RECENT RHIC-MOTIVATED POLARIZED PROTON DEVELOPMENTS IN THE BROOKHAVEN AGS*

V. Schoefer, L. Ahrens, M. Bai, S. Binello, M. Blaskiewicz, K.A. Brown, C.J. Gardner, J.W. Glenn, H. Huang, F. Lin, W.W. MacKay, J. Morris, S. Nemesure, T. Roser, S. Tepikian, N. Tsoupas, K. Yip, A. Zelenski, K. Zeno
BNL, Upton, New York, USA

Abstract

The RHIC polarized proton physics program requires high luminosity and high polarization, which depend directly on the intensity, emittances and polarization delivered to RHIC by the injector chain. In the AGS, two partial snakes create gaps in the realized spin tune around the integers which allow an accelerating beam with sufficiently small vertical emittance and near-integer vertical tune to avoid the vertical imperfection and intrinsic resonances. The same strategy strengthens the many (82) weak horizontal intrinsic resonances crossed during AGS acceleration. A system speeding up these resonance crossings is the AGS JumpQuad system, consisting of 82 small (0.04) fast (100 μs) betatron tune shifts that has been commissioned and evolved during RHIC Runs 09, 10, and 11. Subtle properties of the AGS geometry and lattice, magnified into relevance by the high vertical tune can result in polarization-damaging emittance growth when combined with the Jump Quad gymnastics. Orbit stability is critical. Some aspects of the JumpQuad system, of this commissioning effort and related developments will be described.

INTRODUCTION

Polarized protons are delivered to RHIC via an injector chain consisting of an OPPIS polarized proton source, a 200 MeV Linac, two synchrotrons called the Booster and the AGS and their connecting transfer lines. In addition to preservation of emittance and intensity, the quality of the RHIC physics program depends heavily on the preservation of polarization. The polarized proton beam is created at the source with a polarization of 80%. The primary mechanisms for depolarization are the depolarizing resonance conditions met during acceleration in the AGS. Depolarization in the Linac, Booster and transfer lines is minimal as confirmed by polarization measurements made at AGS injection energy.

In 2006, AGS operations began with a pair of helical dipoles, functioning as partial Siberian snakes [1]. These magnets open small gaps in the spin tune during the acceleration cycle such that if the vertical betatron tune is close to an integer, vertical intrinsic and imperfection resonance conditions are not met and those resonances no longer cause depolarization of the proton beam. In the AGS the vertical tune is kept close to 9 (8.985 for most of the acceleration ramp).

That these are partial, rather than full, snakes means that they do not cause a complete 180° rotation of the spin of a proton on a single pass through the magnet. This results in an equilibrium spin direction which is not exactly vertical. This, in turn, means that the snakes make the beam susceptible to depolarization via horizontal intrinsic resonances [2].

Operational difficulties and limits on present power supplies make acceleration with both betatron tunes near the integer prohibitive. The alternative, if one cannot avoid the intrinsic resonance conditions altogether as with the vertical resonances, is to increase the crossing rate so as to experience the minimum depolarization possible at each resonance crossing. This is the strategy employed in the AGS using a pair of fast-pulsing quadrupoles, colloquially called the tune jump quads.

While these quadrupoles decrease the depolarization from horizontal intrinsic resonances, their effects on the vertical orbit and optics are non-adiabatic and special care must be taken to insure that they do not cause emittance growth. Methods used to ameliorate the effects of the tune jump quadrupoles on emittance will also be described here.

TUNE JUMP SYSTEM

Presented here is a brief description of the theory and operation of the tune jump quadrupole system. For a detailed description of the power supplies and controls, see [4].

The resonance condition for horizontal intrinsic resonances is

$$G\gamma = n \pm \nu_x \tag{1}$$

where G = 1.7928474 is the anomalous gyromagnetic ratio of a proton, γ is the Lorenz factor, *n* is any integer and ν_x is the horizontal betatron tune. In the AGS, the proton beam is accelerated from Gγ of 4.5 to 45.5 and so this resonance condition is met 82 times. As each resonance is approached, the current in each of the jump quads is changed rapidly to change the horizontal tune by 0.04 units in about 100 μs, which is about 30 turns. This increases the effective crossing speed by a factor of five and minimizes the amount of depolarization experienced at each resonance.

The quadrupoles are located in straight sections one AGS superperiod apart, which, with 12 superperiods and a vertical tune near 9 amounts to a phase advance of 270°, selected so that the effects of the quadrupoles on the vertical emittance are minimized. The vertical optics are a particular concern since with near-integer tune, the length of a tune

* Work supported by Brookhaven Science Associates, LLC, under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

jump (30 turns) is smaller than a betatron oscillation period (>60 turns), and therefore the jump is non-adiabatic. If the beam is not centered in each of the quads at the time of the jumps, the beam will experience a dipole kick in addition to a quadrupole kick. The net quadrupole kick can be reduced by insuring that the beta functions at the quadrupoles are equal. The dipole kicks can be eliminated by centering the beam properly in the quads. Strategies for accomplishing both of these tasks are related here and in [3].

Calculation of Resonance Crossing Times

The required timing accuracy for the pulsing of the jump quads is determined by the AGS acceleration rate and the size and time width of the tune steps. Over most of the cycle the windows of enhanced crossing speed are about 500 μs wide. The energy spread of the beam results in much of this window being filled so determining the crossing times to the 100 μs level is desired.

To determine when each resonance condition (Gγ = n $\pm$ ν_x) occurs, the time dependence near a crossing of both the beam energy (hence 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 estimate is learned by 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. Playing the two systems against each other is the primary strategy to improve the resolution. Last run 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 agreement between the two systems to be tightened.

Only one beam-based calibration point of useful accuracy is presently known: the beam crossing of the Gγ = 36+ν_v strong 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 Gγ corresponding to a crossing time error of less than 200 μs.

EFFECT ON POLARIZATION

The tune jump quads, properly timed, are designed to minimize the impact of horizontal intrinsic resonances. The strength of an intrinsic resonance goes as the square root of the particle's betatron amplitude, and so depolarization via intrinsic resonances results in polarization profile, where the portions of the beam with larger betatron amplitudes experience more depolarization than the core, with the design or 'zero-emittance' particle experiencing none. The faster resonance crossing time afforded by the tune jump quads was therefore predicted (and was observed) to improve the horizontal polarization profile, as measured with the AGS CNI polarimeter using a horizontally thin, vertically-oriented carbon target.

Shown in Fig. 1 is the polarization of the AGS beam as measured at top energy. A vertically oriented target is inserted into the beam at different horizontal locations. The horizontal position of the target relative to the beam is calculated using the CNI event rate assuming a Gaussian intensity distribution. The vertical error bars are the statistical error bars reported by the CNI polarimetry for each measurement. There is a clear improvement in the polarization of the high amplitude particles (and therefore of the average polarization) when the jump quads are on. The beam intensity for all measurements was kept at 1x10^{11} particles in a single bunch. In operation the polarization is typically measured with a vertically oriented target at the horizontal peak of the intensity distribution. At 1.5x10^{11} protons per bunch the AGS has achieved 70% polarization measured in this way.

Shown in Fig. 2 is the polarization measured in RHIC at injection energy during a span of about 10 days during the present run (RHIC Run 11). The jump quads were put into operation for RHIC fills for the first time early on Thursday February 17. The improvement to the polarization is confirmed here using the RHIC polarimetry (also a set of CNI devices).

EMITTANCE GROWTH

In a superperiod symmetric AGS, the vertical beta functions at each of the two jump quads should be the same for equal currents in the quads. In the 2010 development run for polarized protons in the AGS, the observation of unequal tune changes for equal currents led to the discovery of a large vertical beta function distortion. The source was ultimately found to be a horizontal equilibrium orbit distortion in the lattice chromaticity sextupole magnets, driven by survey errors in the main dipoles. Details of the measurements and remediation of optics errors in the AGS can be found in [3].

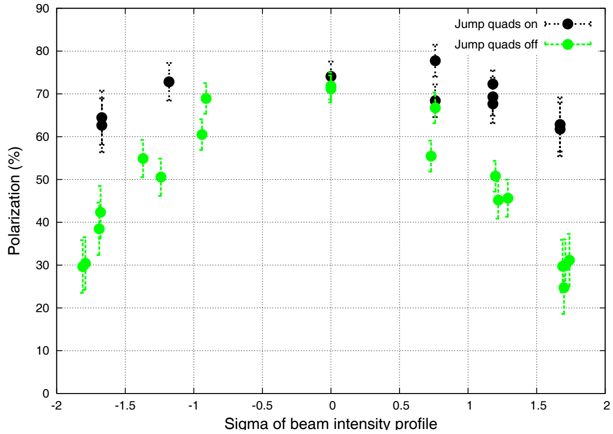

Figure 1: Horizontal polarization profiles at AGS extraction as measured with AGS CNI polarimeter. Green points are with jump quadrupoles off. Black are with jump quadrupoles on. This shows improvement of the polarization of large horizontal betatron amplitude particles.

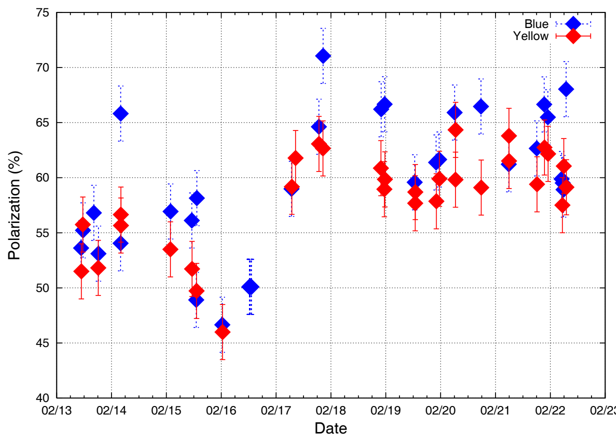

Figure 2: The polarization measured with the RHIC CNI polarimeters at injection energy in both the blue and yellow rings. There is an increase in the polarization starting when the tune jump quadrupoles became operational in the early morning of February 17. All measurements shown are so-called 'sweep' measurements, where the carbon target moves through the beam twice over the course of the measurement. The numbers shown therefore reflect an average over the whole transverse beam distribution.

It was also discovered during Run 11 that the amount of emittance growth caused by the tune jumps is very sensitive to the vertical chromaticity. A normalized vertical chromaticity on the order of 1 unit was observed to drive emittance growth through the AGS cycle amounting to a factor of 5 increase over the emittance measured with the jump quads off (as measured by the AGS ionization profile monitor). Reducing the chromaticity to zero throughout the cycle appears to be necessary to maintain minimum emittance growth. The cause for this strong dependence is still not known.

Orbit Stability and Feedback

In addition to matching optically, it is important to prevent dipole kicks resulting from an off-center vertical equilibrium orbit in the jump quadrupoles at the time of a jump.

At near integer tune, the response of the equilibrium orbit to any change in a single dipole field is dominated by a single orbit harmonic. The AGS Beam Position Monitor system and the associated software are capable of measuring and calculating these harmonics throughout the acceleration cycle. The measurement times are chosen such that one measures the harmonic content of the equilibrium orbit before and after each tune jump. A change in the harmonic content at the time of a tune jump is is a result of a combination of the changing dipole kick experienced by an off-center beam and the change in vertical tune associated with the quadrupole current change. We minimize the dipole contribution to these equilibrium orbit changes by steering the beam in the quads using the AGS orbit steerers and a harmonic orbit correction algorithm.

During the present run we have been commissioning a cycle-to-cycle orbit feedback system specifically designed to measure the effect of the tune jump quadrupoles on the orbit and to use the AGS orbit steerers to correct for that effect. Such a system is challenged by the strong constraints on the AGS equilibrium orbit. The tune jumps occur throughout the cycle, including early acceleration, when the partial snakes still represent a significant perturbation to the AGS lattice (and consequently a decrease in available aperture), through the gamma transition energy, and up through the vertical intrinsic resonance at $G\gamma = 36+\nu_y$. These three times in the cycle also put constraints on the harmonics which have to be respected by any feedback system implemented.

CONCLUSION

The AGS has seen a significant increase in polarization performance over the past run. This increase is due primarily to the successful commission of the tune jump quad system which allows a faster crossing of the eighty-two horizontal intrinsic resonances encountered during the AGS acceleration cycle. This system also represents a strong challenge to maintain the other important beam performance parameters (intensity and emittance) while improving the polarization. This challenge has prompted a series of measurements and development of several tools to allow for the successful acceleration of high intensity, highly polarized proton beams.

REFERENCES

[1] T. Roser *et al.*, Proceedings of SPIN 2004, p. 687.

[2] F. Lin *et al.*, Phys. Rev. ST 10, 044001 (2007).

[3] V. Schoefer *et al.*, Optics Error Measurements in the AGS for Polarized Proton Operation, these proceedings.

[4] J.W. Glenn *et al.*, AGS Tune Jump System to Cross Horizontal Depolarization Resonances Overview, these proceedings.