization transmission $< S >$ is given by the Froissart-Stora formula [1]:

$$< S >= 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1, \qquad (3)$$

where ϵ is the resonance strength, α is the acceleration rate. Apparently, the slow acceleration rate in the beginning of the energy ramping can cause significant polarization loss due to these uncorrected intrinsic resonances in the AGS [8]. In addition, in 2006 the horizontal betatron tune ν_x was around 8.72, resulting in 82 horizontal intrinsic resonances during the whole energy ramping from 2.4 GeV to 24 GeV in the AGS. Even though these horizontal intrinsic resonances are weak resonances, the accumulated effect can still cause mensurable polarization loss.

Therefore, stronger partial snake generates wide spin tune gap , and introduces stronger horizontal intrinsic resonance. Weaker partial snake introduces weaker horizontal intrinsic resonance, but the accompanying narrow spin tune gap means the vertical betatron tune has to be pushed close to an integer to avoid the same partial snake resonance, which is not always possible. One natural question is what is the optimized cold partial snake strength for the AGS under these constraints. The simulations of spin tracking are performed to investigate the polarization with different strengths of cold snake and the same warm snake. 50 particles with Gaussian distribution in both horizontal and vertical phase space are used in those simulations. The momentum spread is also introduced to avoid the spin coherence phenomenon. Figure 2 shows the vertical component of polarization as a function of $G\gamma$ in one acceleration cycle. To eliminate the polarization effect due to some partial

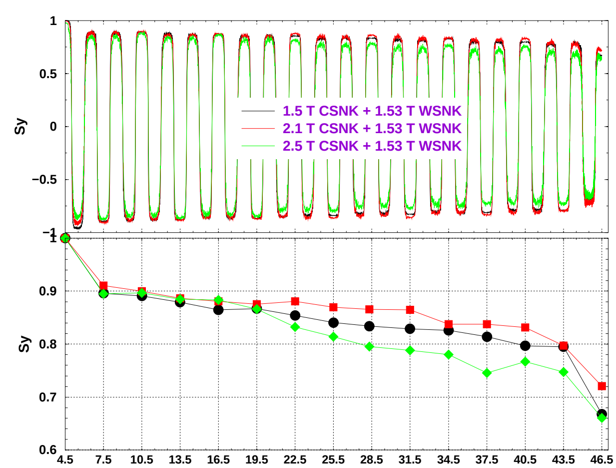

Figure 2: The vertical component of polarization as function of $G\gamma$ for 1.5 Tesla (circle), 2.1 Tesla (square) and 2.5 Tesla (diamond) cold snake. The warm snake strength is fixed. The upper plot shows the whole trace of vertical component of polarization during the acceleration. The bottom one gives the trace at $G\gamma = 3n + 1.5$, where the stable spin direction is more vertical.

snake resonances [9, 10], the vertical tune path has been revised artificially around $G\gamma$ = 27, 45, where the stronger vertical intrinsic resonances locate. The upper plot shows the spin vector flip at each integer because of the two partial snakes. The bottom one is plotted at $G\gamma = 3n + 1.5$ where the spin vector is more vertical. The result shows that 2.5 Tesla strongest cold snake does not show more merit on preserving the polarization of proton beam comparing with the 1.5 Tesla weakest cold snake. The moderate 2.1 Tesla cold snake gives the highest polarization at the end of acceleration cycle.

Figure 3 shows the polarization as function of the strength of cold snake. The black data is obtained by multiplying the transfer efficiency from the simulation to 85% inject polarization. The red data comes from the measurements of polarization in 2006. The discrepancy between the two curves is that the actual horizontal emittance for the run was smaller: 10-11π mm-mrad instead of simulation of around 12 π mm-mrad. It is important is that both give the similar trend. The two sets of data are fitted and gives the optimized cold snake strength is around 9.6% and 9.8%, respectively.

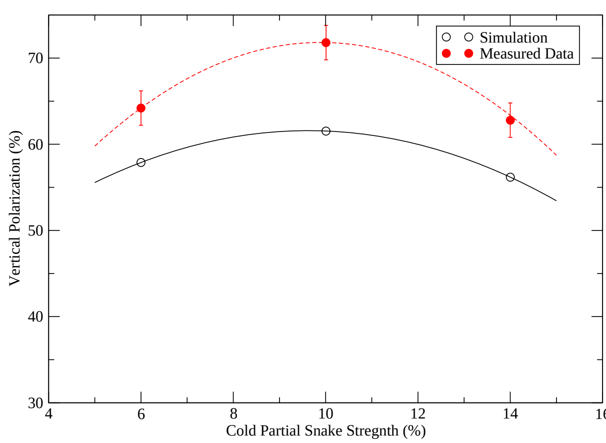

Figure 3: The polarization as function of the strength of cold snake. The solid line comes from the simulation and the dash line from the experiment.

CONCLUSION

The two partial snakes in the AGS, cold snake and warm snake, preserve the polarization of proton beam up to 65% with an initial 85% in the injection. Part of polarization loss is due to these uncorrected vertical intrinsic resonances in the beginning of the acceleration, where the vertical betatron tune is hard to push close to an integer because of the large lattice distortion due to both partial snakes. Another polarization loss comes from the horizontal intrinsic resonances caused by the non-vertical stable spin direction due to the partial snakes. The stronger partial snakes introduce stronger horizontal intrinsic resonances. The variable strength of cold snake gives us an option to balance the polarization loss of proton beam due to the residual vertical intrinsic resonances and the horizontal intrinsic resonances, and optimize the total polarization transfer efficiency.

The simulations of spin tracking are carried out with different strength fields of cold snake at 2.5 Tesla, 2.1 Tesla and 1.5 Tesla. The final polarization is not gained with 2.5 Tesla cold snake comparing with 1.5 Tesla. The modest strength of 2.1 Tesla cold snake shows a higher polarization at the flat top energy. The experiment result agree well with the simulation. This explains that stronger partial snake generates wider spin tune gap for easier correction of vertical intrinsic resonances, but the gained polarization is counteracted by the accompanying horizontal intrinsic resonances. One solution is that putting the horizontal betatron tunes are also inside of the spin tune gap during the acceleration. This is not only a challenge in the real operation of AGS, but also that increases the horizontal resonance strength. The new scheme is the horizontal tune jump that will be discussed in the future.

REFERENCES

[1] S.Y.Lee, *Spin Dynamics and snakes in Synchrotrons*, Singapore: World Scientific (1997)

[2] Ya.S.Derbenev and A.M.Kondratenko, Sov. Phys. Dokl. 20, 562 (1976) Ya.S.Derbenev et al., Part. Accel. 8, 115 (1978)

[3] T.Roser, AIP Conference Proceedings, 187, 1442 (1989)

[4] H.Huang, et al., Phys. Rev. Lett. 73, 2982 (1994); H.Huang, Ph.D. Thesis, Indiana University (1995).

[5] T.Roser, et al., Proceedings of 9^{th} European Particle Accelerator Conference p.1577, Lucerne, Switzerland (2004); T.Roser, et al., Proceedings of SPIN 2004 p.687, Trieste, Italy (2004).

[6] E.Willen, et al., Proceedings of 2005 Particle Accelerator Conference p.2935, Knoxville, Tennessee, USA (2005)

[7] F.Lin, et al., Phys. Rev. ST Accel. Beam, 10, 044001 (2007)

[8] F.Lin, et al., Proceedings of 2007 Particle Accelerator Conference p.3534, Albuquerque, New Mexico, USA (2007)

[9] S.Y.Lee and S.Tepikian, Phys. Rev. Lett. 56, 1635 (1986)

[10] H.Huang, et al. Phys. Rev. Lett. 99, 154801 (2007)