SIMULATIONS ON THE AGS HORIZONTAL TUNE JUMP MECHANISM*

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Abstract

A new horizontal tune jump mechanism has been proposed to overcome the horizontal intrinsic resonances and preserve the polarization of the proton beam in the Alternating Gradient Synchrotron (AGS) during the energy ramp. An adiabatic change of the AGS lattice is needed to avoid the emittance growth in both horizontal and vertical planes, as the emittance growth can deteriorate the polarization of the proton beam. Two critical questions are necessary to be answered: how fast can the lattice be changed and how much emittance growth can be tolerated from both optics and polarization points of view? Preliminary simulations, using a realistic AGS lattice and acceleration rate, have been carried out to give a first glance of this mechanism. Results with different optics are presented in this paper.

INTRODUCTION

With two partial Siberian snakes[1], the polarization of proton beam can be maintained in the AGS during the acceleration. The snakes cause the spin vector locally to precess by an angle of less than or equal to 180^0 around an axis in the horizontal plane. Two important types of spin resonances, imperfection resonance happening at $\nu_s = G\gamma = n$ and intrinsic resonance happening at $G\gamma = kP \pm \nu_y$, are overcome by the two partial snakes. Here ν_s is the spin tune, $G = (g-2)/2 \approx 1.7928$ is the proton anomalous gyromagnetic g-factor, γ is the Lorentz energy factor, ν_y is the vertical betatron tune, n and k are integers and P is the super-periodicity of the machine lattice, 12 for AGS.

In the AGS, two partial helical dipole snakes, cold snake (superconducting magnet) and warm snake (normal conducting magnet), are intentionally separated by $1/3$ of the ring to eliminate the spin mismatching at the injection and extraction energy. Hence, the spin tune is obtained as [2],

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

where χ_c, χ_w are the spin rotation angles caused by the cold and warm snake, respectively. This leads to the spin tune gap which limits the allowed range of tune values to reach its maximum every $G\gamma = 3n$ (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 space for placing the vertical betatron tune in the prohibited region of spin tune at all the strong vertical intrinsic resonances. The spin tune gaps (resonance free space) at all other integers are large enough to avoid all weak vertical spin resonances.

On the other hand, the stable spin direction[3], vertical in a perfect planar accelerator, is titled away from the vertical direction due to the two helical dipole snakes in the AGS. The spin vector of polarized proton will precess around the non-vertical stable spin direction during the acceleration. The interaction between the horizontal displacement and the vertical magnetic field perturbs the spin vector away from the stable spin direction and introduces another type depolarizing resonance, horizontal intrinsic resonance, which happens when $\nu_s = k \pm \nu_x$ [4]. Here ν_x is the horizontal betatron tune, which is around 8.72 on the ramp in AGS. Therefore, the polarized proton beam experiences 82 horizontal intrinsic resonances during the whole energy ramp from 2.4GeV to 24 GeV in the AGS. Realistic simulation and experiment results show that $7-8\%$ polarization loss due to those horizontal intrinsic resonances for the combination of 10% cold snake and 5.9% warm snake, even worse for 15% cold snake and 5.9% warm snake, which tilt the stable spin direction further away from the vertical direction and stronger horizontal resonances are expected[5].

Different mechanism has been proposed to overcome the horizontal intrinsic resonance [6]. An alternate practical proposal is the horizontal tune jump at each resonance location during the acceleration. The detail is described in the following section.

HORIZONTAL TUNE JUMP MECHANISM

The scheme of horizontal tune jump is to accelerate a spin horizontal intrinsic resonance crossing by varying the betatron tune locally when the resonance condition is approaching to $\nu_s = k \pm \nu_x$. As given by the Froissart-Stora Formula [7],

$$\frac{P_f}{P_i} = 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1, \quad (2)$$

where P_i and P_f is the polarization before and after crossing the resonance respectively, ϵ is the resonance strength and $\alpha = \frac{d(G\gamma)}{d\theta} \pm \frac{d(\nu_x)}{d\theta}$ is the resonance crossing rate. To preserve the polarization, it requires either $|\epsilon| \leq 0.056\sqrt{\alpha}$ (fast crossing) to maintain 99% polarization or $|\epsilon| \geq 1.8\sqrt{\alpha}$ (slow crossing) to attain -99% spin flip. Because in the AGS those horizontal intrinsic resonances are mostly weak, a fast crossing is a practical approach to overcome

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the horizontal intrinsic resonance and maintain the polarization during the energy ramping. For a given accelerator, like AGS with two partial snakes, the spin tune path is obtained analytically from Eq.(1). For fast crossing of the horizontal resonance effectively, the horizontal tune path should be perpendicular to the spin tune path.

There are two critical problems: how fast and how much these horizontal tune jumps can be. In the machine operation, a practical experience time could be 100μs for all of these tune jumps during the whole energy ramping. Since there are two kinds of horizontal resonances happening at $N+\nu_x$ and $N-\nu_x$ respectively, the tune has to be jumped up for the $N+\nu_x$ resonances and jumped down for the $N-\nu_x$ ones. In reality, the betatron tune spread and spin chromaticity effect require a larger tune jump amplitude, e.g. a change of horizontal tune 0.04 in 100 μs is more beneficial. This increases the resonance crossing rate by a factor of 4. Considering both the power supply and beta wave generated in the whole ring due to the insertion of horizontal tune jump quads, two jump quads solution gives smaller beta waves, but the locations of the two quads are not so crucial [8]. For our convenience, temporarily the two quads are located after the fifth combined magnet in the I section and J section, named I5 and J5 horizontal tune jump quads. (The 12 super periods of AGS are named from A to L. Each super period has 20 combined magnets from 1 to 20.)

Such a tune jump scheme could introduce a severe problem in the emittance blow-up, not only horizontally but also vertically due to the transverse coupling, if this sudden change is non-adiabatic in the betatron amplitude function and results in the mismatch of the beam size [9]. The emittance growth also deteriorate the proton beam polarization. Therefore, an adiabatic updating of the AGS lattice are requested to maintain the emittance when implementing the horizontal tune jump.

NUMERICAL SIMULATION OF HORIZONTAL TUNE JUMP

Numerical simulations were carried out to investigate and find out how fast the lattice has to be updated and how much emittance growth can be tolerated for the both the optics and polarization request in the AGS operation. To make these simulations more realistic, the real machine status and beam information during the energy ramping are introduced: realistic AGS lattice, acceleration rate, the two partial snakes strength and the operational horizontal and vertical tune.

The simulation at high energy is ideal as a starting point for its importance and simpleness. Since the intrinsic resonance strength is proportional to the square root of the energy factor γ [4], most of the strong horizontal intrinsic resonances happen at high energies. So the simulations at the top energy of the acceleration will be most interesting. $G\gamma = 43.5$ is chosen as the starting point because the stable spin direction is less titled away from the vertical direction here.At the top energy, the both partial snake strengths are constant and all compensation quadrupoles are off. The lattice distortion due to partial snakes are very small and the lattice update during the ramping less a problem, leaving the lattice structure changed only due to the introducing of the two horizontal tune jump quads.

To avoid an additional beta wave due to the two tune jump quads, their strength is adjusted to generate the same tune change when turning on individually. This will lead to a ratio of the strength between the two jump quads and supporting the two quads under the same power supply. In reality, considering that it is quite possible that a random beta wave already exit in the machine optics in case that there is any quads error, a constance error is introduced at L5 quads with strength of 0.0135m^{-2}. Therefore, a total of three special quads are proposed based on the original AGS lattice to investigate any emittance blow-up.

Combining all of these considerations, as well as the realistic beam size in the AGS machine operation, the simulations are performed under the below conditions:

1. The horizontal and vertical tune are set at 8.72 and 8.99 respectively for the case without tune jump,
2. 500 particles with Gaussian distribution in all dimensions (including the momentum spread),
3. Simulations go through $G\gamma$ = 43.5 to 44.5 with two horizontal tune jumps at $G\gamma$ =43.72 (tune jump up from 8.72 to 8.68) and $G\gamma$ =44.28 (tune jump down from 8.68 to 8.72),
4. Two tune jump quads locate after I5 and J5 dipole magnets, and an error quad 0.0135m^{-2} is introduced after L5 dipole magnet that also exists for no tune jump case for a fair comparison,
5. The horizontal tune is jumped by 0.04 in 50 turns (about 100μs) for the request of updating the lattice as adiabatically as possible (meaning the lattice is updated 50 times),

Table 1 lists the horizontal and vertical emittance variation without horizontal tune jump and with tune jump in 50 turns, respectively. For the tune jump, the first one happens between $G\gamma$ = 43.60985 and 43.76701; the second one between $G\gamma$ = 44.22529 and 44.32475. For both cases, the first column gives the $G\gamma$ values; the second and the third column are the horizontal and vertical emittance, the forth and the fifth column represent the emittance variation in terms of percentage of the initial value at $G\gamma$ = 43.5 respectively.

Without horizontal tune jump, the emittance is preserved in both horizontal and vertical motion, which is predicted and also a benchmark for the testing of the simulation tool SPINK [10]. The emittance growth is small and only shown in the vertical plane because of the close to integer vertical tune 8.99 and a large beta wave generated by the error quad at L5.

The corresponding polarizations of the 500 particles are also checked without and with tune jump as given in Fig.1

Table 1: The comparison of the emittance changing without tune jump and with tune jump in 50 turns

	No tune jump			
$G\gamma$	$\epsilon_h \mu$m	$\epsilon_v \mu$m	H%	V%
43.500	4.57229	5.07057	100.000	100.000
43.610	4.57255	5.07038	100.006	99.996
43.767	4.57264	5.07045	100.008	99.998
44.225	4.57266	5.07072	100.008	100.003
44.325	4.57259	5.07080	100.006	100.004
	50 turns tune jump			
43.500	4.57229	5.07057	100.000	100.000
43.610	4.57245	5.07179	100.003	100.024
43.767	4.57159	5.06579	99.985	99.906
44.225	4.57159	5.06640	99.985	99.918
44.325	4.57467	5.07323	100.032	100.033

(full structure) and Fig.2 (first jump (left) and second jump (right)). The simulation shows that the polarization levels are better with horizontal tune jump case comparing to the situation without tune jump. At least on paper, it proved that tune jump works even in the presence of beta wave, introduced by error quad at L5 aimed to simulate any beta wave in the AGS. As the vertical tune is close to integer 9, there is no difference if the error is distributed or from single element.

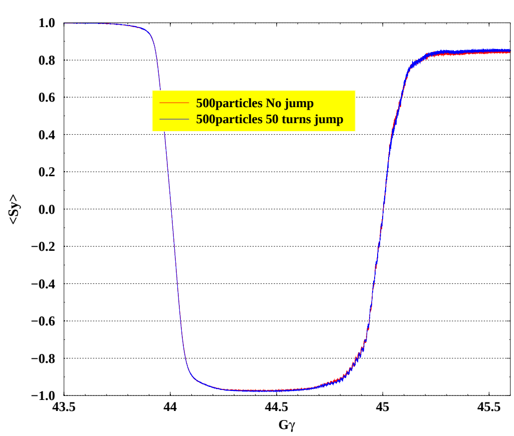

Figure 1: The full structure of polarizations from $G\gamma = 43.5$ to 44.5 without (red) and with (blue) horizontal tune jump.

CONCLUSION

In conclusion, to overcome the horizontal intrinsic resonance of the polarized proton beam in the AGS, a new horizontal tune jump mechanism will be employed by using two tune jump quadrupoles in the AGS. The corresponding beta wave generated by the two tune jump quads could cause the beam emittance growth because of the mismatch between the lattice optics and the beam size if the change

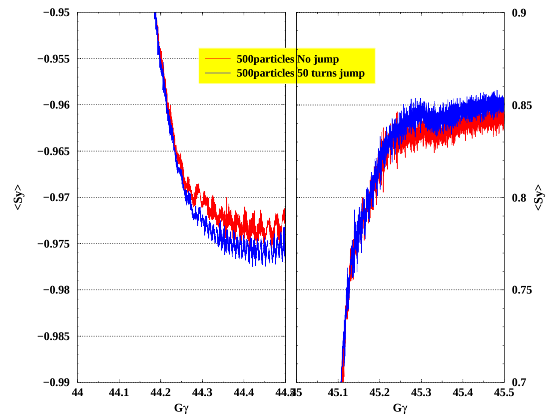

Figure 2: The separated structure of polarizations at the first (left) and second (right) tune jump: red for without tune jump and blue for with tune jump.

is non-adiabatic. Realistic simulations by using the mostly realistic AGS lattice, acceleration rate and beam information were performed to investigate the variation of the emittance. A horizontal tune jump of 0.04 in 100 μs, around 50 turns, is more beneficial. The simulations show that the horizontal emittance growth is very small and only some growth vertically due to the close to integer tune. The simulation shows benefit on polarization from the tune jump mechanism. More detailed investigation will be followed in the future.

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