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OVERCOMING THE HORIZONTAL DEPOLARIZING RESONANCE IN THE BROOKHAVEN AGS *

H. Huang, L. Ahrens, M. Bai, M. Blaskiewicz, K. Brown, R. Connolly, Y. Dutheil,
W. Fischer, C.J. Gardner, W. J. Glenn, T. Hayes, F. Méot, A. Poblaguev, V. Ranjbar,
T. Roser, V. Schoefer, K. Smith, S. Tepikian, N. Tsoupas, K. Yip, A. Zelenski,
K. Zeno, S.Y. Zhang, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Imperfection and vertical intrinsic depolarizing resonances have been overcome by the two partial Siberian snakes in the Alternative Gradient Synchrotron(AGS). The relatively weak but numerous horizontal resonances are the main source of polarization loss in the AGS. A pair of horizontal quads have been used to overcome these weak resonances. This technique needs very accurate jump timing. The keys for the system are the accurate control of the jump quad timing and the elimination of any emittance growth. Fast rollover magnet cycle has been used and it improves the horizontal tune jump quads setup. Recent experimental results including jump quad timing and emittance preservation are presented in this paper.

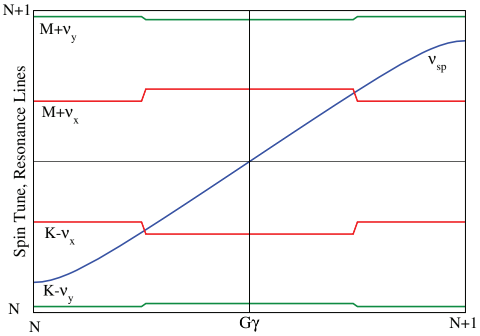

Figure 1: The schematics of tune jump scheme. The blue trace is the spin tune as function of $G\gamma$. The red lines are the horizontal intrinsic resonance lines. The green lines are vertical resonance lines. Over one unit of $G\gamma$, two horizontal resonances are crossed. M, K and N are integers.

HORIZONTAL DEPOLARIZING RESONANCES

A dual partial snake scheme [1] has been used in the AGS to overcome both imperfection and vertical intrinsic depolarizing resonances. For normal synchrotrons, the intrinsic resonance is only associated with the vertical betatron tune ν_y for vertical polarization, as the vertical spin can only be affected by the horizontal magnetic field. However, in the presence of a partial snake, the stable spin direction is not purely vertical. 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 the result, resonances are driven by the horizontal betatron oscillations, and will occur whenever the spin tune satisfies $G\gamma = k \pm \nu_x$, where G is the anomalous magnetic moment of the beam particles, γ is Lorentz factor, k is an integer. For proton, $G = 1.7928$.

To avoid these horizontal intrinsic depolarizing resonances, the horizontal betatron tune can also be put into the spin tune gap generated by the partial snakes, but this is not practical for the two existing partial snakes. Since all these resonances are relatively weak compared to the vertical counterpart, a modest tune jump system can be built to increase the effective resonance crossing rate to mitigate the polarization loss. Because the beam is going to be used for the Relativistic Heavy Ion Collider (RHIC), the emittance blowup due to the non-adiabatic tune jump has to be small. In addition, since the total polarization loss for the 82 horizontal resonances is predicted to be only 15-20% for the given emittance, it is not possible to determine the jump times by time-scanning each resonance individually while measuring the final polarization, as done historically for the fast tune jump for strong vertical intrinsic resonances. This timing has to be calculated based on accurate beam horizontal tune and energy measurements.

When $G\gamma$ is near integer where imperfection and vertical intrinsic resonances are located, the vertical tune must be back to its nominal value, so that the crossings of these resonances are not affected. The scheme is illustrated in Fig. 1. With partial snakes inserted, the spin tune ν_{sp} is almost linearly proportional to $G\gamma$ except when $G\gamma$ is near integer, where a spin tune gap is generated. There are two horizontal intrinsic and two vertical intrinsic resonances in each $G\gamma$ interval. The two vertical resonances are avoided by maintaining the vertical tune inside the spin tune gap. The two horizontal resonances are overcome by tune jump.

The final polarization after crossing an isolated depolarizing resonance is given by Froissart-Stora formula. For a Gaussian beam, it is given as

$$\frac{P_f}{P_i} = \frac{1 - \frac{\pi|\epsilon|^2}{\alpha}}{1 + \frac{\pi|\epsilon|^2}{\alpha}} \tag{1}$$

where P_f and P_i are the polarization before and after crossing the resonance respectively, ϵ is the resonance strength

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and

$$\alpha = \frac{d(G\gamma)}{d\theta} \pm \frac{d\nu_x}{d\theta} \qquad (2)$$

is the resonance crossing rate. For the whole ramp, the final polarization is just the product of the Eq.(1) for all 82 isolated resonances. During normal acceleration, the rate of change of $G\gamma$ in the AGS is about 117/s. The overall polarization loss for typical AGS emittance is about 15-20% over the whole ramp. An increase of the crossing rate by a factor 4 will reduce this loss to 4-5%. The gain from further increase is small. To quadruple the resonance crossing speed, a change of ν_x at rate above 0.35/ms meets the requirement. The AGS horizontal tune jump system can achieve this with a tune jump of 0.04 in $100\mu s$.

Compared to the vertical tune jump done in the past for polarization purposes, there are a few differences. First, this tune jump system has to jump many times (up to 82 times for the full AGS ramp), and the effect on polarization from each one is too small to be measured. This means that the timing has to be dead reckoned. Second, the beam is used for collider injection instead of slow extracted beam. The emittance preservation is important for both polarization preservation and luminosity in the collider.

The associated 0.02 vertical tune motion occurring over $100\mu s$ (about 34 to 37 turns) does pose a problem. Unlike the horizontal tune, which is around 8.70 throughout the ramp, the vertical tune is necessarily close to integer (such as 8.98 or 8.99). The vertical betatron motion at the quad is slow relative to the changing of the jump quad fields, which makes the field change non-adiabatic. Any offset between the equilibrium orbit and the jump quad centers generates a kick, which results in emittance growth. While the steering error can be minimized, some mismatch of the beam beta functions across the jumps is unavoidable. Simulations of the emittance evolution with various jump amplitudes and jump quad locations have been done to make sure the emittance growth is small enough due to the tune jump [2]. From these simulations, we found:

1. The vertical tune jump $\Delta\nu_y$ generated by each of the two jump quads has to be equal for the vertical emittance preservation.
2. There is significant emittance growth for one turn jump (very non-adiabatic), but there is not much gain slowing from 25 to 50 turns.
3. With the existing 20% beta beat included, the vertical emittance growth is about two times larger than without the beta beat. But it is still below 0.1% from one jump. For a total of 82 tune jumps, this translates to no more than 8% emittance growth. Since the 20% beta function beat is an over estimate and the vertical tune is not at 8.99 for most of the ramp, the real emittance growth should be even smaller.

AGS OPERATION AND BEAM SETUP

The polarized H^- beam from the optically pumped polarized ion source was accelerated by the 200MeV linac. The beam polarization at 200MeV was stable and was 80-82%. The beam was then strip-injected and accelerated in the AGS Booster up to 2.36GeV or $G\gamma = 4.5$. At Booster injection, the vertical tune is as high as 4.92 to reduce the horizontal beta function at the stripping foil so that emittance growth due to the multiple-turn injection can be minimized. On the Booster ramp, the vertical tune was chosen to be 4.8 in order to avoid crossing the intrinsic resonance $G\gamma = \nu_y$ in the Booster. The imperfection resonances at $G\gamma = 3$ and 4 are corrected by using orbit harmonic correction. The beam intensity was scraped in the Booster from 5×10^{11} down to 2.5×10^{11}, which reduces beam emittance, mainly in vertical. This is important for beam polarization preservation in the AGS and RHIC.

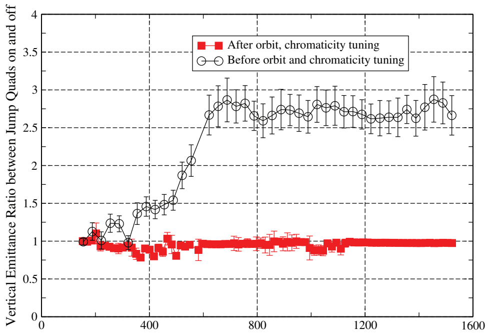

Figure 2: The measured vertical emittance ratio of jump quads on and off on the AGS ramp. The measurements were done through repeated AGS cycles. The error bars are statistical errors only. The large error bars for the emittance growth case were due to fewer cycles for these measurements.

The AGS injection and extraction energies are chosen as $G\gamma$ = 4.5 and 45.5, respectively. At low energies, the helical snake magnets cause significant lattice distortion. Even with each snake complemented by four compensating quads, the vertical tune has to be lower than 8.90 near injection so that the beam size due to beta function distortions does not exceed the aperture limit. The vertical tune is moved into the spin tune gap only after $G\gamma$=5. The detail of the tune jump hardware and controls are given in Ref. [3]-[4].

HORIZONTAL TUNE JUMP RESULTS

With the vertical orbit feed forward jump quad centering, removing the 6th horizontal harmonic [5] and proper chromaticity setup, the emittance is preserved for the horizontal tune jump. Fig. 2 illustrates the emittance ratio on the ramp before and after the emittance growth was fixed. The intensity with jump quads on was slightly lower (1.83×10^{11}vs 1.87×10^{11}, just a 2% difference), but showed no emittance growth.

In the AGS, γ_{tr} quads were turned on at the transition crossing to maintain longitudinal beam stability. It was found that firing horizontal tune jump quads during transi-

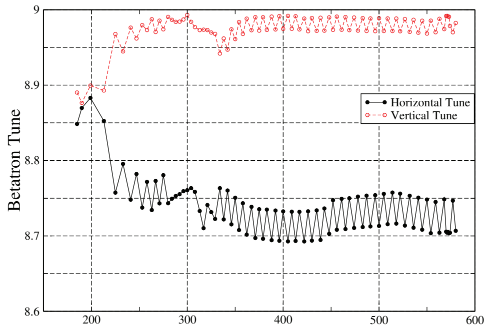

Figure 3: The measured betatron tunes along the ramp as a function of time from AGS T0. The transition is crossed at 313ms. Note that there was no tune jump around 300ms to avoid transition.

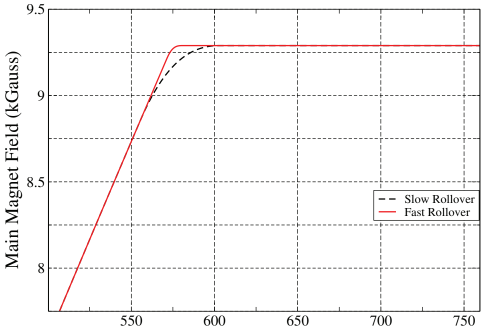

Figure 4: Two AGS main magnet functions near flattop. The resonance crossing speed from the fast one is close to a constant near the end, including the last horizontal resonance.

tion crossing interfered with operation of γ_{tr} quads, which resulted in stronger longitudinal oscillation after transition. To preserve the longitudinal emittance, six (12 jumps) tune jump pulses were left off around transition. As a result, 70 out of 82 horizontal resonances were jumped.

The measured betatron tunes on the AGS ramp as a function of ramp time are shown in Fig. 3. The tune measurement time was chosen such that it gave tunes alternatively as jump up value and jump down value (or no jump value). The ramp starts at 149ms and reaches flattop at 581ms. The figure shows that the horizontal tune jump amplitude is about 0.04 and the vertical one is about 0.02.

The jump timing determination requires accurate determination of beam energy as function of ramp time. The beam energy information on the energy ramp comes from measuring the AGS main magnetic field and measuring the beam momentum offset using the radial average from the beam position measuring system. As a cross check, the second set of beam energy information is derived from beam frequency and beam path length. The jump timing is then derived from the beam energy and horizontal tune as function of time.

Since the polarization gain from individual jump is too small, one can only scan the overall jump timing with a fixed shift. To make this possible, it is desired that all resonances are crossed with similar speed. A new main magnet function with fast rollover on the flattop has been used. A radial steering function was used to compensate for the overshoot of the main magnet current and to maintain energy stability. The AGS fast roll-over function is shown in Fig. 4. Polarization measurements were done for fast and slow rollover in conditions of jump quads on and off with 2×10^{11} intensity. The results are listed in Table 1. As the results show, in the jump quads on case, there is not much difference in polarization. The horizontal resonance crossing speed has been dominated by the tune jump. The vertical intrinsic resonance and imperfection resonances are avoided by dual partial snakes. The effect of snake resonance is not sensitive to crossing speed. In the jump quads off case, polarization is lower for slow rollover, because the crossing speed for horizontal intrinsic resonances is slower.

Table 1: Polarization with Different Magnet Cycles

Magnet	JQ on	JQ off	On/Off Ratio
Slow	$63.3 \pm 1.1\%$	$53.9 \pm 1.1\%$	1.17 ± 0.03
Fast	$63.9 \pm 1.1\%$	$61.4 \pm 1.1\%$	1.04 ± 0.02

After further improvement in energy calibration and jump quads timing [6], the jump quad's benefits improved. With 2×10^{11} intensity, a series of polarization measurements were taken. The polarization was measured with jump quads on as $72.8 \pm 1.8\%$, with jump quads off as $63.5 \pm 1.8\%$. The gain factor of polarization is 1.15 ± 0.04.

CONCLUSIONS

Vertical intrinsic resonances and imperfection resonances have been avoided by introducing two partial snakes in the AGS. But the partial snake magnets also move the stable spin direction away from the vertical and consequently excite the so-called horizontal intrinsic resonances. A modest horizontal tune jump system has been used to overcome these weak but numerous resonances while maintaining the transverse emittances. A relative gain of 15% polarization has been achieved with the tune jump system. This scheme paves the way to use partial snakes to preserve polarization in the medium energy synchrotrons without the concern of losing polarization due to additional horizontal depolarizing resonances.

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