INCREASING THE AGS BEAM POLARIZATION WITH 80 TUNE JUMPS*

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Abstract

Vertical depolarizing resonances in the AGS are removed by partial Siberian snakes. These magnets also move the stable spin direction away from vertical and excite horizontal depolarizing resonances. The tune jump quadrupole system reduces the resulting depolarization by increasing the resonance crossing rate for the horizontal resonances by a factor of six. This presentation will review the partial Siberian snake solution, the resulting horizontal intrinsic resonance mechanism and describe recent experimental evidence at the AGS demonstrating improvements to beam polarization and the beam dynamics challenges posed by the tune jump.

INTRODUCTION

The Relativistic Heavy Ion Collidier (RHIC) spin program requires high polarization (70% or better) while maintaining high luminosity. Achieving this goal requires careful avoidance of sources of depolarization throughout the acceleration cycle, from source to collision. In particular, what concerns us in this paper is the careful avoidance of depolarization in the AGS, the injector into RHIC, without ruining the intensity or emittance in the process.

The motion of the spin of a particle moving at relativistic speeds in a magnetic field is given by the Thomas-BMT equation [1]

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \frac{e}{\gamma m}\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \quad (1)$$

Here $\vec{S}$ is the spin vector of the particle, e, m and G its charge, mass, and anomalous gyromagnetic ratio respectively, γ the Lorentz factor, and finally $\vec{B}$ is the externally applied magnetic field. The subscripts $\perp$ and $\parallel$ denote the components of the field perpendicular and parallel to the particle velocity. We have neglected the effects of electric fields.

In a synchrotron lattice, the field in the Thomas-BMT equation are periodic and the spin motion can be described with a one-turn map (OTM). The fixed point of the OTM is called the spin closed orbit, and is denoted $\hat{n}_{co}$. In general it depends on the phase space coordinates of the particle. Spin vectors not parallel with the spin closed orbit will precess about $\hat{n}_{co}$ at a rate of ν_s times per revolution. We call ν_s the spin tune. For an unperturbed, planar accelerator, the stable spin direction is vertical (parallel to the main bending field) and the spin tune is exactly $G\gamma$. The direction of the spin can be perturbed away from vertical by horizontally oriented magnetic fields, like those used to keep the beam vertically focused. These fields cause depolarization when the spin precession frequency equals the frequency with which the particle samples these fields and the particle experiences a depolarizing resonance.

When the resonance is due to closed orbit distortions, they are called imperfection resonances and occur when $G\gamma = n$ for any integer n. Even in the absence of closed orbit errors, the finite emittance of the beam guarantess that most particles will be off-center in quadrupoles, leading to so-called intrinsic resonances when $G\gamma = n \pm Q_y$ where Q_y is the vertical tune.

Helical dipole magnets called Siberian snakes can be used to overcome these resonances by manipulating the spin tune away from $G\gamma$ so that these resonance conditions are never met. A pair of 'full', or 100% snakes, snakes that turns the spin 180° during each transit through the magnets, can be used to fix the spin tune at 1/2, independent of energy such that all imperfection and intrinsic resonances are avoided. This is the solution employed in RHIC. In the AGS, however, the orbit excursions created by a full snake of the length available in the straight sections would be outside the aperture at injection. Therefore a different solution, so-called partial snakes, that rotate the spin vector by less than 180° was developed [2].

THE PARTIAL SNAKE SOLUTION

Currently the AGS polarized proton lattice includes two partial snakes separated by 1/3 of the ring. The first, a normal conducting helical dipole (the 'warm snake'), was installed in 2004 rotates the spin vector by 10° (a 5% snake). The other, a superconducting helical dipole (the 'cold snake'), installed in 2005, is capable of rotating the spin by as much as 45° (a 25% snake). In typical operation the cold snake is run at a lower current as a 10% snake.

In the presence of two partial snakes with spin rotation angles χ_w and χ_c the spin tune ν_s and the vertical component of the stable spin direction S_y are given by:

$$\begin{aligned}\nu_s &= \frac{1}{\pi}\arccos(\cos\frac{\chi_c}{2}\cos\frac{\chi_w}{2}cos[G\gamma\pi] \\ &\quad -\sin\frac{\chi_c}{2}\sin\frac{\chi_w}{2}\cos[G\gamma\frac{\pi}{3}]) \quad (2)\end{aligned}$$

$$\begin{aligned}S_y &= \frac{1}{\sin\pi\nu_s}(\cos\frac{\chi_w}{2}\sin\frac{\chi_c}{2}\cos\left[G\gamma\left(\pi-\theta\right)\right] \\ &\quad +\sin\frac{\chi_w}{2}\cos\frac{\chi_c}{2}\cos[G\gamma\left(\frac{\pi}{3}-\theta\right)]) \quad (3)\end{aligned}$$

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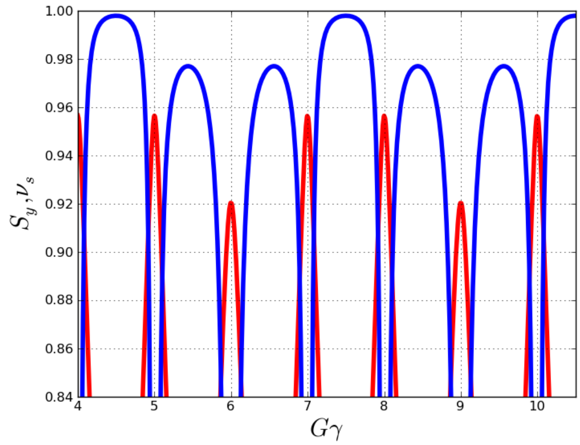

Figure 1: The magnitude of the vertical component of the stable spin direction S_y (blue) and the spin tune ν_s (red) for an AGS lattice with two partial snakes set to 10% and 5.9% spin rotation. AGS injection energy is Gγ=4.5.

These are plotted over a range of $G\gamma$ near the AGS injection energy in Figure 1.

Two things are of particular note here. The first is that the spin tune, ν_s, is no longer strictly equal to $G\gamma$. When $G\gamma$ approaches an integer (i.e. when an imperfection resonance is approached), the spin tune 'turns over' and a so-called 'spin tune gap' opens up near integer values of the spin tune. This means that imperfection resonances are completely avoided, since $\nu_s \neq n$. Furthermore, if the vertical tune is placed near the integer ('in the gap'), the intrinsic resonance condition $\nu_s = n \pm Q_y$ can also be avoided. The strong partial snakes allowed a polarization of 60% to be achieved at 1.5×10^{11} proton per bunch intensity.

The next thing of note is that the stable spin direction is no longer uniformly vertical. It develops a horizontal component as each $G\gamma = n$ is approached and indeed changes sign as the integer is crossed. This horizontal component means that vertically oriented magnetic fields can also produce depolarization via intrinsic resonance with the horizontal component of the spin vector. It is these resonances, the horizontal intrinsics at $\nu_s = n \pm Q_x$, that the AGS tune jump is meant to address.

HORIZONTAL TUNE JUMP

Horizontal intrinsic resonances could in principle also be avoided by putting Q_x in the spin tune gap alongside Q_y, but previous attempts to operate in this mode have resulted in serious limits to the intensity transmission.

If a resonance condition cannot be avoided, the crossing rate can be increased to limit the resulting depolarization by non-adiabatic change in one of the resonance terms. A pair of fast-pulsing quadrupoles, hereafter the 'jump quads', have been installed in the AGS to rapidly change the horizontal tune near each horizontal intrinsic resonance.

As each horizontal intrinsic resonance is approached, the current in the jump quads is changed rapidly to change the horizontal tune by 0.02 units (per quad) with a rise time of 100 μs, which is about 30 revolution periods. This increases the effective crossing speed by a factor of six and minimizes the amount of depolarization at each resonance. The AGS accelerates protons from a $G\gamma$ of 4.5 to 45.5 and so 82 of these resonances must be crossed. A high voltage supply creates the fast tune jump and then a switch is made to a low voltage supply which holds the quadrupole current at a DC level until the next jump, when the current is jumped back down to zero. Figure 2 illustrates the tune jump principle schematically. More detailed discussion of the implementation and control of the jump quad power supplies can be found in Refs. [3, 4].

The quadrupoles themselves are located in straight sections separated by one AGS superperiod, resulting in a vertical phase advance between the two of nearly 270°. This is necessary because the duration of the tune jump is non-adiabatic with respect to the vertical betatron period owing to the high vertical tune necessary to avoid vertical intrinsics (the period is about 100 turns at Q_y = 8.99). This placement is therefore meant to minimize the impact of the jump quads on the vertical emittance.

Non-adiabatic jumping of the vertical tune was actually a strategy employed early in the AGS polarized proton program to reduced the impact of the vertical intrinsic resonances. The depolarization from any individual vertical resonance is large enough to be easily measurable with the AGS internal carbon polarimeter and so the timing of each jump could be optimized empirically [5]. Simulation indicates that the total loss of polarization from all of the uncompensated horizontal intrinsic resonance crossing is about a 10% relative loss [6]. This puts the effect of any single resonance below the resolution of a polarization measurent of any reasonable duration and so the crossing time must be inferred from other measurements.

Calculation of the resonance crossing times

The most significant challenge to successful operation of the jump quads is the determination of the appropriate jump times, which requires precise knowledge of the beam energy.

The required timing accuracy is set by the beam acceleration rate and the duration and amplitude of the tune jump. In the AGS we have a tune jump of 0.04 units in 100 μs and an acceleration rate of 1 unit of Gγ per millisecond, and one finds that a timing error of 250 μs means that a resonance jump is just completely missed.

To determine when each resonance condition occurs the time dependence near a crossing of both the beam energy (Gγ) and the horizontal tune are required. A 2x82 point time set with pairs near each crossing is established. Horizontal tunes are measured (via turn-by-turn fitting of the coherence created by a single turn horizontal dipole kick) at each of these times. For the same time set the beam energy is deduced from the AGS Gauss clock. With the two pairs of (energy, tune) near the crossing the crossing time

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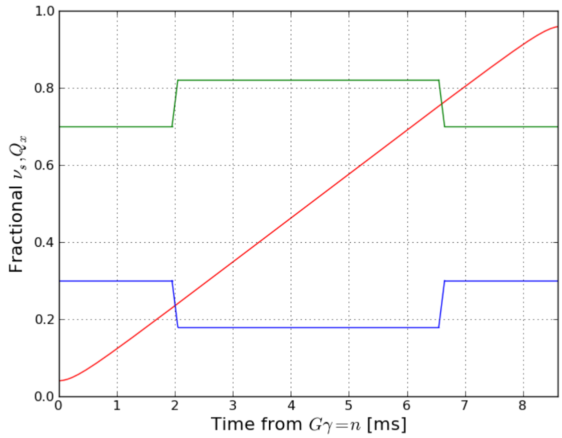

Figure 2: Schematic of horizontal tune jump. Between each pair of imperfection resonances ($G\gamma = n$) there are two horizontal intrinsics ($\nu_s = n \pm Q_x$). The spin tune is shown in red. The blue and green lines are at 1-Q_x and Q_x respectively where in this plot Q_x = 0.7. The jump quads raise Q_x (lowering 1-Q_x) to cross the first resonance and lower Q_x to cross the second. The jump duration shown is 100 μs, the jump height shown has been exagerated from the operational ΔQ_x = 0.04 by a factor of three for illustration.

estimate is learned by linear interpolation.

The AGS Gauss clock system measured the voltage induced by the magnet ramp on a long coil located inside a standard vacuum chamber inside of the AGS reference magnet (which is in series with the ring magnets). From a careful integration of this voltage the beam energy is calculated. This system is calibrated by an independent energy measurement based on measuring the beam frequency again throughout the cycle. Both systems also get the beam radius information from the AGS Beam Position Monitor system. The frequency-based system has superior accuracy early in the acceleration cycle when the beam is less relativistic ($\beta \approx 0.9$ at injection) but loses accuracy as the beam becomes very relativistic. The early data allows the Gauss clock to be calibrated and then provide the energy information throughout the cycle. Comparison of the calculations of energy from revolution frequency and magnetic field is the primary strategy to improve the resolution. In Run 10 it became visible that the Gauss clock suffers a subtle change in calibration at times in the acceleration cycle when the voltage applied to the main magnet is changing (i.e. the second derivative of the main bend field magnitude with respect to time is non-zero). For the current running period an empirical correction for this phenomenon, which is not yet fully understood, has been added into the system allowing the disagreement between the two systems to be reduced.

Only one beam-based calibration point of useful accuracy is presently known: the beam crossing of the Gγ = 36+ν_v strong vertical intrinsic resonance. Though the system predicts this point accurately, there are too many variables for this alone to be an adequate constraint. It is primarily just the energy comparison between frequency and Gauss clock that sets the calibration. This disagreement varies through the cycle but generally less than 0.02 untis of Gγ corresponding to a crossing time error of less than 200 μs. Further calibration of the energy by using the jump quads to jump an artificially excited vertical intrinsic resonance are being pursued.

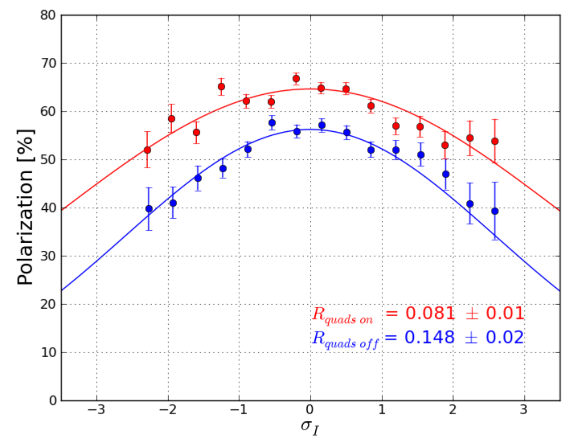

Figure 3: Polarization measured as a function of carbon target position with respect to the beam center. Position in the figure is given in units of the sigma of a Gaussian fit to the intensity distribution. Red is a measurement made with the jump quads on, and blue with them off.

IMPROVEMENT TO POLARIZATION

The depolarization resulting from a horizontal intrinsic resonances is dependent on the horizontal betatron amplitude of the particle. The design particle that passes through the centers of all the lattice quadrupoles (sometimes called the ‘zero-emittance’ particle) experiences no depolarization. One can therefore measure the effect of the tune jumps by measuring the polarization as a function of horizontal position in the beam, the horizontal polarization profile. The polarization profile is measured at AGS extraction energy with a carbon CNI polarimeter by sweeping a horizontally thin, vertically oriented target horizontally across the beam. The horizontal position of the target during the sweep relative to the center of the beam is inferred from the CNI event rate and the asymmetry binned according to horizontal position. The results of such a measurement are shown in Fig. 3.

The steepness of the polarization profile can be quantified by fitting both the intensity and polarization distributions to Gaussians and calculating the so-called R parameter,

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$$R = \frac{\sigma_P^2}{\sigma_I^2} \quad (4)$$

where σ_P is the standard deviation of the (fitted) polarization distribution and σ_I that of the intensity distribution. Ideally there is no loss of polarization with amplitude and R = 0. The R values for the measurement are given alongside the profiles in Fig. 3.

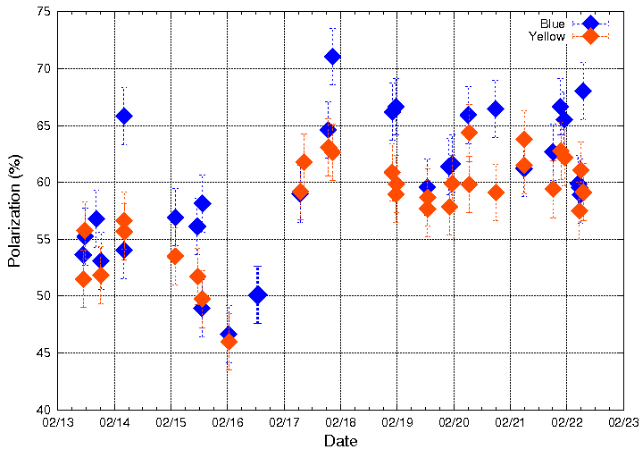

Figure 4: Polarization measured in RHIC at injection energy during the initial commissioning of the jump quads for all physics production fills starting on 2/17/11. In RHIC the polarization is measured by sweeping the carbon target through the beam, so this reflects an improvement in the average beam polarization.

The jump quad system was used for the first time for RHIC operation during RHIC Run 11. Figure 4 shows polarization measurements (made with a carbon polarimeter) in RHIC at injection energy for about a week spanning the initial use of the jump quads for RHIC physics fills. The improvement of from 55% to 62% is in good agreement with the simulation prediction of 10% relative gain.

OPERATIONAL EXPERIENCE

The cost of the improvement to the polarization is an increased sensitivity to orbit and optics errors. As mentioned earlier, the tune change caused by the jump quads in the vertical plane is non-adiabatic and as a result special care must be taken to preserve vertical emittance in the face of 82 non-adiabatic jumps. Emittance growth from the jumps has three possible sources, one from dipole kicks resulting from imperfect centering in each quadrupole, one from optical mismatch between the two quadrupoles and another from have unsynchronized jump times betwee the two quadrupoles.

Inductive pickup coils placed in the field regions of the jump quads allow synchronization of the jumps to the level of 1 μs, which is less than one revolution period.

Orbit Stability and Feedback

With the vertical tune at 8.985 or higher throughout acceleration, the vertical closed orbit is very sensitive to small dipole errors. Each pulsing of the jump quads represents a non-adiabatic change to closed orbit if the beam is not properly centered in each quadrupole. Since the resulting change in the orbit is dominated by a single harmonic, it is sufficient to measured the harmonic content of the closed orbit just before and just after a jump. An addition to the standard AGS orbit control application has been developed that allows operators to specify target harmonic content throughout the AGS cycle and which automatically corrects the harmonics so as to center the beam in the jump quadrupole and minimize the closed orbit contributions to emittance growth.

Optical Mismatch

During most of the AGS acceleration cycle the AGS optics are nominally superperiod symmetric (near injection energy the optical effects of the snakes break this symmetry). Since the jump quads are symmetrically located, the vertical beta functions at their location should be equal, but during development with the jump quads in 2010, we discovered that for equal current changes in the quadrupoles, the resulting vertical tune changes were different by nearly a factor of two, implying a similar difference between the beta functions. Subsequent measurement of the beta functions, revealed a beta wave consistent with systematic horizontal offsets in the lattice chromaticity control sextupoles [7]. Prior to the 2011 RHIC run, we undertook a survey of the AGS ring and realigned a subset of the AGS main magnets and the chromaticity sextupoles so as to minimize the contribution of sextupole-feeddown to the optical mismatch. Figure 5 illustrates the improvement in the optical matching.

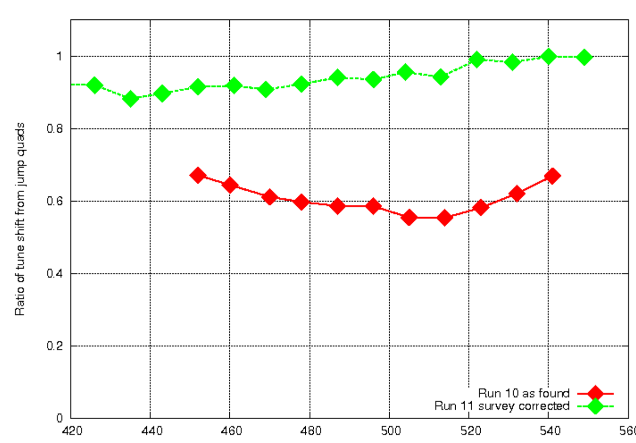

Figure 5: Ratio of the tune shifts measured from equal changes in current in the jump quads, reflecting a significant vertical β function distortion. Red was as measured in Run 10 and green shows a ratio much closer to one after a realignment of several AGS main magnets.

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Chromaticity

Without the jump quads pulsing, the vertical emittance of the proton beam at AGS extraction was typically 18-20π mm mrad as measured by the AGS IPM in Run 11. When we initially turned the jump quads on, we measured as much as 100 π mm mrad as a result of constant increase throughout acceleration, even with the above mentioned improvements to the lattice errors. The cure for the emittance growth was to reduce the vertical chromaticity ($dQ_x/\frac{dp}{p}$) from an already small value of 1 to zero for the entire acceleration ramp. This solution is robust, and has not resulted in other instabilities at intensities as high as 3×10^{11}, but it is still not well understood why the jump quads put such a tight constraint on the chromaticity. The vertical tune spread is so small at this chromaticity that if a tune jump induces coherent vertical dipole motion in the beam, that motion persists at roughly constant amplitude until the next jump, some 4 ms later.

SUMMARY

The horizontal tune jump scheme in the AGS has been successfully commissioned. It has reduced the polarization loss from the eighty-two horizontal intrinsic resonances excited by the partial snakes. An increase of 5-8% (absolute) has been realized, allowing for routine delivery of 65% polarized beam at intensities of 2×10^{11} for the RHIC SPIN program [8, 9]. The non-adiabatic tune jump introduces a possible source of emittance growth and several strategies have been employed to reduce the impact of orbit and optics mismatch on the emittance.

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